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Synthesis of a Flight Control System via Nonlinear Model Matching Theory

Shigeru UCHIKADO*, Nobuaki KOBAYASHI**, ●Yasuhiro OSA***, Kimio KANAI**** and Takayoshi NAKAMIZO*****

* Fuculty of Science and Engineering, Tokyo Denki University, Ishizaka, Hatoyama-cho, Hiki-county, Saitama Prefecture, 350-03 Japan

** Kanazawa Institute of Technology, 7-1 Ogigaoka, Nonoichi-cho, Isikawa-county, Isikawa Prefecture, 921 Japan

*** Department of Mechanical Engineering, Kobe City College of Technology, 8-3 Gakuen Higashi-cho, Nishi-Ku, Kobe-city, Hyogo Prefecture, 651-21 Japan

**** Department of Aerospace Engineering, The National Defence Academy, 1-10-20 Hashirimizu, Yokosuka, Kanagawa Prefecture, 239 Japan

***** Department of Information Engineering, The National Defence Academy, 1-10-20 Hashirimizu, Yokosuka, Kanagawa Prefecture, 239 Japan

Abstract

In this paper we deal with a synthesis of flight control system via nonlinear model matching theory.

First, the longitudinal and lateral-directional equations of aircraft motion on CCV mode are considered, except the assumption "variations on steady straight flight due to disturbances are very small". Next, a design method of the dynamic model matching control system based on Hirschorn's Algorithm[4)5)] is proposed to the above nonlinear system.

Finally, the proposed control system is applied to the small sized, high speed aircraft, T-2 on CCV[1)] mode and numerical simulations are shown to justify the proposed scheme.

1. Introduction

In this paper, we propose a design of flight control system via a Nonlinear Model Matching Theory. Generally, model following control approach is very useful on designing flight control system satisfying the critical control requirements, in which airplanes can fly over a wide range and at high speed, etc.. However, it seems that the fighters like F-16 with TVC, which is developed in U.S.A. presently, require to fly at a range of more high angle of attack. Such a system becomes nonlinear longitudinal and lateral-directional equation of motion, so the existing model following control system can not be applied to such a case directly.

In this study, first, the longitudinal and lateral-directional equations of aircraft motion on CCV mode are considered. When if it is not assumed that variations on steady straight flight due to disturbances are very small, the longitudinal and lateral-directional equations of motion become coupled nonlinear equations of motion. And we consider that elevator angle, flap-aileron angle, aileron angle, rudder angle and vertical canard angle are used as inputs, also vertical velocity, pitch angle, side-slip angle, bank angle and yaw angle are measured as outputs. Second, a disign method of the dynamic model matching control system based on Hirschorn's Algorithm extended with Silverman's Structure Algorithm[6)7)8)] is proposed to the above nonlinear system. Then, the conditions, to produce control input without model matching and differential values of signals are shown, also it is shown that this result is the extention of linear model following control system. Third, we attempt to design of CCV Flight Control System via Nonlinear Model Matching Theory and the proposed control system is applied to the small sized, high speed aircraft, T-2 on CCV mode. At the end of paper, numerical simulations are shown to investigate the feasibility of the proposed approach.

* TVC = Thrust Vector Control

* CCV = Control Configured Vehicle

2. Equations of Aircraft Motion (CCV mode)

In this paragraph, the equations of aircraft motion to achieve the CCV mode are described. Where, the longitudinal and lateral directional equations of aircraft motion are obtained except the assumption[1] "variations on steady straight flight due to disturbances are very small", that is, the angle of attack, the pitch angle and bank angle are very small. And the flap-aileron and the vertical canarad are included as the new control surfaces.

