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# Design of CCV Adaptive Flight Control System under Microburst Type Disturbances

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## Abstract

In this paper we deal with a design of CCV adaptive flight control system having adaptive observer under the mircroburst circumstances.

First, based on the observcrbility indices of the controlled system, which is a general multivariable one, the adaptive observer is constructed, and the unknown interactor matrix can be estimated by using the identified parameters. Next, CCV adaptive flight control law is calculated based upon the estimated ones.

Finally, the proposed CCV adaptive flight controller is applied to STOL flying boat and numerical simulations under the microburst circumstances can be shown to justify the proposed scheme.

## 1. Introduction

"A design of CCV adaptive flight control system having unknown interactor1)" was already published by the authors, and the adaptive flight control system was designed based on the direct control method2). With the above design, if we try to construct SAS and CAS3), it needs the construction of the same adaptive flight control system again. But, when an adaptive obsever2),4) which can estimate the unknown paremeters and state values of the aircraft with only signals of inputs and outputs is designed, various closed-loop control systems can be realized with the information of this adaptive observer.

In this study, we propose a design of CCV adaptive flight control system having adaptive observer under Microburst type distrubances5)-8), which often causes the aircraft accident during landing and taking-off. First, the longitudinal equation of aircraft motion is shown. Secondly, by using the observability indices of the controlled system, which is a general multivariable one, the adaptive observer is constructed, and the unknown interactor matrix can be estimated using the identified parameters. Third, the CCV adaptive flight control law is derived by using the estimated ones. Then, a simple design of the controlled system using the above information of the adaptive observer is shown. Finally, the proposed CCV adaptive flight controller is applied to STOL (Short Take-off and Landing) flying boat and numerical simulations under the microburst circumstances are shown to investigate the feasibility of the proposed approach.

## 2. Longitudinal equations of aircraft motion

Let the state vector, $\bar{x}(t)$, be defined as

$$\bar{x}(t) = [u(t), w(t), \theta(t), q(t)]^T \qquad (1)$$

where u(t) is the aircraft velocity in the direction to X-axis (m/sec), w(t) is the velocity in the direction to Z-axis (m/sec), $\theta(t)$ is the pitch angle (rad) and q(t) is the pitch rate (rad/sec).

Further, suppose that the elevator angle $\delta_e(t)$ (rad), the flap-aileron angle $\delta_f(t)$(rad) and the throttle variation (%) are dealed as the input vector $\delta(t)$, it is described by

$$\delta(t) = [\delta_e(t), \delta_f(t), \delta_t(t)]^T \qquad (2)$$

Generally, the equation of aircraft motion using the stability axes is given with the state vector3) by

$$\dot{\bar{x}}(t) = A_c\bar{x}(t) + B_c\delta(t) \qquad (3)$$

where

$$A_c = \begin{bmatrix} X_u & Z_w & -g & 0 \\ Z_u & Z_w & 0 & U_o \\ 0 & 0 & 0 & 1 \\ M_u+M_{\dot{w}}Z_u & M_w+M_{\dot{w}}Z_w & 0 & M_q+M_{\dot{w}}U_o \end{bmatrix}$$

$$B_c = \begin{bmatrix} X_{\delta_e} & X_{\delta_f} & X_{\delta_t} \\ Z_{\delta_e} & Z_{\delta_f} & Z_{\delta_t} \\ 0 & 0 & 0 \\ M_{\dot{w}}Z_{\delta_e}+M_{\delta_e} & M_{\dot{w}}Z_{\delta_f}+M_{\delta_f} & M_{\dot{w}}Z_{\delta_t}+M_{\delta_t} \end{bmatrix}$$

In the above, $X_u$, $X_w$, $Z_{\delta_e}$, ⋯ in the matrix $A_c$ and $B_c$ are the stability and control derivatives. Considering CCV-mode, the output is given by

$$y(t) = C\bar{x}(t) \qquad (4)$$

where, $y(t) = [u(t),\ w(t),\ \theta(t)]^T$

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

Next, the discrete-time expression of Eqs.(3) and (4) is considered. Let the sampling time " T ", Eqs.(3) and (4) are given by1)

$$\bar{x}(k+1) = \bar{A}\,\bar{x}(k) + \bar{b}\,\delta(k) \qquad (5)$$
$$y(k) = C\,\bar{x}(k)$$

where

$$\bar{A} = e^{A_c T} \qquad (6)$$
$$\bar{b} = \int_0^T e^{A_c T(T-\tau)} B_c\, d\tau$$

and this system is controllable and observable.

