A Design Method of BTT Missile Autopilot with the Impact of Feedforward

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Abstract
In order to solve the feedforward problem of traditional back-to-turn (BTT) missile autopilot, this paper proposed a controller design method considering the forward effect. Firstly, according to the three-channel mathematic model of BTT missile, we built a mathematic model of autopilot control system. Secondly, by employing the Nussbaum-type gain technique as well as the adding a power integrator design, and based on the design needs of tracking and controlling overload steadily, we proposed a global nonlinear control strategy, and then designed a continuous nonlinear autopilot, which solved the feedforward problem of BTT missile on pitching channel. Thirdly, we strictly proved the stability of the control system in finite time by applying the method of Lyapunov stability theory. Finally, we gave a simulation example to show that the designed control system not only overcome the influence of uncertain factors and the problem of the stable error, but also improved the tracking precision.

Keywords: BTT, Feedforward controller, Nonlinear systems, Adaptive control, Output tracking

1. Introduction
No matter whether it is back-to-turn (BTT) or slide-to-turn (STT) missile, the change of the vertical or lateral overload of rudder is through autopilot by the deflection. When the rudder is deflected, the missile’s postures are adjusted accordingly, so as to change the vertical or lateral aerodynamics of missile body and missile wings; meanwhile, the rudder yields another vertical or lateral aerodynamics, which influences the loading of missile. These influences are the missile’s forward effect from the missile surface deflection to the missile body.

The existence of the forward effect actually adds a zero-point to the system, which makes the design of the missile autopilot (especially the design based on the modern control theory) more difficult; thus most the previous missile autopilots always ignored the forward effect, which makes the system design easier but brings large errors to the system. Meanwhile, when the forward effect is strong, these errors are always leading to a failure of the design(Zhou Jun, Chen Xin-hai, Zhou Feng-qi, 1994)(Xing Li-dan, Chen Wan-chun, Yin Xing-liang, 2008)(Tong Chun-xia, Wang Zheng-jie, Zhang Tian-qiao, 2006).

In this paper, in view of the pitching channel of BTT missile, we convert the mathematic model of missile body into a state equation, apply Nussbaum-type gain technology and back-stepping design method, propose a global nonlinear control strategy based on the design requirement of stable trace controlling, and design a continuous nonlinear autopilot to make sure the missile body vertical \( n_z \) traces homing order \( n_{uc} \), thereby we resolve the problem of BTT missile’s pitching channel forward effect. Finally, we use Lyapunov stable theory to strictly prove that our control system can achieve the overall situation’s stability in finite time.

2. Dynamic model of missile body
For advanced BTT missile, since the rolling channel is not stable anymore, there exist many strong couplings between each channel, among these couplings, the inertia coupling and the dynamic coupling are especially
important. After considering the effect of inertia coupling and dynamic coupling, the three channels body mathematic model for BTT missile can be written as follows:

\[
\begin{align*}
\dot{\alpha} &= w_z - w_y \beta - a_1 \alpha - a_2 \delta_z \\
\dot{\beta} &= w_y + w_x \alpha - b_1 \beta - b_2 \delta_y \\
\dot{w}_z &= -a_1 w_z - a_1' \dot{\alpha} - a_2 \alpha - a_3 \delta_z + \frac{J_z - J_x}{J_z} w_z w_y \\
\dot{w}_y &= -b_1 w_y - b_1' \dot{\beta} - b_2 \beta - b_3 \delta_y + \frac{J_z - J_y}{J_y} w_y w_z
\end{align*}
\]

(1)

where \(\alpha\) and \(\beta\) are the missile’s attack angle and sideslip angle respectively; \(w_x, w_y\) and \(w_z\) are the rotational angular velocities in missile body coordinate; \(\delta_y\) and \(\delta_z\) are the rudder’s deflexion angles on the yaw channel and pitching channel; \(J_x, J_y\) and \(J_z\) are the moments of inertia in missile body coordinate; \(a_1, a_1', a_2, a_3, a_4, b_1, b_1', b_2, b_3, b_4\) and \(b_5\) are the aerodynamic parameters on the pitching channel and yaw channel.

Here, the vertical overload of missile body can be expressed as:

\[n_y = V(\alpha \omega y + \alpha \delta_y) / g\]  

(2)

We can see from (2) that the pitching channel exists a forward effect from the rudder’s deflexion to the vertical overload.