Then, considering T-2CCV as the controlled system, the longitudinal equations of aircraft motion on CCV mode become as follows.

$$(s - X_u)u(t) - X_w w(t) + g\cdot\sin[\theta(t)] = X_{\delta_e}\delta_e(t) + X_{\delta_f}\delta_f(t)$$

$$-Z_u u(t) + (s - Z_w)w(t) + U_0 q(t) = Z_{\delta_e}\delta_e(t) + Z_{\delta_f}\delta_f(t)$$

$$s\theta(t) = q(t)\cdot\cos[\phi(t)] - r(t)\cdot\sin[\phi(t)]$$

$$-M_u u(t) - (M_{\dot{w}} s + M_w)w(t) + (s - M_q)q(t) = M_{\delta_e}\delta_e(t) + M_{\delta_f}\delta_f(t)$$

And the lateral-directional equations of aircraft motion become as follows.

$$(s - Y^*_\beta)\beta(t) + r(t) - (g/U_0)\cdot\cos[\theta(t)]\cdot\sin[\phi(t)] = Y^*_{\delta_a}\delta_a(t) + Y^*_{\delta_r}\delta_r(t) + Y^*_{\delta_{vc}}\delta_{vc}(t)$$

$$s\phi(t) = p(t)$$

$$-L'_\beta\beta(t) + (s - L'_p)p(t) - L'_r r(t) = L'_{\delta_a}\delta_a(t) + L'_{\delta_r}\delta_r(t) + L'_{\delta_{vc}}\delta_{vc}(t)$$

$$-N'_\beta\beta(t) - N'_p p(t) + (s - N'_r)r(t) = N'_{\delta_a}\delta_a(t) + N'_{\delta_r}\delta_r(t) + N'_{\delta_{vc}}\delta_{vc}(t)$$

$$s\psi(t) = r(t)$$

where

$u(t)$: forward velocity (m/sec)
$w(t)$: vertical velocity (m/sec)
$\theta(t)$: pitch angle (rad)
$q(t)$: pitch rate (rad/sec)
$\beta(t)$: side-slip angle (rad)
$\phi(t)$: bank angle (rad)
$p(t)$: roll rate (rad/sec)
$r(t)$: yaw rate (rad/sec)
$\psi(t)$: yaw angle (rad)
$\delta_e(t)$: elevator angle (rad)
$\delta_f(t)$: flap-airelon angle (rad)
$\delta_a(t)$: airelon angle (rad)
$\delta_r(t)$: rudder angle (rad)
$\delta_{vc}(t)$: vertical canard angle (rad)
g : gravity acceleration (9.8m/sec^2)
U_0 : air speed (m/sec)
X_u, Z_w, M_{δ_e}, etc.
: stability and control derivatives

Now, setting the next state vector and input,

$$x(t)^T = [u(t)\ w(t)\ \theta(t)\ q(t)\ \beta(t)\ \phi(t)\ p(t)\ r(t)\ \psi(t)] \quad (1)$$
$$u_f(t)^T = [\delta_e(t)\ \delta_f(t)\ \delta_a(t)\ \delta_r(t)\ \delta_{vc}(t)]$$

Using above $x(t)$ and $u_f(t)$, the above equations of aircraft motion can be described as the following state vector nonlinear equation (System Σ).

(System Σ)

$$\dot{x}(t) = F(x(t)) + Bu_f(t) \quad (2)$$

where

$$F(x(t)) = [f_1(t), f_2(t), \cdots, f_9(t)]^T$$

$$f_1(t) = X_u u(t) + X_w w(t) - g\cdot\sin[\theta(t)]$$
$$f_2(t) = Z_u u(t) + Z_w w(t) + U_0 q(t)$$
$$f_3(t) = q(t)\cdot\cos[\phi(t)] - r(t)\cdot\sin[\phi(t)]$$
$$f_4(t) = (M_u + M_{\dot{w}} Z_u)u(t) + (M_w + M_{\dot{w}} Z_w)w(t) + (M_q + U_0 M_{\dot{w}})q(t)$$
$$f_5(t) = Y^*_\beta\beta(t) + (g/U_0)\cdot\cos[\theta(t)]\cdot\sin[\phi(t)] - r(t)$$
$$f_6(t) = p(t)$$
$$f_7(t) = L'_\beta\beta(t) + L'_p p(t) + L'_r r(t)$$
$$f_8(t) = N'_\beta\beta(t) + N'_p p(t) + N'_r r(t)$$
$$f_9(t) = r(t)$$