The longitudinal CCV-mode[1),3)];

Let the aircraft motion modelled as Multi-Input and Multi-Output, let the other control loops added to existing Single-Input and Single-Output feedback control method in order to improve the performance, applying Active Control Technology (ACT) since the beginning of the design of aircraft, and the aircraft form is constructed based on this idea. The aircraft which can realize "new ways to fly ( CCV-mode )" different from existing basic ones, is called "Control Configured Vehicle (CCV)", it can realize Direct-Lift ($A_N$) mode, Fuselage Pitch Pointing ($\alpha_1$) mode, Vertical Translation ($\alpha_2$) mode.

## 3 . Construction of the Multi-variable Adaptive Observer

In this paragraph, we show a construction of adaptive observer which estimates the parameters and state values of the system with only signals of inputs and outputs, and the identification of the interactor[9),10)] which plays an important roll on model matching of multivariable system.

### 3 . 1 Formulation of the Problem

Eq.(5), without loss of generality, is also described by[2)]

$$x(k+1) = Ax(k) + B\delta(k) \qquad (7)$$
$$y(k) = Cx(k)$$

where state value $x(t) \in R^n$ is unobservable and input signal $u(t) \in R^m$ and output signal $y(t) \in R^r$ are observable. And,

$$x(k) = [x_1(k)\ x_2(k)\ \cdots\ x_n(k)]^T,$$
$$A = (\ A_{ik}\ ),\quad i=1,2,\cdots,r \quad k=1,2,\cdots,r$$
$$A_{ii} = \left[\begin{array}{c|c} & d_i-1 \\ -a_{ii} & \hline & 0\cdots 0 \end{array}\right] \in R^{d_i \times d_i}$$
$$A_{ik} = (-a_{ik}\quad \mathbb{O}\ ) \quad R^{d_i \times d_k}\ (i \neq k)$$
$$C = [h_1\ 0\ h_2\ 0\ \cdots\ h_r\ 0],\ H = [h_1\ h_2\ \cdots\ h_r]$$
$$h_i^T = (0\ \cdots\ 0\ 1\ x\ \cdots x),\quad x\ ;\text{non-zero element}$$
$$a_{ik}^T = [a_{s_{i-1},k}\ \cdots\ a_{s_{i-1}+d_i-1,k}\ ]$$
$$s_i = d_0 + d_1 + \cdots + d_i \qquad (\ d_0 = 1\ )$$

where, n=4, m=3, r=3 and $d_i$ is the observability index.

The purpose of this paragraph is to design an adaptive observer which estimates state variable x(k) of the system (7) with observed signals of inputs and outputs, and the identification of the interactor[9),10)] and identifies unknown parameters ($a_{ik}$,B,H).

Defining, $X_s(k) = [x_{s_0}(k)\ x_{s_1}(k)\ \cdots\ x_{s_{r-1}}(k)]^T$. Then output Eq.(7) becomes

$$y(k) = Hx_s(k) \qquad (8)$$

where H has certainly an inverse matrix based on that structure.

And, Eq.(7) is devided to following "r" subsystems.

$$x^i(t+1) = \sum_{t=1}^{r} A_{it}x^t(k) + B_i\delta(k) \qquad (9)$$
$$y_i(k) = C_i^T x^i(k) + \tilde{h}_i x_s(k)\ ,\ (i=1,2,\cdots,r) \qquad (10)$$

where,

$$x^i(k) = [x_{s_{i-1}}(k)\ \cdots\ x_{s_{i-1}+d_i-1}(k)]^T$$
$$C_i^T = (\ 1\ 0\ \cdots\ 0\ ) \in R^{1\times d_i}$$
$$H = \begin{bmatrix} \tilde{h}_1 \\ \tilde{h}_2 \\ \hdashline \tilde{h}_r \end{bmatrix} + \mathbb{I}_r\ ,\quad B = \begin{bmatrix} B_1 \\ B_2 \\ \hdashline B_r \end{bmatrix}$$

Further, taking notice of the structure of $A_{it}$, Eq.(9) becomes

$$x^i(k+1) = A_{ii}x^i(k) - \sum_{t=1(t\neq i)}^{r} a_{it}x_{s_t}(k) + B_i\delta(k) \qquad (11)$$

Introducing the design paramerter "$\lambda_i$" and using the relation of Eq.(8), Eqs.(10) and (11) can be described as follows[3)].