The design of pitching channel autopilot is to make sure the vertical overload \(n_y\) of missile body can trace homing order \(n_{yc}\) effectively:

\[\lim_{t \to \infty} (n_y - n_{yc}) = 0\]  

(3)

When ignoring the forward effect, the vertical overload of missile body is

\[n_{y1} = V a_4 \alpha / g\]  

(4)

For this situation, according to (1) and (4), literature (Lin W, Qian C J. 2000) concluded a pitching channel control law of BTT missile as follows:

\[\delta_z = f(\alpha, \beta, \alpha \omega y, \omega y, \alpha \delta_y, V, n_{y1})\]  

(5)

The control law (5) can ensure \(n_{y1}\) to trace \(n_{yc}\), and \(n_{y1} = n_{yc}\) in steady state; however, due to the existence of the forward effect, the actual vertical overload of missile body \(n_y\) doesn’t trace \(n_{yc}\) in steady state, and \(n_y\) is

\[n_y = n_{y1} + \frac{V a_4 \delta_z}{g} = n_{yc} + \frac{V a_4 \delta_z}{g} \neq n_{yc}\]  

(6)

So we can see that the control law (5) fails to achieve the design aim of pitching channel autopilot (3). To solve this problem, we need to design a new forward controller.

According to (1) and (2), the overload control system model of autopilot is

\[
\begin{align*}
\dot{\alpha} &= \frac{V a_4}{g} w_y - a_1 n_y - \frac{V a_4}{g} w_y \beta + \frac{V a_4}{g} \delta_z \\
\dot{\beta} &= \frac{V a_4}{g} w_y + \frac{g}{V} (a_1' - a_2) n_y + \left(\frac{a_2 a_3}{a_4} - a_3\right) \delta_z + \frac{J_z - J_y}{J_x} w_y w_z \\
\dot{w}_z &= (-a_1 - a_1') w_z + \frac{g}{V} (a_1' - a_2) n_y + \left(\frac{a_2 a_3}{a_4} - a_3\right) \delta_z + \frac{J_z - J_x}{J_y} w_y w_z
\end{align*}
\]

(7)

Taking \(X = [n_y, w_y]^T\) as the system states, and \(\delta_z\) as the control variable, we can obtain from (7) the pitching channel mathematical model of missile body as follows:
\[
\begin{align*}
\dot{x}_1 &= \frac{Va_4}{g}x_2 - a_4x_1 - \frac{Va_5}{g}w_z\beta + \frac{Va_6}{g}\delta_z \\
\dot{x}_2 &= \left(\frac{a_4a_5}{a_4} - a_3\right)u_1 - (a_4 + a_1')x_2 + \frac{g}{V}(a_1' - \frac{a_2}{a_4})x_1 + \frac{J_x - J_y}{J_z}w_xw_y
\end{align*}
\]  

(8)

where \( x_1 = n_z \), \( x_2 = w_z \) and \( u_1 = \delta_z \). The disturbing items in (8) include all the coupling effects on the pitching channel.

3. Controller design with the impact of feedforward

3.1 Controller design of the nonlinear system

We firstly study the output tracking problem of SISO nonlinear system, which can be expressed as (Wang Q D, Jing Y W, Zhang S Y, 2004) (Wang Qiang-de, Jing Yuan-wei, Zhang Si-ying, 2006):

\[
\begin{align*}
\dot{x}_1 &= cx_2 + \phi_1(x, u, d(t)) \\
\dot{x}_2 &= cx_3 + \phi_2(x, u, d(t)) \\
\vdots \\
\dot{x}_n &= g(t)u + \phi_n(x, u, d(t)) \\
y &= x_1
\end{align*}
\]  

(9)

where \( x = (x_1, \ldots, x_n)^T \in \mathbb{R}^n \), \( u \in \mathbb{R} \) and \( y \in \mathbb{R} \) are the system states, input and output respectively; \( g(t) \neq 0 \) and \( d(t) \) are two unknown limit piecewise continuous time-variation functions (their borders are unknown), \( \phi_i \) is a continuous function of its variables. In the following, combining Nussbaum-type gain technology with back-stepping design method, we study the output problem of nonlinear system (9).

