JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 26, No. 1, January–February 2003

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

F-14 Aircraft Lateral–Directional Adaptive Control Using Subspace Stabilization

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Introduction

PRECISE directional control of an aircraft landing on a carrier requires the pilot to coordinate lateral stick inputs with rudder pedal inputs. In this F-14 application, lateral–directional control is achieved using differential spoiler deflection δ_{dsp}, differential stabilizer deflection δ_{dstab}, and rudder deflection δ_{rud}. Fialho et al.[1] proposed a design to reduce cross effects based on μ techniques and a gain-scheduling, angle-of-attack dependence. This approach significantly decreased both sideslip angle response to a stick command and roll rate response to pedal commands. Previous work by Tournes and Johnson[2] demonstrated that the application of subspace stabilization[3] and linear-adaptive control allows the effective decoupling of motions that are naturally coupled. This Note presents a controller design based on the aforementioned techniques that produces almost total decoupling of the channels.

Controller Performance Requirements

The proposed controller design considers existing mechanical connections from the stick input to the stabilizer and from the pedal input to the rudder deflection. It also includes previously recommended[1] feedforward, angle-of-attack scheduled control interconnections, $W_{ss}(\alpha)$ and $W_{sr}(\alpha)$, designed to compensate for the variation in sideslip directionality during roll maneuvers. Desired time behaviors of the roll rate and sideslip angle error responses are specified by constant coefficient, second-order linear differential equations:

$$\dot{e}_p + 1.4\varpi_p e_p + \varpi_p^2 \int_0^t e_p \,\mathrm{d}\tau = 0, \qquad e_p = p^* - p \tag{1}$$

$$\dot{e}_\beta + 1.4\varpi_\beta e_\beta + \varpi_\beta^2 \int_0^t e_\beta \,\mathrm{d}\tau = 0, \qquad e_\beta = \beta^* - \beta \tag{2}$$

where $\varpi_p = 5$ rad/s and $\varpi_\beta = 5$ rad/s. The proposed design aims to minimize the coupling of the sideslip response to stick inputs and the roll angle response to pedal inputs.

Received 9 November 2000; revision received 26 April 2002; accepted for publication 19 June 2002.

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Aircraft Model

The $\boldsymbol{ABCD}$ state model of Ref. 1 was modified to include a crosswind disturbance, $w = 30\sin(0.5t)$ ft/s, and is represented by

$$\begin{bmatrix} \dot{v} \\ \dot{r} \\ \dot{p} \\ \dot{\phi} \\ \hline \beta \\ \dot{\beta} \\ p \\ r \\ \phi \\ y_{\mathrm{acc}} \end{bmatrix} = \boldsymbol{M} \begin{bmatrix} v - w \\ r \\ p \\ \phi \\ \hline \delta_{\mathrm{dstab}} \\ \delta_{\mathrm{rud}} \\ \delta_{\mathrm{dsp}} \end{bmatrix} + \begin{bmatrix} \dot{w} \\ 0 \\ 0 \\ 0 \\ 0 \\ \dot{w}/u \\ 0 \\ 0 \\ 0 \\ \dot{w}/g \end{bmatrix}, \qquad \boldsymbol{M} = \left[\begin{array}{c|c} \boldsymbol{A} & \boldsymbol{B} \\ \hline \boldsymbol{C} & \boldsymbol{D} \end{array}\right] \tag{3}$$

To test the robustness of the design, time-varying model errors were introduced in Eq. (3). The model terms are represented by a nominal value plus an uncertainty term, $M_{i,j} = \bar{M}_{i,j} + \tilde{M}_{i,j}$, with relative model errors $(\tilde{M}_{i,j}/\bar{M}_{i,j})$ as large as 20%. Because there are two controlled outputs and three control inputs, there can only be two closed-loop inputs. The nonunique choice adopted in this design is to use the rudder and the differential spoilers as closed-loop controls and to use the differential stabilizer as an open-loop, feedforward control.

Total actuator deflections are split into three types of terms. Terms indexed by (0) represent the existing mechanical connections discussed earlier. Terms indexed by (1) represent the discussed feedforward terms introduced in Ref. 1 and maintained in the current design. Finally, terms indexed by (2) represent the feedback control terms that are redesigned in this study.