$$B = [b_1^T, b_2^T, \cdots, b_9^T]^T$$

$$b_1 = [\ X_{\delta_e}\quad X_{\delta_f}\quad 0\quad 0\quad 0\ ]$$
$$b_2 = [\ Z_{\delta_e}\quad Z_{\delta_f}\quad 0\quad 0\quad 0\ ]$$
$$b_3 = [\ 0\quad 0\quad 0\quad 0\quad 0\ ]$$
$$b_4 = [\ M_{\delta_e} + M_{\dot{w}} Z_{\delta_e}\quad M_{\dot{w}} Z_{\delta_f} + M_{\delta_f}\quad 0\quad 0\quad 0\ ]$$
$$b_5 = [\ 0\quad 0\quad Y^*_{\delta_a}\quad Y^*_{\delta_r}\quad Y^*_{\delta_{vc}}\ ]$$
$$b_6 = [\ 0\quad 0\quad 0\quad 0\quad 0\ ]$$
$$b_7 = [\ 0\quad 0\quad L'_{\delta_a}\quad L'_{\delta_r}\quad L'_{\delta_{vc}}\ ]$$
$$b_8 = [\ 0\quad 0\quad N'_{\delta_a}\quad N'_{\delta_r}\quad N'_{\delta_{vc}}\ ]$$
$$b_9 = [\ 0\quad 0\quad 0\quad 0\quad 0\ ]$$

Then, $F(x(t))$ is the real function about the state and is analytical at the adequate open domain within R^n, $\mathcal{R} \in R^n$. And the initial value; $x_0 \in \mathcal{R}$.

Considering CCV mode, the output is set as follows.

$$y(t) = Cx(t) \tag{3}$$

where

$$y(t)^T = [w(t)\ \theta(t)\ \beta(t)\ \phi(t)\ \psi(t)]$$

Then, the matrix C becomes

$$C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

3. Sysnthsis of the Flight Control System via Model Matching Theory

In this paragraph, the dynamic model matching control system based on Hirschorn's Algorithm extended with Silverman's Structure Algolithm is producted to the nonlinear system in the second paragraph. Then, the conditions, to produce control input without model matching and differential value of signals are shown, also it is shown that this result is the extention of linear model following control system.

3.1 Formulation of the Problem

Considering the next 2nd order system as the reference model (System Σ_M) which is set by the designer adequately.

(System Σ_M)

$$\begin{aligned} \dot{x}_{Mi}(t) &= A_M x_{Mi}(t) + B_M u_{Mi}(t) \\ y_{Mi}(t) &= C_M x_{Mi}(t) \end{aligned} \qquad (i=1,2,\cdots,5) \tag{4}$$

where $x_{Mi}(t) \in R^2$, $u_{Mi}(t) \in R^1$, $y_{Mi}(t) \in R^1$ and they are assigned respectively as follows.

$$y_M(t) = [y_{M1}(t)\ y_{M2}(t) \cdots y_{M5}(t)]$$
$$x_M(t) = [x_{M1}(t)\ x_{M2}(t) \cdots x_{M5}(t)]$$
$$u_M(t) = [u_{M1}(t)\ u_{M2}(t) \cdots u_{M5}(t)]$$
$$A_{Mi} = \begin{vmatrix} 0 & 1 \\ -\omega_n^2 & -2\zeta\omega_n \end{vmatrix}$$
$$B_{Mi} = [0 \quad 1]^T$$
$$C_{Mi} = [\omega_n^2 \ 0]$$

where ζ is the damping ratio and ω_n is the undamped natural frequency (rad/sec).

The objective here is to construct the model matching control system which forces the output of the nonlinear equation of aircraft motion, $y(t)$, to truck the reference model output, $y_M(t)$, aymptotically.

Where, the condition of the model matching considered here is defined as follows.

(Definition)

For the following conditions

$$F(x_0) = 0,\ A_M x_{M0} = 0,\ C(x_0) = C_M x_{M0},$$

when

$$y_M(t) - y(t) = 0$$

is achieved, the system Σ can be model-matched to the model system Σ_M.

Where A_M and C_M are given by

$$A_M = \mathrm{diag}(A_{Mi}) \quad C_M = \mathrm{diag}(C_{Mi})$$

3.2 Construction of the Control System

Considering the next procedures to the system Σ with Hirschorn's Algorithm[5],

(Step I)

Considering the time differential of the output, $y_i(t)$, left-multiplying $y_i(t)$ by $(s+g_0)$, the next equation is obtained

$$(s+g_0)y_i(t) = [C_i F(x(t)) + g_0 C_i x(t)] + C_i B u_f(t) \tag{5}$$

where, $g_0 > 0$, $s = d/dt$.