For the output tracing problem of nonlinear system (9), the controlling aim is to construct a robust adaptive state feedback nonlinear controller, so as to make the system’s output tracing error \( y(t) - y_r(t) \) globally uniformly bounded, which is to say that:

\[
\lim_{{t \to \infty}} |y - y_r(t)| < \varepsilon
\]  

(10)

Meanwhile, the controller also needs to ensure all the other signals of the closed-loop system globally uniformly bounded.

For the convenience of controller design, we give some Lemmas and definitions as follows:

Lemma 1 (Wang Qiang-de, Jing Yuan-wei, Zhang Si-ying, 2006): For any positive integer \( m, n \) and any real-value function \( r(x, y) > 0 \), the following inequality exists:

\[
\left| x \right|^m \left| y \right|^n \leq \frac{m}{m+n}r(x, y)\left| x \right|^{m+n} + \frac{n}{m+n}r^{-\Delta/n}(x, y)\left| y \right|^{m+n}
\]  

(11)

Lemma 2 (Wang Qiang-de, Jing Yuan-wei, Zhang Si-ying, 2006): For \( \phi_i(x, u, d(t)) \) in system (1), there exists a known smooth function \( \overline{f}_i(x_1, \ldots, x_i) \geq 1 \) and an unknown constant \( \Theta \geq 1 \) to make \( |\phi_i(x, u, d(t))| \leq \overline{f}_i(x_1, \ldots, x_i)\Theta \).

Lemma 3 (Wang Qiang-de, Jing Yuan-wei, Zhang Si-ying, 2006): For any real numbers \( a \geq 0, b > 0 \) and \( m \geq 1 \), a inequality \( a \leq b + \frac{a}{m!}\left| m! \right|^{b+1} \) holds.

We use the Nussbaum-type gain technology to overcome the difficulty of the control direction unknown, and submit some correlative definition and lemma as following:

Definition 1 (Nussbaum R D, 1983): Function \( N(\chi) \) is named Nussbaum-type function, if it has the following properties:
\[
\limsup_{s \to \infty} \frac{1}{s} \int_0^s N(\chi) d\chi = +\infty \\
\liminf_{s \to \infty} \frac{1}{s} \int_0^s N(\chi) d\chi = -\infty
\] (12)

where \( N(\chi) = \exp(\chi^2) \cos|\pi \chi|/2 \).

Lemma 4 (Nussbaum R D, 1983): Suppose \( V(t) \) and \( \chi(t) \) are two smooth functions which are defined in the interval \([0, t_f]\), for \( \forall t \in [0, t_f] \) and \( V(t) \geq 0 \), \( N(\chi) \) is a suitable and smooth Nussbaum-type function, if the following inequality holds:

\[
V(t) \leq c_0 + e^{-\delta t} \int_0^t (g(\tau) N(\chi) + 1) \dot{\chi} e^{\delta \tau} d\tau
\] (13)

where \( c_0 \) is a suitable constant, \( c_i > 0 \), \( g(t) \) is the variable time-varying parameter which is in an unknown closed interval \( I = [I_1, I_2] (0 \notin I) \), thus \( V(t), \chi(t) \) and \( \int_0^t (g(\tau) N(\chi) + 1) \dot{\chi} e^{\delta \tau} d\tau \) must have borders in \( [0, t_f] \).

The controller design of nonlinear system can be described as follows:

Step 1: Give a bounded smooth reference signal \( y_r \), let \( \xi_1 = x_1 - y_r \) as the error signal, then construct a positive-define and proper Lyapunov function \( V_1(\xi_1) = \xi_1^2 / 2 \), and a direct calculation is given as

\[
\dot{V}_1 = \xi_1 [c_2 + \phi_1(x, u, d(t)) - \dot{y}_r(t)]
\] (14)

Since \( y_r \) is bounded, there exists a smooth function \( \gamma_1(\xi_1) \) satisfying the following inequality.

\[
|\phi_1(x, u, d(t)) - \dot{y}_r(t)| \leq \gamma_1(\xi_1)
\] (15)

According to Lemma 3, for any constant \( \delta_1 > 0 \), there exists a smooth function \( \rho_1(\xi_1) \geq 0 \); let \( a = |\xi_1| \gamma_1(\xi_1) \), \( b = \delta_1 \) and \( m = 2 \), we can obtain the following result:

\[
|\xi_1| \gamma_1(\xi_1) \leq \xi_1^2 \rho_1(\xi_1) + \delta_1
\] (16)

where \( \rho_1(\xi_1) = \delta_1 + \xi_1^2 \gamma_1^2(\xi_1)/4\delta_1 \)