$$z^i(k+1) = \Lambda_i z^i(k) + K^i y(k) + L^i\delta(k) \qquad (12)$$
$$y_i(k) = P_i^T z^i(k) + \gamma^i y(k)\ ,\ i=1,2,\cdots,r$$

where

$$z^i(k) \in R^{d_i},\ P_i^T = (\ 1\ 1\ \cdots\ 1\ ),$$
$$H^{-1} = \mathbb{I}_r - \begin{bmatrix} \gamma^1 \\ \gamma^2 \\ \hdashline \gamma^r \end{bmatrix},\quad \begin{array}{l} \Lambda_i = \mathrm{diag}(-\lambda_j), j=1,\cdots,d_i \\ \lambda_t > 0,\ \lambda_i \neq \lambda_t \text{ for } i \neq t \\ \gamma^i = (x\cdots x\ 0\cdots 0) \end{array}$$

The relation between Eqs.(10),(11) and Eq.(12) is described with nonsingular transformation matrix $T_i(\lambda)$ as follows.

$$x^i(k) = T_i(\lambda)z^i(k)$$
$$B_i = T_i(\lambda)L^i$$
$$K^i = \alpha_i(t)H^{-1} \qquad (13)$$
$$a_{it} = -T_i(\lambda)\alpha_{it}$$
$$a_{ii} = T_i(\lambda)\alpha_{ii} - D_i(\lambda)$$

where

$$\alpha_i = [\alpha_{i1}\ \alpha_{i2}\ \cdots\ \alpha_{ir}]$$
$$T_i(\lambda) = [C_i(\lambda_1)\ C_i(\lambda_2)\ \cdots C_i(\lambda_{di})]$$
$$C_i^T(\Lambda_i) = [\ 1\ \ D_i^T(\lambda)\ ]$$
$$L^i = [L_1^i\ L_2^i\ \cdots\ L_m^i]\quad R^{d_i \times m}$$
$$K^i = [K_1^i\ K_2^i\ \cdots\ K_r^i]\quad R^{d_i \times r}$$

Therefore, the problem of the design of an adaptive observer is to introduce the adaptive method which identifies unknown parameters ($K^i, L^i, \gamma^i$) with the input signal and output signal, and which estimates the internal state $z^i(k)$.

### 3 . 2 Construction of the Observer

At first, defining the following state variable filter.

$$V_o(k+1) = \Lambda_o V_o(k) + P_o y(k)^T\ ,\ V_o(0)=0$$
$$W_o(k+1) = \Lambda_o W_o(k) + P_o \delta(k)^T,\ W_o(0)=0 \qquad (14)$$
$$\theta_o(k+1) = \Lambda_o \theta_o(k),\ \theta_o(0) = [1\ 1\cdots 1]^T$$

where $V_o(k) \in R^{\tilde{d} \times r}$, $W_o(k) \in R^{\tilde{d} \times m}$, $\theta_o(k) \in R^{\tilde{d}}$, $\tilde{d} = Max(d_i, i=1,2,\cdots,r)$ is the maximum observable index. Using this signals, Eq.(14) becoms

$$z^i(k)=K^i \circledast V^i(k)+L^i \circledast W^i(k)+z_o^i \circledast \theta^i(k) \qquad (15)$$

$$y_i(k) = P_i^T z^i(k) + \gamma^i y(k) = g^{iT} \eta^i(k), \quad i=1,2,\cdots,r \qquad (16)$$

where

$$V^i(k)=(\mathbb{I}_{d_i} \ 0)V_o(k)=[v_1^i(k) \ \cdots \ v_r^i(k)] \in R^{d_i \times r}$$

$$W^i(k)=(\mathbb{I}_{d_i} \ 0)W_o(k)=[w_1^i(k) \ \cdots \ w_m^i(k)] \in R^{d_i \times m}$$

$$\theta^i(k) = (\mathbb{I}_{d_i} \ 0)\theta_o(k) \in R^{d_i}$$

$$g^{iT} = [K_1^{iT} \ \cdots \ K_r^{iT} \ L_1^{iT} \ \cdots \ L_m^{iT} \ z_0^{iT} \ \bar{\gamma}^{iT}]$$

$$\eta^{iT}(k) = [v_1^{iT}(k) \ \cdots \ v_r^{iT}(k) \ w_1^{iT}(k) \ \cdots \ w_m^{iT}(k) \ \theta^{iT}(k) \ \bar{y}^{iT}(k)]$$

$$\bar{\gamma}^i = (\mathbb{I}_{i-1} \ 0)\gamma^{iT} \ ( \bar{\gamma}^1 = 0 )$$

$$\bar{y}^i(k) = (y_1(k) \ y_2(k) \ \cdots \ y_{i-1}(k)) \ (\bar{y}^1(k)=0)$$

The simbol $\circledast$ means the sum of the product of corresponding element of an each row.