Next, formally replacing the Eq.(5) with the next equation

$$(s+g_0)^{f_{i1}} y_i(t) = C_{ai1}(x) + D_{ai1}(x) u_f(t) \tag{6}$$

In the above equation, when if $D_{ai1}(x) \neq 0$, replacing the subindexes "i1" of f, C_a and D_a with "i". And going to the next step.

When if $D_{ai1}(x)=0$, with differentiating again, the next equation is obtained

$$(s+g_0)^{f_{i1}} y_i(t) = C_{ai1}(x) + D_{ai1}(x) u_f(t) \tag{7}$$

Where $D_{ai1}(x) \neq 0$. Then, replacing the subindex "1i" of the above equation with "i" and going to the next step. Where f_{ii} is an integer, $y_i(t)$ and C_i are the i-th element and the i-th column respectively.

(Step II)

Doing the same procedures at Step I to $y_2(t)$, the next equation is obtained

$$(s+g_0)^{f_{21}} y_2(t) = C_{a21}(x) + D_{a21}(x) u_f(t) \tag{8}$$

(Step III)

When if $D_{a21}(x) \neq \alpha_{21}(x) D_{a1}(x)$; $[\alpha_{21}(x) \neq 0]$, replacing the subindex "2i" with "2", doing the same procedures since Step II to the output, $y_3(t)$.

When if $D_{a21}(x) = \alpha_{21}(x)D_{a1}(x)$, doing the same procedures since Step II to the new output

$$-\alpha_{21}(x)(s+g_0)^{f_1}y_1(t) + (s+g_0)^{f_{21}}y_2(t)$$

Repeating the above procedures to the output $y_5(t)$, the next equation is obtained

$$N_a(s,x)y(t) = C_a(x) + D_a(x)u_f(t) \quad (9)$$

where $N_a(s,x)$ is the lower triangler matrix which the diagonal elements are $(s+g_0)^{f_1}$, and $C_a(x)$ and $D_a(x)$ are respectively

$$C_a(x) = [C_{a1}(x)\ C_{a2}(x)\ \cdots\ C_{a5}(x)]^T$$
$$D_a(x) = [D_{a1}(x)\ D_{a2}(x)\ \cdots\ D_{a5}(x)]^T$$

Using the above relation, the next theorem is obtained.

<Theorem>

If the next conditions are satisfied, the system Σ can be matched to the reference model system Σ_M.

(i) $\mathrm{rank}(D_a(x)) = 5$ for $x(t)\in R$

(ii) $D_{Ma}(x,x_M)$ and $C_{Ma}(x,x_M)$ which satisfy the next equation exist

$$N_a(s,x)y_M(t) = C_{Ma}(x,x_M) + D_{Ma}(x,x_M)u_M(t) \quad (10)$$

Then, the model matching can be achieved by the following control law

$$u_f(t) = D_a^{-1}(x)[-C_a(x)+C_{Ma}(x,x_M) + D_{Ma}(x,x_M)u_M(t)] \quad (11)$$

(Certification)

The condition (i) and the control law, Eq.(11), can be realized. And defining the output error, e(t), as follows

$$e(t) = y_M(t) - y(t) \quad (12)$$

The next equation is obtained with Eqs.(9)~(11)

$$Na(s,x)e(t) = 0 \quad (13)$$

Here taking notice of the construction of $N_a(s,x)$, for the following case,

$$x(0) = 0,\ x_M(0) = 0$$

the relation

$$y(t) = y_M(t) \qquad t \geqq 0 \quad (14)$$

is obtained. And the model matching can be achieved.

(Annotation)

This proposed method can be applied to the system,

$$(\text{System}\,\Pi)\quad \dot{x} = A(x) + \sum_{i=1}^{m} u_i B_i(x),\qquad y = C(x) + D(x)u$$

Where, $x\in R^n$, $u\in R^m$, $y\in R^p$ are the state, input and output vectors.

And $A(x)\in R^n$, $B_i\in R^{n\times 1}$, $C(x)\in R^{p\times n}$, $D(x)\in R^{p\times m}$ are the real function vectors and matrices about the state, and are analytical (sufficient-continuously differentialble) at the adequate open domain within R^n, $R\in R^n$.