Combining (14) with (16), we have the following result:

\[
\dot{V}_1 = \xi_1 [c_2 + \xi_1 \rho_1(\xi_1)] + \delta_1
\] (17)

After we choose \( x_2^* = -\xi_1^2 / 2 + \rho_1(\xi_1) = -\xi_1^2 \rho_1(\xi_1) \) as the virtual smooth controller, (17) can be rewritten as:

\[
\dot{V}_1 = -2\xi_1^2 + \xi_1 [c_2 - x_2^*] + \delta_1
\] (18)

Step 2: Suppose at step k-1, there are a set of smooth virtual controllers and coordinate changes, which are defined by

\[
\begin{align*}
\xi_1 &= x_1 - x_1^* \\
x_2 &= -\xi_1^2 \beta_1(\xi_1) \\
\vdots \\
x_k &= -\xi_{k-1}^2 \beta_{k-1}(\xi_{k-1}, \xi_{k-2}, ..., \xi_1) \\
\end{align*}
\]

where \( \beta_1(\xi_1) > 0, ..., \beta_{k-1}(\xi_{k-1}) > 0 \) are smooth. There exists a smooth Lyapunov function \( V_{k-1} = \sum_{i=1}^{k-1} \frac{1}{2} \xi_i^2 \) satisfying the following inequality.
\[ V_{k+1} \leq -\sum_{i=1}^{k-1} \xi_{k+1}^2 - 2\xi_{k+1} \xi_{k-1} \{cx_k - x_k^*\} + \delta_{k-1} \]  

(19)

According to Lemma 1 and Lemma 2, and based on a Lyapunov function \( V_k = V_{k+1} + \xi_k^2 / 2 \), we can acquire the following inequality:

\[
V_k \leq -\sum_{i=1}^{k-1} \xi_{k+1}^2 - 2\xi_{k+1} \xi_{k-1} \{cx_k - x_k^*\} + \delta_{k-1} + \xi_k \{x_{k+1} + \phi_k(x, u, d(t)) - \sum_{i=1}^{k-1} \partial x_k \xi_k \} \]

(20)

According to \( |x + y|^p \leq 2^{n-1} (|x|^p + |y|^p) \), there exists a smooth function \( \overline{\rho}_k(\xi_1, \ldots, \xi_n) \geq 0 \), and we have

\[
\{\xi_{k+1} \{cx_k - x_k^*\}\} \leq \xi_{k+1}^2 + \xi_k^2 \overline{\rho}_k(\xi_1, \ldots, \xi_k) \]

(21)

According to Lemma 1, it is not difficult to prove the following relations:

\[
\{\xi_k \{\phi_k(x, u, d(t)) - \sum \partial x_k \xi_k \} \} \leq \xi_k^2 \overline{\rho}_k(\xi_1, \ldots, \xi_k) + \delta_k
\]

(22)

where \( \delta_k = k \delta_1 \), \( \overline{\rho}_k() \) is a nonnegative smooth function.

Putting the above relations and (20) together, we have

\[
V_k \leq -\sum_{i=1}^{k-1} \xi_{k+1}^2 - 2\xi_{k+1} \xi_{k-1} \{cx_k - x_k^*\} + \overline{\rho}_k(\xi_1, \ldots, \xi_n) + \delta_k
\]

(23)

Clearly, the virtual smooth controller \( x_k^* = -\xi_k \{2 + (\rho_k + \overline{\rho}_k)\} = -\xi_k \overline{\rho}_k(\xi_1, \ldots, \xi_k) \) can yields the following inequality.

\[
\dot{V}_k \leq -\sum_{i=1}^{n-1} \xi_{n+1}^2 - 2\xi_{n+1} \xi_{n-1} \{cx_{n+1} - x_{n+1}^*\} + \overline{\rho}_k(\xi_1, \ldots, \xi_n) + \delta_n
\]

(24)

Step 3: Using the derivation above, we conclude that at the nth step, there are a group of transformations of the form in the step 2, a smooth Lyapunov function \( V_n = V_{n+1} + \xi_n^2 / 2 \) and a smooth controller \( u \) can yield the following inequality.