Corresponding to Eqs.(15) and (16), defining the following adaptive observer.

$$\hat{z}^i(k)=\hat{K}^i(k) \circledast V^i(k)+\hat{L}^i(k) \circledast W^i(k)+\hat{z}_o(k) \circledast \theta^i(k) \qquad (17)$$

$$\hat{y}_i(k) = \hat{g}^{iT}(k)\eta^i(k), \quad i=1,2,\cdots,r \qquad (18)$$

where

$$\hat{g}^{iT}(k) = [\hat{K}_1^{iT}(k) \ \cdots \ \hat{K}_r^{iT}(k) \ \hat{L}_1^{iT}(k) \ \cdots \ \hat{L}_m^{iT}(k) \ z_0^{iT} \ \hat{\bar{\gamma}}^{iT}(k)]$$

Cosidering the relation of Eqs.(16) and (18), the following recursive least estimation method is used as the adaptive algorithm[1), 4)].

$$\hat{g}^i(k+1) = \hat{g}^i(k) + Q^i(k)\eta^i(k+1)[y_i(k+1) - \hat{g}^{iT}(k)\eta^i(k+1)]/\varepsilon^i(k+1) \qquad (19)$$

$$Q^i(k+1) = Q^i(k)-Q^i(k)\eta^i(k+1)\eta^{iT}(k+1) \cdot Q^i(k)/\varepsilon^i(k+1) \qquad (20)$$

$$\varepsilon^i(k+1)= 1 + \eta^{iT}(k+1)Q^i(k)\eta^i(k+1) \qquad (21)$$

where, $Q^i(0) = Q^{iT}(0) > 0$.

Using this adaptive algorithm, if the signal $\eta^i(k)$ is bounded and sufficiently rich, it gives following equations[3)]

$$\lim_{k \to \infty} \hat{g}^i(k) = g^i \qquad (22)$$

$$\lim_{k \to \infty} \hat{z}^i(k) = z^i(k) \quad , \quad i=1,2,\cdots,r \qquad (23)$$

Next, we show the detail[1), 10)] to decide the interactor with the identified $\hat{A}(k)$, $\hat{B}(k)$ and $\hat{C}(k)$.

(Step 1); consider the time-shift of the output $y_i(k)$.

$$zy_i(k)=\hat{C}_i^T(k)\hat{A}(k)\hat{x}(k)+\hat{C}_1^T(k)\hat{B}(k)\delta(k) \qquad (24)$$

where, z is the time-shift operator.

Setting the above equation to the following equation formally

$$zy_i(k)=\hat{d}_{T_1}^{f_{1i}}(k)x(k)+\hat{C}_{T_1}^{f_{1i}}(k)\delta(k) \qquad (25)$$

Then, if $\hat{C}_{T_1}^{f_{1i}}(K) \neq 0$ in the above equation, set $f_{1i} = f_1$ and go to next step.

If $\hat{C}_{T_1}^{f_{1i}}(K) = 0$, differentiating it again, the the following equation is obtained.

$$z^{f_{1i}}y_1(k)=\hat{d}_{T_1}^{f_{1i}}(k)x(k)+\hat{C}_{T_1}^{f_{1i}}(k)\delta(k) \qquad (26)$$

where, $\hat{C}_{T_1}^{f_{1i}}(k) \neq 0$.

setting $f_{1i}=f_1$, where $f_{1i}$ is integer and $\hat{C}_i(k)$ is the i-th matrix of $\hat{C}(k)$, go to the next step.

(Step 2); doing the same detail as Step 1 about $y_2(k)$, the following equation is obtained

$$z^{f_{2i}}y_2(k)=\hat{d}_{T_2}^{f_{2i}}(k)x(k)+\hat{C}_{T_2}^{f_{2i}}(k)\delta(k) \qquad (27)$$

(Step 3); if $\hat{C}_{T_2}^{f_{2i}}(k) \neq \alpha_{21}\hat{C}_{T_2}^{f_1}(k)(\alpha_{21} \neq 0)$, set $f_{2i}=f_2$ and do the same detail since Step 2 about $y_3(t)$.

if, $\hat{C}_{T_2}^{f_{2i}}(k)=\alpha_{21}\hat{C}_{T_2}^{f_1}(k)$, go to next step

(Step 4); doing the same detail as Step 2 about new output $-\alpha_{21}z^{f_1}y_1(k)+z^{f_{2i}}y_2(k)$, following equations are obtained

$$-\alpha_{21}z^{f_1}z^{f_{2j}-f_{2i}}y_1(k)+z^{f_{2j}}y_2(k) = \hat{d}_{T_2}^{f_{2j}}(k)x(k)+\hat{C}_{T_2}^{f_{2j}}(k)\delta(k) \qquad (28)$$

And do the same detail since Step 3 again about this new output.

