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An Optimal Backstepping Design for Blended Aero and Reaction-Jet Missile Autopilot

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Abstract: A novel robust adaptive backstepping control approach is presented to design a pitch controller for missiles employing blended aerodynamic control and Reaction-jet Control System (RCS). The main features of this study are that a certain type of control Lyapunov function is obtained by function reconstruction to decrease the control-input fluctuation caused by mismatched controller parameters, optimal backstepping parameter set and Lyapunov function choice are gotten by Genetic Algorithm (GA). So both system stability and dynamic performance are guaranteed. Since the model of a missile with RCS is inaccurate with uncertain effect of RCS and aerodynamic parameters, a Fuzzy Cerebellar Model Articulation Controller (FCMAC) neural network is used to guarantee controller robustness, thus the bounds of model uncertainties are not needed. Finally, simulation results demonstrate the efficiency and advantages of the proposed method.

Key words: Backstepping control, genetic algorithm, Lyapunov function, missile control, robustness

INTRODUCTION

Blended aerodynamic control and Reaction-jet Control System (RCS) has been studied in recent years (Chamberlain, 1990; Rui and Koichi, 2001; Thakral and Innocenti, 1998) to improve missile maneuverability. Compared with normal aerodynamic control, missile with RCS is difficult to design. The model inaccuracies such as uncertain reaction-jet effect and parametric uncertainties propose challenge to design for missile control system. Furthermore, how reaction-jet forces and aerodynamic forces are distributed needs a blended strategy.

In prior studies, Rui and Koichi (2001) proposed the coefficient of diagram method (CDM) for the control of RCS. Thakral and Innocenti (1998) proposed variable structure method for blended control to show the decreasing of fin-rate could be reached by RCS.

In this study, a Modified Backstepping Method (MBM) is used to design autopilot balancing stability and response for aero-fin controlled missile with RCS. By backstepping (Kokotovic, 1999), control law is obtained from recursive procedure derived from Lyapunov function, which guarantees stability in design. Polycarpou and Ioannou (1996) and Krstic and Kokotovic (1996), proposed adaptive backstepping to guarantee uniform ultimate boundness despite model uncertainties. But in previous researches, Lyapunov function was chosen in advance and backstepping controller coefficients were decided by trial and error, that is low-efficiency. In addition, the bounds of uncertain parameters had to be known. In MBM, a reformed Lyapunov function was used, which decreased control-input fluctuation caused by mismatched backstepping parameters and genetic algorithm (GA) was used to choose parameters with optimal dynamic response. We used a fuzzy cerebellar model articulation controller (FCMAC) neural network (Kwan *et al*., 1996; Kim, 2002) to estimate modelling errors and parameter uncertainties without knowing the variation bounds of the uncertainties. Computer simulations show that this approach is very promising for autopilot design for the missiles with RCS.

BLENDED SYSTEM DESCRIPTION

A missle with RCS was described in Fig. 1. The RCS is located in ahead of the center of gravity (e.g.). Side force can be generated by controlling jet valves. $ox_1y_1z_1$ is body coordinate system with the origin being at c.g. and ox_1,oy_1,oz_1 are direct-axis and longitudinal-axis, lateral-axis respectively. The distance between c.g. and the RCS location is l_s, aero-fin angle is δ_a. f_s, the force by RCS is defined using δ_a as follow,

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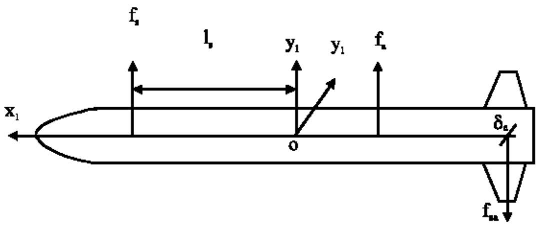


Fig. 1: RCS Mechanism

$$\delta_s = (f_s/f_{sm})\delta_{am} \tag{1}$$

where f_{sm}, δ_{am}, are the maximum force by RCS and the maximum fin-deflection angle, respectively. f_a and $f_{\delta a}$ are force by attack angle α and aero-fin angle δ_a, individually.