\[
\dot{V}_n = -\sum_{i=1}^{n-1} \xi_{n+1}^2 + \xi_{n+1} \xi_{n-1} \{cx_{n+1} - x_{n+1}^*\} + \xi_n \{g(t)u + \phi_n - x_n^*\}
\]

(25)

Using the method above, it is very easy to get the equation as follows:

\[
\dot{V}_n = -\sum_{i=1}^{n} \xi_{n+1}^2 + \xi_{n+1} g(t)u + \xi_n \{1 + \rho_n(\xi) + \overline{\rho}_n(\xi)\} + \delta_n
\]

(26)

where \( \rho_n(\xi) \) and \( \overline{\rho}_n(\xi) \) are two nonnegative smooth functions, \( \delta_n \) is an unknown positive constant. We choose the smooth adaptive control law as follows:

\[
\begin{cases}
\dot{u} = \Gamma \xi_n N(\chi)(1 + \rho_n(\xi) + \overline{\rho}_n(\xi)) \\
\dot{\chi} = \lambda \xi_n^2 (1 + \rho_n(\xi) + \overline{\rho}_n(\xi))
\end{cases}
\]

(27)

where \( \Gamma > 0 \) and \( \lambda > 0 \) are the designed constants. Based on the control law, we obtain the following relations:

\[
\dot{V}_n \leq -\sum_{i=1}^{n} \xi_{n+1}^2 + \Gamma \hat{\xi} g(t)N(\chi) + \hat{\chi} + \delta_n
\]

(28)

3.2 BTT missile controller design with the impact of forward

We make the rudder model of BTT missile equal to a first-order actuator model:

\[
\dot{\delta}_2 = -\frac{\delta_2}{r_1} + \frac{\delta_n}{r_2}
\]

(29)
where \( \tau_1 \) and \( \tau_2 \) are two coefficients of rudder model, \( \delta_\alpha \) is the rudder angle order. Putting (29) and (8) together, we have

\[
\begin{align*}
\dot{x}_1 &= \frac{Va_4}{g} x_2 - a_4 x_1 - \frac{Va_5}{g} w_c \beta - \frac{Va_5}{g} r_1 - \frac{Va_5}{g} r_2 u \\
\dot{x}_2 &= \left( \frac{a_4 a_5 - a_3}{a_4} \right) x_3 - (a_1 + a_0') x_2 + \frac{g}{V} \left( a_0' - \frac{a_2}{a_4} \right) x_1 + \frac{J_z - J_y}{J_y^*} w_x y \\
\dot{x}_3 &= -\frac{1}{\tau_1} x_3 + \frac{1}{\tau_2} u
\end{align*}
\]

and

\[
\begin{align*}
&\dot{x}, u, d(t) = -a_4 x_1 - \frac{Va_4}{g} w_c \beta - \frac{Va_5}{g} r_1 - \frac{Va_5}{g} r_2 u \\
&\phi(x, u, d(t)) = -(a_1 + a_0') x_2 + \frac{g}{V} \left( a_0' - \frac{a_2}{a_4} \right) x_1 + \frac{J_z - J_y}{J_y^*} w_x y \\
&g(t) = 1/\tau_2, [x, u, d(t)] = x_3 / \tau_2
\end{align*}
\]

There exists an unknown constant \( M_1 \geq 0 \), render \( |Va_4 w_c \beta / g| \leq M_1 \), such that

\[
\begin{align*}
V_1(\xi) &= \frac{1}{2} \xi_1^2 \\
V_2(\xi_1, \xi_2) &= \frac{1}{2} \xi_1^2 + \frac{1}{2} \xi_2^2 \\
V_3(\xi_1, \xi_2, \xi_3) &= \frac{1}{2} \xi_1^2 + \frac{1}{2} \xi_2^2 + \frac{1}{2} \xi_3^2 \\
V_4 &= -2 \xi_1^2 + \xi_1 \left[ cx_2 - x_2^* \right] + \delta_1 \\
V_5 &= -\xi_2^2 - \xi_3^2 + \frac{\Gamma}{\lambda} g(t) N(\chi) \chi + \xi_3 + \delta_3
\end{align*}
\]

where \( \xi_1 = x_1 - y_r, \xi_2 = x_2 - x_2^*, x_3 = -\xi_1 \beta_1(\xi_1), \xi_3 = x_3 - x_3^*, x_3^* = -\xi_3 \beta_2(\xi_2) \)