Moreover, to $x_0\in R$ and the piecewise-continuous input "u", the above system has the single solution within R.

Then, the next model system is given as the adequate model sytem to be matched

$$(\text{System}\,\Pi_M)\quad \dot{x}_M = A_M(x_M) + \sum_{i=1}^{m} u_{Mi}B_{Mi}(x),\qquad y_M = C_M(x_M)$$

Where $y_M\in R^P$ and the system Π_M, as same as the system Π, whose $A_M(x_M)$, $B_M(x_M)$, $C_M(x_M)$ are analytical within R and has the single solution to piecewise-continuous input "u_M".

4. Application to the CCV Flight Control System

In this paragraph, we attempt to apply the proposed control sytem to the flight control system on CCV mode of the small sized and high speed aircraft, T-2CCV, and investigate the feasibility of the proposed approach. First, the practical derivatives are applied to the longitudinal and lateral equations of aircraft motion on CCV mode at Chap.2. Next, the systhesis of a CCV flight control system via nonlinear model matching thory described at Chap.3 are shown.

Now, using the derivatives on the flight condition which T-2CCV flies at the altitude 6000 (m) and the velocity M = 0.8, $f_i(t)$ and b_i incluled in Eq.(1) becomes as follows

$$f_1(t) = -0.0084u(t) + 0.0385w(t) - 9.8\sin[\theta(t)]$$
$$f_2(t) = -0.077u(t) - 0.882w(t) + 254.4q(t)$$
$$f_3(t) = q(t)\cdot\cos[\phi(t)] - r(t)\cdot\sin[\phi(t)]$$
$$f_4(t) = 0.0001u(t) - 0.008w(t) - 1.217q(t)$$
$$f_5(t) = -0.259\beta(t) + 0.039\cos[\theta(t)]\cdot\sin[\phi(t)] - r(t)$$
$$f_6(t) = p(t)$$
$$f_7(t) = -65.05\beta(t) - 3.p(t) + 2.04r(t)$$

$$f_8(t) = 7.88\beta(t) - 0.06p(t) - 0.47r(t)$$
$$f_9(t) = r(t) \quad (15)$$

$$
\begin{aligned}
b_1 &= [\ 0 \quad 0 \quad 0 \quad 0 \quad 0\ ] \\
b_2 &= [-14.446 \quad -18.409 \quad 0 \quad 0 \quad 0\ ] \\
b_3 &= [\ 0 \quad 0 \quad 0 \quad 0 \quad 0\ ] \\
b_4 &= [-22.062 \quad -2.343 \quad 0 \quad 0 \quad 0\ ] \\
b_5 &= [\ 0 \quad 0 \quad -0.008 \quad 0.121 \quad 0.081\ ] \\
b_6 &= [\ 0 \quad 0 \quad 0 \quad 0 \quad 0\ ] \\
b_7 &= [\ 0 \quad 0 \quad 151.0 \quad 46.20 \quad 7.106\ ] \\
b_8 &= [\ 0 \quad 0 \quad 3.654 \quad -15.94 \quad 6.206\ ] \\
b_9 &= [\ 0 \quad 0 \quad 0 \quad 0 \quad 0\ ]
\end{aligned}
$$

Next, differentiating the output, Eq.(3), based on the proposed method of Chap.3, the next equation is obtained

$$N_a(s)y(t) = C_a(x) + D_a(x)u_f(t) \quad (16)$$

where

$$N_a(s) = \mathrm{diag}[(s+g_0),(s+g_0)^2,(s+g_0),(s+g_0)^2,(s+g_0)^2]$$

$$
\begin{aligned}
C_a(x)^T &= [C_{a1}(t),C_{a2}(t),\cdots,C_{a5}(t)] \\
C_{a1}(t) &= g_0 w(t) + f_2(t) \\
C_{a2}(t) &= g_1\theta(t) + g_2 f_3(t) + f_{10}(t) \\
f_{10}(t) &= f_4(t)\cos[\phi(t)] + q(t)p(t)\sin[\phi(t)] \\
&\quad -f_8(t)\sin[\phi(t)] + r(t)p(t)\cos[\phi(t)] \\
C_{a3}(t) &= g_0\beta(t) + f_5(t) \\
C_{a4}(t) &= g_1\phi(t) + g_2 p(t) + f_7(t) \\
C_{a5}(t) &= g_1\psi(t) + g_2 r(t) + f_8(t) \\
g_1 &= g_0\cdot g_0,\ g_2 = 2\cdot g_0
\end{aligned}
$$