Repeating the above detail until getting $y_r(k)$, the following equation is obtained.

$$N_T(z,k)y(k)=\hat{D}_T(k)\hat{x}(k)+\hat{C}_T(k)\delta(k) \qquad (29)$$

where

$$\hat{D}_T(k)=[(\hat{d}_{T_1}^{f_1}(k))^T,(\hat{d}_{T_2}^{f_2}(k))^T,\cdots,(\hat{d}_{T_r}^{f_r}(k))^T]^T$$

$$\hat{C}_T(k)=[(\hat{C}_{T_2}^{f_1}(k))^T,(\hat{C}_{T_2}^{f_2}(k))^T,\cdots,(\hat{C}_{T_r}^{f_r}(k))^T]^T$$

where $N_T(z,k)$ is lower triangler matrix which the diagonal elements are all $z^{f_i}$, and the elements of the i-th column can be divided by $z^{f_i}$ or are all "0".

Also, it means that "k" is an estimated interactor based on the identified $\hat{A}(k)$, $\hat{B}(k)$ and $\hat{C}(k)$.

## 4. Construction of the Adaptive CCV Flight Control System

In this paragraph, at first we show a construction of the system with known parameters and the expantion to the adaptive system with outputs of adaptive observer proposed in the former paragraph. Also, we consider a flight control system with deterministic disturbances because the aircraft is continuously effected by wind gust during flight.

### 4. 1 Formulation of the Problem

Considering following equations with disturbances like wind gust based on the discretized equation of motion (7) which lets the aircraft regarded as the controlled system.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + Dv(k) \\ y(k) &= Cx(k) \end{aligned} \qquad (30)$$

where, $v(t) \in R^r$ is the bounded deterministic disturbances like step type, ramp type and acceleration type as basic disturbances. And the invertible system is stable.

Corresponding with this controlled system, Eq.(30), the following equation is given as the reference model selected by the designer.

$$\begin{aligned} x_M(k+1) &= A_M x_M(k) + B_M u_M(k) \\ y_M(k) &= C_M x_M(k) \end{aligned} \qquad (31)$$

where, $x_M(t) \in R^n$

$$u_M^T(k) = [u_{M1}(k), u_{M2}(k), u_{M3}(k)]$$

$$y_M^T(k) = [y_{M1}(k), y_{M2}(k), y_{M3}(k)]$$

and $\det(sI - A_M)$ is a stable polynomial.

The purpose is to construct an adaptive CCV flight control system which the outputs $y(k)$ of controlled system Eq.(30) with deterministic disturbances follows the outputs $y_M(k)$ of reference model asymptotically.

### 4. 2 Construction of the Control System

Considering the expanded system with disturbances of system Eq.(30) before considering the construction of control system. At first, the left coprime expression of system (31) using the shift operator becomes

$$y(k) = P(z)^{-1}[R(z)\delta(k) + G_v(z)v(k)] \qquad (32)$$

where $P(z)$ and $R(z)$ are left coprime, $P(z)$ is row proper[10].

Considering disturbances, the control inputs are made as the following equation

$$\delta(k) = [1/(z-1)^i]\delta_v(k) \qquad (33)$$

where, in case of step type disturbances: i=1, ramp type ones: i=2, $\delta_v(k)$ will be defined later.

And the following plant expression is obtained by Eqs.(32) and (33).

$$(z-1)^i y(k) = P(z)^{-1}R(z)\delta_v(k) \qquad (34)$$

Then, let the state expression of this system following

$$\begin{aligned} x_v(k+1) &= A_v x_v(k) + B_v \delta_v(k) \\ y(k) &= C_v x_v(k) \end{aligned} \qquad (35)$$

where, $x_v(k)$ $R^{3+3i}$.

Further, doing the detail from Step 1 to Step 3 of the third paragraph to this expanded system, Eq.(35),

$$N_{Tv}(z)y(k) = D_{Tv}x_v(k) + C_{Tv}\delta_v(k) \qquad (36)$$

is obtained. Using this $N_{Tv}(z)$ to the reference model: Eq.(31), it becomes

$$N_{Tv}(z)y_M(k) = D_{Mv}x_M(k) + C_{Mv}u_M(k) \qquad (37)$$

The control inputs $\delta(k)$ that achieve the model matching becomes following[1].

$$\begin{aligned} \delta(k) &= [1/(z-1)^i]\delta_v(k) \\ \delta_v(k) &= C_{Tv}^{-1}[-D_{Tv}x_v(k) + D_{Mv}x_M(k) + C_{Mv}u_M(k)] \end{aligned} \qquad (37)$$

where, to realize Eq.(37), let the interactor of the reference model $N_M(z)$, the next model matching condition

$N_{Tv}(z)N_M(z)^{-1}$ : proper

must be satisfied[10].