The longitudinal dynamics of the missile are modeled as follow (Qian *et al.*, 2000)

$$\dot{x}_1 = f_1(x_1) + x_2 + \Delta_1(x_1, x_2) \tag{2}$$

$$\dot{x}_2 = f_2(x_1, x_2) + c(x)u + \Delta_2(x_1, x_2) \tag{3}$$

$$\dot{y} = n_y = qsc_y^{\alpha}/(mg)\dot{x}_1 \tag{4}$$

where x = $[\alpha, \omega_z]$, α, ω_z are the attack angle and rotation rate about oz_1 acceleration respectively. u = $[\delta_a, \delta_s]$ are control-input vector. y is controller output, tracking longitudinal acceleration, n_y.
$f_1(x_1) = -(T\sin x_1 + c_y^{\alpha}qsx_1)/(mv)$, $B = qsc_y^{\alpha}/(mg)$
$f_2(x_1, x_2) = (mgLm_z^{\alpha}/(J_z c_y^{\alpha}))x_1 + (qsL^2 m_z^{\omega_z}/(2vJ_z))x_2$,
$c = [c_1 \;\; c_2]$, $c_1 = qsbm_z^{\delta_z}/J_z, c_2 = l_s f_{sm}/J_z$, Δ_1 and Δ_2 denote model uncertainties; q, s, L and J_z are missile dynamic pressure, reference area, length of aerodynamic chord and inertial, respectively; m, v, T are missile mass, speed and propulsion force, respectively; c_y^{α}, $m_z^{\alpha}, m_z^{\delta_z}$ and $m_z^{\omega_z}$ are aerodynamic coefficients.

ROBUST BACKSTEPPING CONTROL OF MISSILE

The control objective is to track a given reference n_{yc} ($=y_{id}$). In the controller design, we don't considered uncertainties Δ_1, Δ_2 first, let it be handled by robustness analysis. The proposed control system is described via backstepping technique step-by-step as follows:

Step 1: Define error variables $z_i = x_i - x_{id}$, i = *l*, 2, x_{id} represents the desired value of state x_i, $x_{1d} = \alpha_d$, decided by n_{yc} in Eq. (4). The deriveative of z_1 is

$$\dot{z}_1 = \dot{x}_1 - \dot{x}_{1d} \tag{5}$$

x_2 is regard as a virtual control to stabilize Eq. (5) by selecting

$$x_{2d} = -f_1(x_1) - k_1 z_1 + \dot{x}_{1d} \tag{6}$$

Where k_1 is positive constant that is to be determined later. So Eq. (5) can be rewritten as

$$\dot{z}_1 = f_1(x_1) + x_2 - \dot{x}_{1d} = -k_1 z_1 + z_2 \tag{7}$$

Step 2: Take the time derivative of z_2 to have

$$\dot{z}_2 = \dot{x}_2 - \dot{x}_{2d} \tag{8}$$

Substitute Eq. (3), (6) into (8), to get

$$\begin{aligned}\dot{z}_2 = f_2 + c(x)u - (\partial x_{2d}/\partial x_1)\dot{x}_1 - \\ (\partial x_{2d}/\partial x_{1d})\dot{x}_{1d} - (\partial x_{2d}/\partial \dot{x}_{1d})\ddot{x}_{1d}\end{aligned} \tag{9}$$

Step 3: Lyapunov function is vital to stabilize the system (2). It is traditional to set function form in advance, such as $V_1(z_1) = z_1^2/2$ to stabilize Eq. (5). Here, without taking the traditional way, function of V is chosen as a general form and then reconstruct it later by considering the influence of function on control law. The function is chosen as

$$\begin{aligned}V_1(z_1) &= F(z_1) \\ V_2(z_1, z_2) &= F(z_1) + z_2^2/2\end{aligned} \tag{10}$$

Where $F(z_1)$ is a general Lyapunov function of z_1, V_1 and V_2 stabilize subsystem (2) and (3), respectively. The derivative of Eq. (10) is:

$$\begin{aligned}\dot{V}_2(z_1, z_2) &= \dot{F}(z_1)\dot{z}_1 + z_2\dot{z}_2 \\ &= -k_1\dot{F}(z_1)z_1 + z_2[\dot{F}(z_1) + f_2(x_1, x_2) + cu \\ &\quad -(\partial x_{2d}/\partial x_1)\dot{x}_1 - (\partial x_{2d}/\partial x_{1d})\dot{x}_{1d} - (\partial x_{2d}/\partial \dot{x}_{1d})\ddot{x}_{1d}] \\ &= -k_1\dot{F}(z_1)z_1 + z_2[\dot{F}(z_1) + l_2(m_z^{\alpha} - l_1 l_3 - l_3 k_1)z_1 \\ &\quad + l_2(l_3 z_2 + (m_z^{\alpha} - l_1 l_3)x_{1d} + l_3\dot{x}_{1d}) - k_1\dot{x}_{1d} - \ddot{x}_{1d} + cu] \\ &= -k_1\dot{F}(z_1)z_1 + z_2[\dot{F}(z_1) + (l_2(m_z^{\alpha} - l_1 l_3) - (l_1 + l_2 l_3) \\ &\quad k_1 - k_1^2)z_1 + (k_1 + l_1 + l_2 l_3)z_2 + l_2(m_z^{\alpha} - l_1 l_3)x_{1d} \\ &\quad + (l_2 l_3 + l_1)\dot{x}_{1d} - \ddot{x}_{1d} + cu]\end{aligned} \tag{11}$$

where
$l_1 = -(T + c_y^{\alpha}qs)/(mv)$, $l_2 = qsL/J_z$, $l_3 = Lm_z^{\omega_z}/(2v)$, k_1 and k_2 are to be decided later. The assumption $\sin x_1 \approx x_1$ is taken in Eq. (11), since x_1 is generally small.

It is clear from Eq. (11) that to stabilize whole system, the following equations are valid

$$\dot{F}(z_1) = -(l_2(m_z^{\alpha} - l_1 l_3) + (-l_1 - l_2 l_3)k_1 - k_1^2)z_1 \tag{12a}$$

$$l_2(m_z^\alpha - l_1 l_3) + (-l_1 - l_2 l_3)k_1 - k_1^2 < 0 \qquad (12b)$$

$$k_2 > k_1 + l_l + l_2 l_3 \qquad (13a)$$

$$\begin{aligned} u_i = c_i^{-1}(-k_2 z_2 - l_2(m_z^\alpha - l_1 l_3) \\ x_{1d} - (l_2 l_3 + l_1)\dot{x}_{1d} + \ddot{x}_{1d}) \end{aligned} \qquad (13b)$$

It is known from Eq. (12-13), Lyapunov function can be decided by choosing k_1, k_2, which in turn are restricted by Eq. (12-13). So concrete function form can be obtained by analyzing them. The analysis process is as follows

- If $l_2(m_z^\alpha - l_1 l_3) + (l_1 + l_2 l_3)^2/4 < 0$, Eq. (12b) is constant valid. The control law from Eq. (13b) will stabilize system (2) with $k_1>0$ and k_2 satisfies Eq. (13a);
- If $l_2(m_z^\alpha - l_1 l_3) + (l_1 + l_2 l_3)^2/4 > 0$, then k_1 is decided by Eq. (12b). But if $k_1>50$, part of $l_2(m_z^\alpha - l_1 l_3) + (l_1 + l_2 l_3)^2/4$ should be compensated by control law in order to avoid large gain. Define $l_2(m_z^\alpha - l_1 l_3) = t_1 + t_2$, since $m_z^\alpha < 0$, $l_1<0$, $l_2>0$, $l_3<0$. So Eq. (12-13) can be rewritten as

$$\left.\begin{aligned} \dot{F}(z_1) = -t_1 + (-l_1 - l_2 l_3)k_1 - k_1^2)z_1 \\ k_1^2 + (l_1 + l_2 l_3)k_1 - t_1 > 0 \\ u_i = c_i^{-1}(-t_1 z_1 - k_2 z_2 - l_2(m_z^\alpha - l_1 l_3) \\ x_{1d} - (l_2 l_3 + l_1)\dot{x}_{1d} + \ddot{x}_{1d}) \end{aligned}\right\} \qquad (14)$$

where the control parameters $k = [k_1,k_2]$, the ratio $t = [t_1,t_2]$ are decided by genetic algorithm later. It is obvious that such Lyapunov function choice can reduce the influence of z_1 on control law when mismatched k_1 causes error to fluctuate.