$$
\begin{aligned}
D_a(x)^T &= [D_{a1}(t)\ D_{a2}(t)\ \cdots\ D_{a5}(t)] \\
D_{a1}(x)^T &= [18.409 \quad 14.446 \quad 0 \quad 0 \quad 0] \\
D_{a2}(x)^T &= [D_{a21}(t)\ D_{a22}(t) \quad 0 \quad 0 \quad 0] \\
D_{a21}(t) &= 22.062\cos[\phi(t)] \\
D_{a22}(t) &= 2.343[\phi(t)] + 3.654\sin[\phi(t)] \\
D_{a3}(t)^T &= [0 \quad 0 \quad -0.008 \quad 0.121 \quad 0.081] \\
D_{a4}(t)^T &= [0 \quad 0 \quad 151.0 \quad 46.20 \quad 7.106] \\
D_{a5}(t)^T &= [0 \quad 0 \quad 3.654 \quad -15.94 \quad 6.206]
\end{aligned}
$$

Here multiplying element $N_a(s,x)$ is independent to the variable x.

Also, Da(x) is

$$\mathrm{rank}\ D_a(x) = 5 \quad (\phi(t) \neq 79.5) \quad (17)$$

And with the square matrix, Da(x), producing the control input, $u_f(t)$, to the model matching, as follows

$$u_f(t) = D_a^{-1}(x)[-C_a(x) + N_a(s)y_M(t)] \quad (18)$$

Then, the each CCV mode can be achieved with the adequate reference input.

(Stability)

The left invertible system of "$N_a(s)y(t) = C_a(x) + D_a(x)u_f(t)$", that is, if

$$\dot{\hat{x}}(t) = \hat{F}(\hat{x}(t)) + \hat{B}(\hat{x}(t))\hat{u}_f(t)$$
$$\hat{y}(t) = \hat{C}(\hat{x})\hat{x}(t)$$
$$\hat{x}_0 = x_0 \in R$$

is stable, then, the entire system is stable.

Where

$$\hat{F}(\hat{x}) = F(\hat{x}) - B\ D_a(\hat{x})^{-1}C_a(\hat{x})$$
$$\hat{B}(\hat{x}) = B\ Da(\hat{x})^{-1}$$
$$\hat{C}(\hat{x}) = -Da(\hat{x})^{-1}C_a(\hat{x})$$

And using the control input, Eq.(18), the entire system becomes as follows

$$d/dt\begin{bmatrix} x(t) \\ x_M(t) \end{bmatrix} = \begin{bmatrix} \hat{F}(x) + \hat{B}(x)C_{Ma}x_M(t) \\ A_M x_M(t) \end{bmatrix} + \begin{bmatrix} \hat{B}(x)D_{Ma} \\ B_M \end{bmatrix} u_M(t)$$
$$y(t) = Cx(t)$$

(Annotation)

The above description means the equivalence to the strongly detectability at the linear system (including the time-variable system). And it means a minimum phase system.

Simulation(A_N mode and A_Y mode[1])

To achieve the CCV Direct Lift(A_N) mode and Direct Sideforce(A_Y) mode, setting the parameters of the reference model and g_0 as follows

$$g_0 = 5$$
$$\zeta = 0.7,\ \omega_n = 5.2\ \text{(rad/sec)}$$
$$u_M^T = [0\pm0.0174 \quad 0 \quad 0\pm0.0174]$$

And the simulation results are shown in Fig.1 and Fig.2.

(Evaluation)

The results show that the direct lift mode which forces the vertical flight path angle to ±1 (deg) with the constant angle of attack (0 deg) and the direct side-force mode which forces the lateral-directional flight path angle to ±1 (deg) with the constant bank angle and side-slip angle (0 deg) are achieved.