Then it shows that each CCV-mode is achieved by the reference output selected adequately.

First, in case of $A_N$-mode the vertical directional flight path angle can be controlled to ±a (rad) with constant angle of attack (=0) by setting the objective value $y_M=(0,0,\pm a)$. In case of $\alpha_1$-mode the aircraft can be controlled to nose up and down ±a(rad) with constant flight path angle (=0) by setting $y_M = (0, \pm aU_0, \pm a)$. And in case of $\alpha_2$-mode the vertical velocity can be controlled to ±a(m/sec) with the constant pitch attitude (=0) by setting the objective value $(0, \pm a, 0)$.

Therefore, control input: Eq.(37) can not be made because the parameters and the interactor of controlled system are unknown. Then, we show the expantion to adaptive system. Where it is assumed that $\rho$ which satisfies $\det(C_{Tv}) \geqq \rho$ is known on identifying the interactor in order to avoid the generation of excessive control input.

First, constructing the adaptive observer of the third paragraph corresponding with the expanded system: Eq.(35), estimating the state values, the unknown parameters and the interactor, making the control input corresponding with Eq.(37) as follows

$$\begin{aligned} \delta(k) &= [1/(z-1)^i]\delta_v(k) \\ \delta_v(k) &= \hat{C}_{Tv}(k)^{-1}[-\hat{D}_{Tv}(k)x_v(k) \\ &\quad + \hat{D}_{Mv}(k)x_M(k) + \hat{C}_{Mv}(k)u_M(k)] \end{aligned} \qquad (38)$$

where the estimation parameter $\hat{C}_{Tv}(k)$ is made as follows

if $\det(\hat{C}_{Tv}(k)) \geqq \rho$, then $\hat{C}_{Tv}(k) = \hat{C}_{Tv}(k)$

if $\det(\hat{C}_{Tv}(k)) < \rho$, then $\hat{C}_{Tv}(k) = \hat{C}_{Tv}(k-1)$

where if the signals are sufficiently rich, the estimated parameters of the adaptive observer converge to the some limiting values, Eq.(38) matches Eq.(37) and the control objective is achieved[3].

## 5. Applicaton to STOL flying boat

In this paragraph the $\alpha_2$-mode CCV flight control system proposed in the former paragraph is applied to the approach of landing ground and on the water as the important mission of the STOL flying boat[1][11].

First, using the data $C_L$=6. in the bibliography literature 9), setting the sampling time 0.01(s), the controlled system: Eq.(30) becomes as follows

$$x(k+1) = \begin{bmatrix} 0.998 & -.0038 & 0 & -.0033 \\ 0 & 1.997 & 1 & 0 \\ 0.0004 & -.996 & 0 & 0.0005 \\ 0.187 & 0.0033 & 0 & 0.9997 \end{bmatrix} x(k) + \begin{bmatrix} 0 & 0 & 0.0004 \\ -.01 & -.011 & 0.05 \\ 0.01 & 0.013 & -.053 \\ 0.02 & 0.0132 & -.06 \end{bmatrix} \delta(k) + Dv(k) \qquad (39)$$

$$y(k) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 1.2 & 0 & 1 \end{bmatrix} x(k)$$

where this system has a stable invertible system.

On the other hand, the reference model is considered as follows which is discretized with the sampling time 0.01(s) based on a 2-nd order system having a damping ratio 0.9 and an undamped natural frequencey 5.2(rad/sec).

$$x_{M1}(k+1)=\begin{bmatrix} 0.999 & 0.0095 \\ -0.258 & 0.9094 \end{bmatrix} x_{M1}(k)+\begin{bmatrix} 0 \\ 0.0095 \end{bmatrix} u_{M1}(k)$$

$$y_{M1}(k)=(-27.04 \quad 0 \quad )x_{M1}(k), \quad i=1,2$$

$$x_{M3}(k+1)=\begin{bmatrix} 0.999 & 0.0099 & 0.00005 \\ -0.013 & 0.994 & 0.00905 \\ -2.448 & -1.105 & 0.8189 \end{bmatrix} x_{M3}(k) + \begin{bmatrix} 0 \\ 0.00005 \\ 0.00907 \end{bmatrix} u_{M3}(k)$$

$$y_{M3}(k)=(-270.4 \quad 0 \quad )x_{M3}(k)$$

where $x_M(t)=(x_{M1}(t)^T, x_{M2}(t)^T, x_{M3}(t)^T)^T$.