Step 4: In the backstepping design procedure, key parameters are, *k* or *k* and, *t* if $k_1>50$. Proper values will bring better performance. So we chose these values by genetic algorithm (GA). GA is a kind of optimization technology by nature evolution. If population size and fitness functions (Chen and Ying, 2004) are decided rightly, GA will optimize objectives efficiently, which set the optimal value for k and t, here. The process of optimization is as follow:

- Initial individuals for k, or t were generated randomly in eight-bit binary, but with restrictions by Eq. (12-14), the individuals number can be small. The smaller population sizes are, evolution times will be shorter. The number of individuals is 20.
- Define the objective function for the optimization of control parameters

$$J = \int_0^\infty (w_1|e(t)| + w_2 u^2(t) + w_3|ey(t)|)dt + w_4 t_u \qquad (15)$$

where w_1, w_2, w_3 and w_4 are weights to adjust the effect of tracking error, control input, overshoot and transition time. Here, $w_1 = 0.99$, $w_2 = 0.01$, $w_3 = 5$, $w_4 = 80$. Making J be the least, integrated performance of controller can be optimal.

- Make crossover at one point, which is simple since individuals has been filtered by restriction of Eq. (12-14). The crossover probability and mutation probability are Pc = 0.15 and Pm = 0.01, respectively.

Step 5: In blended control system, RCS responds faster than aero-fin control and it was used when findeflection angles exceeds their maximum value, traditionally (Cheng *et al*., 2003). But system responses become slow and transition process was not smooth. Here, we use energy optimal strategy to distribute two inputs. The brief design is as follow:

Define energy function as

$$J = [(n_{ya}/n_{yamax})^2 + (n_{yr}/n_{yrmax})^2]/2 \qquad (16)$$

where n_{ya} and n_{yamax} are overload and the maximum one by aerofin angles, n_{yr} and n_{yrmax} are overload and the maximum one by RCS, which n_{ya} and n_{yr} can be drawn from moment Eq. (2) n_{yamax} and n_{yrmax} are decided by missile configuration. The function will distribute command overload to aero-fin and RCS, according to function extremum when energy consumptions are optimal. The distributing ratio is gotten through partial derivation

$$\begin{aligned} n_{yr} = \frac{k_2^2 f_{symax}^2}{k_2^2 f_{symax}^2 + k_1^2 \delta_{emax}^2} \cdot n_{yc}, \\ n_{ya} = \frac{k_1^2 \delta_{emax}^2}{k_2^2 f_{symax}^2 + k_1^2 \delta_{emax}^2} \cdot n_{yc} \end{aligned} \qquad (17)$$

where $k_1 = \frac{qs}{mg}(-c_y^\alpha \frac{m_z^{\delta_e}}{m_z^\alpha} + c_y^{\delta_z})$, $k_2 = \frac{1}{mg}$. The energy optimal distributing strategy of aero-fin and RCS can make both actuators consume energy least.

Step 6: It is obvious the ideal backstepping control law Eq. (13b), (14) were gotten by neglecting the model uncertainties of Δ_1 and Δ_2. Since the plant dynamics $f_i(t,x)$, c_i, i = 1, 2 are not precisely known, the ideal backstepping control law Eq. (13b), (14) are unachievable. We use FCMAC neural network to approximate model errors. The system control law is assumed to take following form:

$$u = u_d + u_{rb} \quad (18)$$

where u_d is system ideal control law and u_{rb} is the estimation of system errors. According to Daijin (2002), any continuous nonlinear function h(x) can be expressed as

$$h(x) = \sum_{j=1}^{M} w_j{}^T \Gamma_j \quad (19)$$

Where $\Gamma_j = \min\{\mu_{1.j_1}(x_1)\mu_{2.j_2}(x_2)\cdots\mu_{m.j_m}(x_m)\}$ is fire strength $w = [w_1, w_2, ..., w_M]$, is weight vector, M is the number of fuzzy rules $\mu_{i,ji}(x_i)$, is the jth membership function of the ith input control i = 1, 2,..., m_i, m_i is state number, j_i = 1,2,...,m_i, m_i is the quantization number of the ith input variabl,

$$M = \sum_{i=1}^{m} m_i.$$

If FCMAC is utilized to mimic nonlinear function f_i of Eq. (2), f_i can be expressed as

$$f_i = w_i{}^T \Gamma_i + \varepsilon_i, i = 1, 2 \quad (20)$$

where w_i, Γ_i and ε_i denote the ideal connecting weight value of the network, fire strength of fuzzy rules and the minimum reconstructive errors, respectively. Since ideal f_i can not be obtained, the estimation of f_i can be written as follows:

$$\hat{f}_i = \hat{w}_i{}^T \Gamma_i \quad (21)$$

Where $\hat{w}_i$ is the estimates of w_i, I = 1, 2. Subtract Eq. (21) from Eq. (20), the approximation error is

$$u_{rb} = f_i - \hat{f}_i = \tilde{w}_i{}^T \Gamma_i + \varepsilon_i \quad (22)$$

with $\tilde{w}_i = w_i - \hat{w}_i$

Next select the update laws as

$$\dot{\hat{W}} = R\Gamma Z - k_w R \|Z\| \hat{W} \quad (23)$$

where R = diag{r_1,r_2} is positive matrix, k_w is a positive constant, $\|z\|$ is the Frobenius norm of Z. Finally the control law Eq. (18) can be obtained.