The control aim is to design a smooth adaptive control law to make the practical output trace the reference signal \( y_r(t) \) \( \left( y_r(t) \leq M, \ |\dot{y}_r(t)| \leq M \right) \) and \( M \geq 0 \) is an unknown constant. According to (28), we have

\[
\begin{align*}
u &= \Gamma \xi_1 N(\chi)(1 + \rho_3(\zeta) + \rho_3(\zeta)) \\
\chi &= \lambda \xi_2^2 (1 + \rho_3(\zeta) + \rho_3(\zeta))
\end{align*}
\]

Applying the designed controller into system (8) and (9), we can make the following conclusions:

For any initial conditions, all the closed-loop system’s signal is bounded in the interval \([0, +\infty)\). In addition, if adjusting the design parameter properly, we can make the output tracking error become appropriately small in a finite time.

Proof: The design controller above is smooth, so the closed-loop system’s solution has a definition in the interval \([0, t_f)\). We convert (28) into:

\[
\begin{align*}
\dot{\chi} &= \lambda \xi_2^2 (1 + \rho_3(\zeta) + \rho_3(\zeta)) \\
\dot{V}_n &\leq -2V_n + \frac{\Gamma}{\lambda} g(t) N(\chi) \chi + \frac{\xi_3}{\lambda} + \delta_n
\end{align*}
\]

From (28), it follows that
\[ 0 \leq V_n(t) \leq V_n(0) + \frac{1}{\lambda} e^{2t} \int_0^t \Gamma g(\tau) N(x) + 1 \right) \hat{x} \, d\tau + e^{-2t} \int_0^t |\hat{X}|^2 \, d\tau \hspace{1cm} (35) \]

Since \( \delta_n \) is a constant, \( e^{-2t} \int_0^t |\hat{X}|^2 \, d\tau \) is bounded; According to Lemma 4, \( V(t), \chi(t) \) and \( \int_0^t (g(\tau) N(\chi) + 1) \hat{x} \, d\tau \) are all bounded in the interval \([0, t_f]\), thus the closed-loop system’s state variables are bounded in \([0, t_f]\), further it is easy to infer that the virtual control law \( x^*_i \) and control law \( u \) are all bounded. By the controller design and the conclusions above, we can see that, properly adjusting the parameter \( \Gamma, \lambda, \delta \) can make output tracking error appropriately small in a finite time.

4. Simulation

We perform a simulation taking into account of three-channel coupling. In the simulation, the initial conditions are set to \( x_1(0) = 0.1, \ x_2(0) = 0.1 \) and \( \chi(0) = 0 \); the other parameters are designed as \( \Gamma = 0.1, \ \lambda = 1 \) and \( \delta = 10 \); and the lateral overload \( n_l \) keeps track the square wave overload instruction \( n_w \). The simulation results are shown as follows: Fig1-fig5.

5. Conclusion

In this paper, we studied a design method of BTT missile autopilot with the impact of feedforward; and we obtained the conclusions as following:

(1) From the comparison between Fig. 1 and Fig. 2, we can see that the designed controller with the impact of feedforward can not only reduce the stable errors but also make tracking precision is obviously better than the controller without any consideration of feedforward effect.

(2) By employing the Nussbaum-type gain technique and the adding a power integrator design, a global nonlinear control strategy was proposed to obtain the continuous autopilot. The stability of the control system in finite time was strictly proved applying the method of Lyapunov stability theory.

(3) A simulation example is given to demonstrate that the designed control system not only overcome the influence of uncertain factors and the problem of the stable error, but also improved the tracking precision by adjusting the design parameter properly.

References


Figure 1. Output response of vertical overload $n_y$ to instruction $n_{yc}$ with the impact of feedforward

Figure 2. Output response of vertical overload $n_y$ to instruction $n_{yc}$ without the impact of feedforward

Figure 3. Output response of rotational angular velocity $w_z$ to instruction $n_{yc}$ with the impact of feedforward

Figure 4. Output response of adaptive parameter $\chi$ to instruction $n_{yc}$ with the impact of feedforward
Figure 5. Output response of sideslip angle $\beta$ to instruction $n_{sc}$ with the impact of feedforward.