Considering the constant disturbances, the interactor $N_{Tv}(s)$ of the expanded system and the interactor $N_M(s)$ of the reference model becomes

$$N_{Tv}(s) = N_M(s) = \mathrm{diag}(z^2 \; z^2 \; z^3)$$

it satisfies the condition of model matching.

### <Simulation>

The numerical similaion of the approach of the landing on the water is shown to investigate the feasibility of the proposed approach, then considering the disturbances we deal with the mathematical model of the Microburst which is given attention recently as the cause of the aircrat accident on taking off and landing[6),7)].

This simulation is applied to the approach of landing on the water proving the maximum feasibility of the proposed CCV flight control system in the former paragraph. In other words, considering the STOL flying boat without the backside phenomenon, setting its pitch angle "0(rad)" so that the pilot make it land on the water safely on looking the condition of the wave of sea surface in the hazard weather, and applying the reduction of cost time of landing on the water with a large vertical velocity until it reachs a safe altitude.

The control objective is to achieve the $\alpha_2$-mode approch of landing on the water with the angle of attck 10 (deg), flight path angle 10 (deg) to the altitude 10 (m) and 1 (deg) under the altitude 1(m). Then the condition of the numerical simulation is described by

$$u_M(t)=[0 \quad 4.5 \quad 0]^T \qquad (91m \geqq h(t) \geqq 15m)$$

$$u_M(t)=[0 \quad .45 \quad 9]^T \qquad (15m \geqq h(t) \geqq 3m)$$

$$\lambda_1= -0.1, \; \lambda_2= -0.2, \; \lambda_3= -0.1, \; \tilde{d}=3$$

$$Q^i(0)=10^{10} \qquad (i=1,2,3), \; \rho=10^{-8}$$

Other conditions except above are all "0".

The more strict condtion of micro burst than one given by the bibliography literature 6) are assumed.

$$D=\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ -0.0027 & 0.0027 & 0 \end{bmatrix}$$

$$v(k)=(v_u \quad v_w \quad 0)$$

$$v_u=-7.71, \; v_w= 0 \;, \qquad 0 < t \leqq 10$$

$$v_u=-6.68, \; v_w= 7.2, \qquad 10< t \leqq 20$$

$$v_u= 0 \;, \; v_w=12.9, \qquad 20< t \leqq 30$$

$$v_u= 7.71, \; v_w=6.68, \qquad 30< t \leqq 40$$

$$v_u= 5.14, \; v_w= 0 \;, \qquad 40< t \leqq 50$$

where $h(t)$ is the altitude (m), $v_u$ is the horizontal directional velocity (m/sec) and $v_w$ is the vertical directional velocity (m/sec).

In this simulation, at first considering the case of no disturbance, the results of the response of input and output, the altitude and the result of the identification of parameters are shown in Fig.1 - Fig.4. Next, the results with Microburst are shown in Fig.5 - Fig.7.

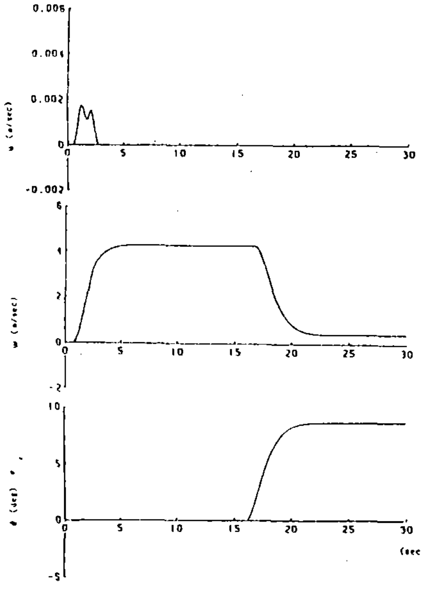

Fig.1 The response of Output
(without disturbance)

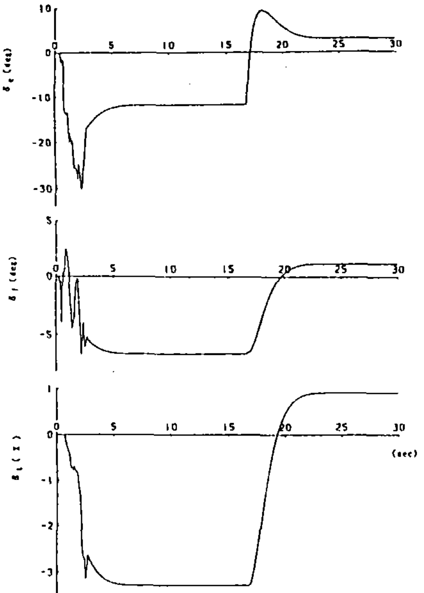

Fig.2 The response of Input
(without disturbance)