Assumption 1: $\|W\| \le W_m$, W_m is the maximum norm of W.

Assumption 2: $\|\varepsilon_i\| \le \varepsilon_m$, ε_m is the maximum norm of ε_i.

Theorem: The robust control law described by Eq. (13, 14 and 18) with the update law of Eq. (23) and assumption 1, 2 can guarantee the stability of the backstepping control system.

Proof: A Lyapunov function is defined as

$$V(z_1, z_2) = V_2 + \tilde{W}^T R^{-1} \tilde{W} / 2 \quad (24)$$

Taking the derivative of (24) and substituting (11) into (24), it is concluded that

$$\begin{aligned}\dot{V} &= \dot{V}_2 + \left\{\tilde{W}_1{}^T r_1^{-1} \dot{\tilde{W}}_1 + \tilde{W}_2{}^T r_2^{-1} \dot{\tilde{W}}_2\right\} \\ &= -k_1 z_1 \dot{F}(z_1) - (k_1 + l_1 + l_2 l_3 - k_2) z_2{}^2 \\ &\quad + k_w \|Z\| tr\left\{\tilde{W}\hat{W}\right\} + z^T \varepsilon \\ &= -Z^T p(k) Z + k_w \|Z\| tr\left\{\tilde{W}\hat{W}\right\} + z^T \varepsilon\end{aligned}$$

Where p(k) = diag{p_1,p_2} denotes positive function of k, drawn from V(z_1,z_2), Z = [z_1 z_2]^T. Applying the schwartz inequality (Kwan, 2000)

$$tr\left\{\tilde{W}\hat{W}\right\} \le \|\tilde{W}\|\|W\| - \|\tilde{W}\|^2 \quad (25)$$

We have

$$\begin{aligned}\dot{V}(z_1, z_2) &\le -k_{min}\|Z\|^2 + k_w\|Z\|\|\tilde{W}\|(W_M - \|\tilde{W}\|) + \|Z\|\varepsilon \\ &= -\|Z\|[k_{min}\|Z\| + k_w\|\tilde{W}\|(W_M - \|\tilde{W}\|) - \varepsilon_{max}] \\ &= -\|Z\|[k_{min}\|Z\| - \varepsilon_{max} + k_w(\|\tilde{W}\| - W_M/2)^2 \\ &\quad - k_w W_M^2/4]\end{aligned}$$

which is negative as long as the term in square bracket is positive. Here k_{min} is the minimum eigenvalue of k with p(k)>k_{min}, $\tilde{W} = [\tilde{w}_1 \ \tilde{w}_2]^T$, $\varepsilon = [\varepsilon_1 \ \varepsilon_2]^T$. Thus $\dot{V}$, is negative as long as $k_{min} > (k_w W_M^2/4 + \varepsilon_m)/\|Z\|$ or $\|\tilde{W}\| > W_M/2 + \sqrt{W_M^2/4 + \varepsilon_m/k_w}$.

It can be shown that the errors of Z = [z_1 z_2]^T converge to zero as t→8.

SIMULATION STUDIES

The proposed control strategy is tested by the nonlinear model of missile with RCS. The main objectives were to test autopilot tracking performance and to test the robustness of the methodology with respect to aerodynamic parameter variations. The actual configuration in the system are f_{sm} = 5000N, m = 102 kg, S = 0.013 m^2, L = 70 kg m^2.