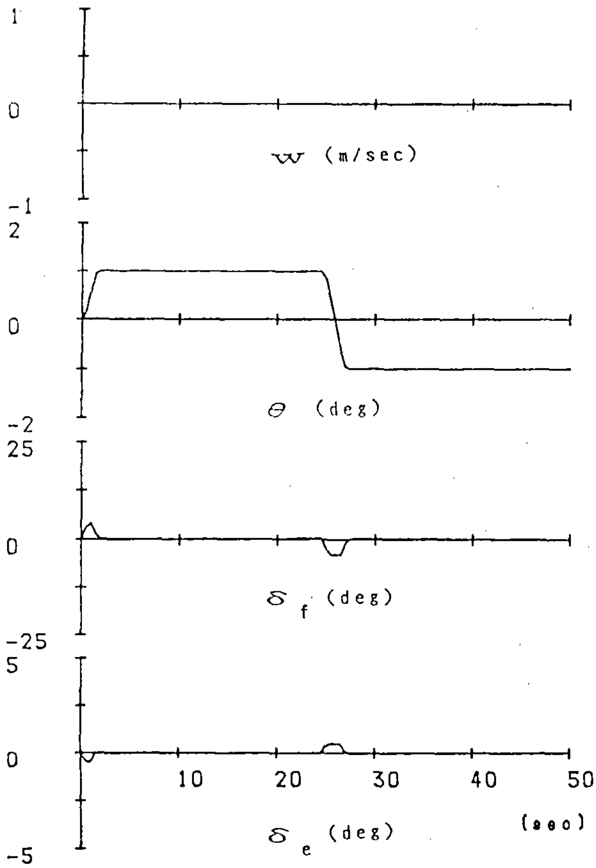

Fig.1 The response of the input-output on Direct Lift (A_N) mode

4. Conclusion

We propose a synthesis of flight control system via nonlinear model matching theory based on Hirschcrn's Algorithm extended with Silverman's Structure Algorithm. The proposed control system is applied to the small sized and high speed air-craft, T-2CCV, and we show the feasibility of the proposed approach with numerical simulations.

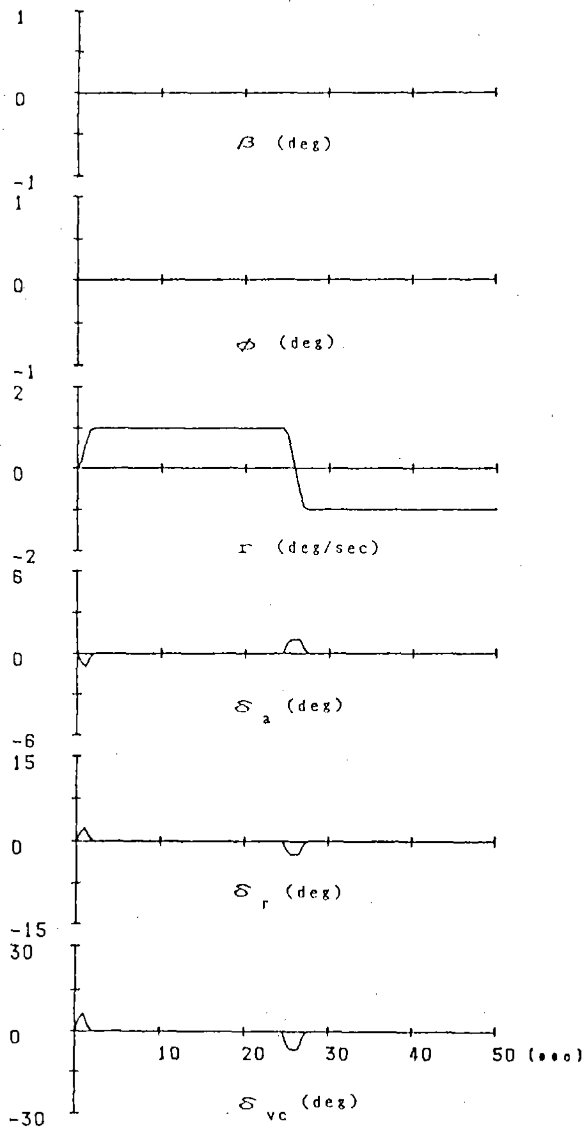

Fig.2 The response of the input-output and the state [r(t)] on Direct Sideforce (A_Y) mode

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