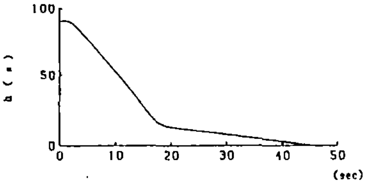

Fig.3 The response of Altitude
(without disturbance)

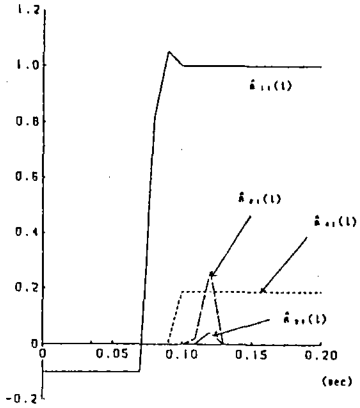

Fig.4 A part of Estimated
Parameters

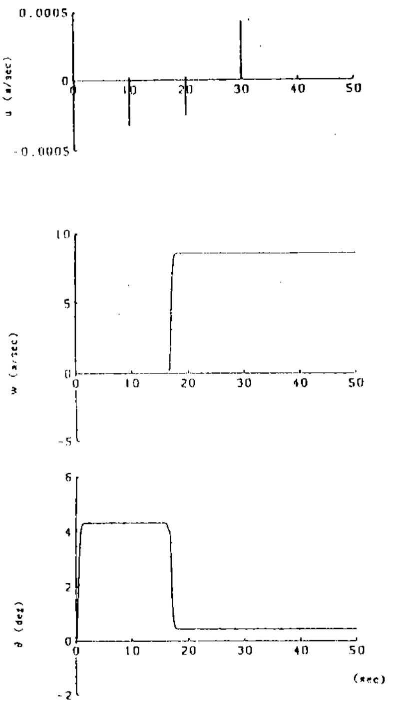

Fig.5 The response of Output

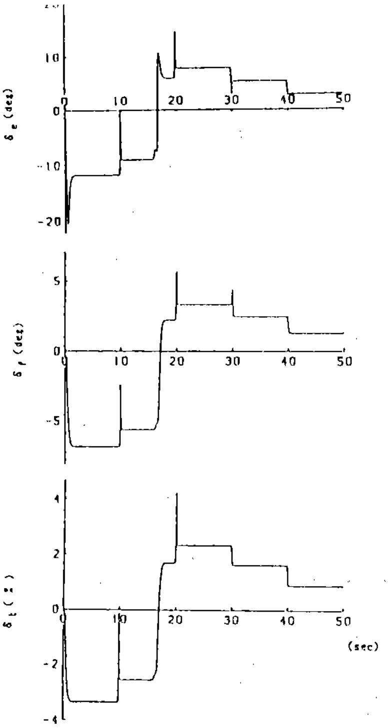

Fig.6 The response of Input

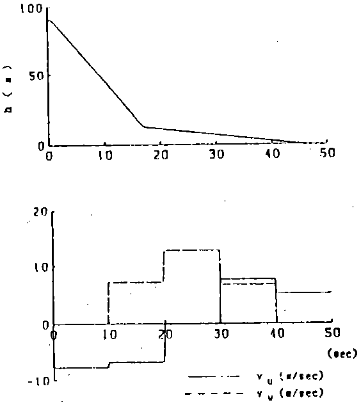

Fig.7 The response of Altitude and Microburst

These results show that the landing on the water are achieved safely and quickly with the satisfication of the designer whether Microburst exists or not. Especially, when the value of Micro burst changes, the transient phenomenon like impulse appears, its value is within the movable limit of the elevator, etc..

## 6. Conclusion

In this paper we propose a Design of Adaptive CCV Flight Control System with disturbances, apply its system to the STOL flying boat, and prove the feasibility by the numerical simulaton.

This design is a method with adaptive observer in the study of adaptive control system, the observer needs only observable index to the normal Multi-variable System and this design has an advantage which the advance information about the structure of the interactor that plays important roll on the Multivariable Model Following Control. Moreover, in the practical point of view, the Micro burst which often causes the aricraft accident during landing and taking-off, is considered.

The results of the numerical simulations show that $\alpha_2$-mode can be applied to the approach of the landing on the water for the rescue activity as the important mission of the flying boat. And flying boat can land on the water more safely and quickly than one with an existing automatic thrust control system whether Microburst exists or not.

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