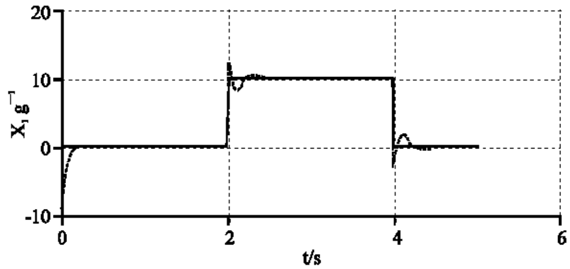
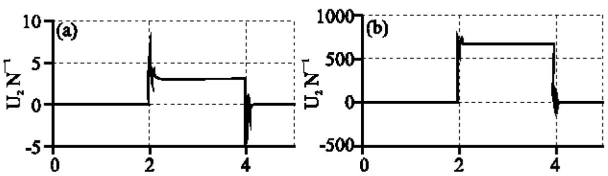


Fig. 2: Longitude acceleration response (g).



0Fig. 3: Response by blended MBM control (A) fin angle response (g). (B) RCS response (N)

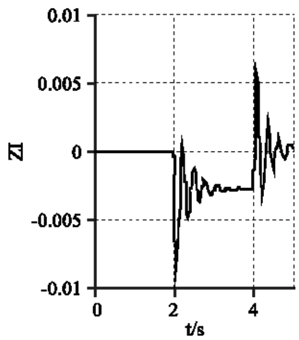


Fig. 4: Tracking error of z_1z_1 control with mismatched k and function of $V_1 = z_1^2/2$

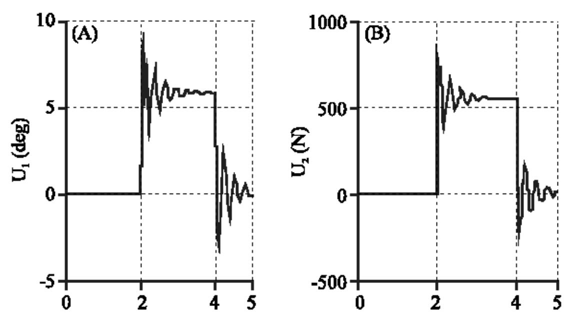


Fig. 5: Control response with fluctuating error effect of z_1. (A) fin angle response (g) (B) RCS response (N)

The flight condition is in pitch at Mach 0.8, height of 10000 ft and desired output 10 g. The aerodynamic coefficients are taken from (13). Since parameters satisfy $l_2(m_z^\alpha B - l_1l_3) + (l_1 + l_2l_3)^2/4 < 0$, so if $k_1>0, k_2 > (k_1 + l_1)B^{-1} + l_2l_3$, value of k is ok. The initial controller parameters were chosen as k_i = 1, i = 1,2. It should be noted that the larger the values of k_i are, the better tracking accuracy will be given, but control effort will become larger. In order to get proper values, GA was used to give the best set of k in the study. The final values are: k_1 = 18.6, k_2 = 34.3, by GA in the 10th generation evolution. The results of simulation are shown in Fig. 2-6. Figure 2 shows that control output converges to the command quickly, with overshoot smaller than 0.2. Figure 3a and b are input responses, fin-deflection angle and reaction-jet force, respectively, which distributed by optimal energy strategy. Figure 4 shows fluctuating error convergence affects control input when k is mismatched (k = 0.1, 0.5), without GA optimization, the Lyapunov function is the traditional $V_1(z_1) = z_1^2/2$. Figure 6 shows system robustness to aerodynamic coefficients varying from -50 to 100%, that is pert = 100 and pert = -50%. The simulations indicate that proposed controller remain robustness to improper value of k and aerodynamic parameters variation.

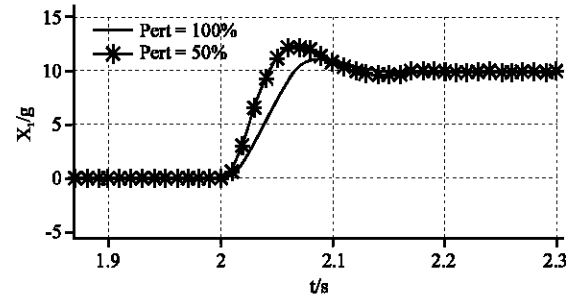


Fig. 6: Accleration responsence with parameters perturbation

CONCLUSIONS

This study described an adaptive backstepping controller with optimization by GA and Lyapunov function reformation. GA is used to optimize backsttepping coefficients and choose Lyapunov function to get better dynamic performance and lower the sensibility of control law to coefficient variation of k. FCMAC is used to compensate model errors, with uncertainties bound are not given. Simulations show that system responses faster and has robustness against aerodynamic parameters variation and fluctuating error with mismatched parameter k.

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