Linear-Adaptive Control Methodology

Linear-adaptive control methodology is used to address the uncertain nature of the control problem posed by the model uncertainty and crosswind disturbance. Equations governing roll rate and sideslip angle errors with respect to commanded profiles can be written as

$$\dot{e}_\beta = \dot{\beta}^* + h_\beta - \tilde{M}_{6,6}\delta_{\mathrm{rud}_2} - \bar{M}_{6,6}\delta_{\mathrm{rud}_2} \tag{4}$$

$$\dot{e}_p = \dot{p}^* + h_p - \tilde{M}_{3,7}\delta_{\mathrm{dsp}_2} - \bar{M}_{3,7}\delta_{\mathrm{dsp}_2} \tag{5}$$

Aggregate unknown functions h_β and h_p represent the effects that all terms, including external disturbances, but not the feedback controls δ_{rud_2} and δ_{dsp_2}, have on the controlled variables β and p. Here, $\dot{\beta}^*$ and $\dot{p}^*$ are the first time derivatives of the command signals. When unknown aggregate "disturbance variables" z_β and z_p are defined, Eqs. (4) and (5) can be written as

$$\dot{e}_\beta = z_\beta - \bar{M}_{6,6}\delta_{\mathrm{rud}_2} \tag{6}$$

$$\dot{e}_p = z_p - \bar{M}_{3,7}\delta_{\mathrm{dsp}_2} \tag{7}$$

One of the essential ideas of linear-adaptive control[4] is to separate each feedback control actuator deflection into three terms: $\delta_{k_2} = \delta_{ff}^k + \delta_h^k + \delta_e^k$, $k = \beta,\ p$, according to the nature of the effects that the term aims to compensate. The first term, δ_{ff}^k, is an open-loop term that compensates for known effects, such as the commanded maneuver. The second term, δ_h^k, compensates for the effects of the uncertain terms. The third term, δ_e^k, is the feedback control aimed at achieving the prescribed error response.

If one can provide accurate real-time disturbance estimates $\hat{z}_\beta$ and $\hat{z}_p$, the terms compensating for the effects of disturbances are represented by

$$\delta_h^\beta = \hat{z}_\beta / \bar{M}_{6,6}, \qquad \delta_h^p = \hat{z}_p / \bar{M}_{3,7} \tag{8}$$

Replacing feedback control deflections by $\delta_{\text{rud}_2} = \delta_h^{\text{rud}} + \delta_e^{\text{rud}}$ and $\delta_{\text{dsp}_2} = \delta_h^{\text{dsp}} + \delta_e^{\text{dsp}}$ in Eqs. (6) and (7) leads to the system

$$\dot{e}_\beta \approx -\bar{M}_{6,6}\delta_e^{\text{rud}} \tag{9}$$

$$\dot{e}_p \approx -\bar{M}_{3,7}\delta_e^{\text{dsp}} \tag{10}$$

Thus, the initial multiple-input/multiple-output (MIMO) uncertain time-varying control problem of Eq. (3) has been transformed into two very simple single-input/single-output (SISO) systems. The only terms of the $\boldsymbol{M}$ matrix in Eq. (3) that need to be included in the proposed design are $M_{6,6} = \partial\dot{\beta}/\partial\delta_{\text{rud}}$ and $M_{3,7} = \partial\dot{p}/\partial\delta_{\text{dsp}}$.

Control Architecture

The control architecture is shown schematically in Fig. 1. Ideal roll rate p^* and sideslip angle responses β^* are generated from the lateral stick and pedal inputs. Ideal closed-loop responses are generated according to the requirements of Ref. 1. Two disturbance observers[4] provide real-time estimates of roll rate and sideslip tracking errors $e_p = p^* - p$ and $e_\beta = \beta^* - \beta$, their time derivatives, as well as roll and sideslip disturbance states (z_p and z_β). Feedback controls are split into two types of terms with u_h^k, $k = \beta$, p compensating for the effects of the disturbance terms. Two subspace-stabilization controllers generate the second type, u_e^k, $k = \beta$, p, to achieve prescribed error responses. Design of the sideslip channel is very similar to the roll channel and, thus, omitted here.

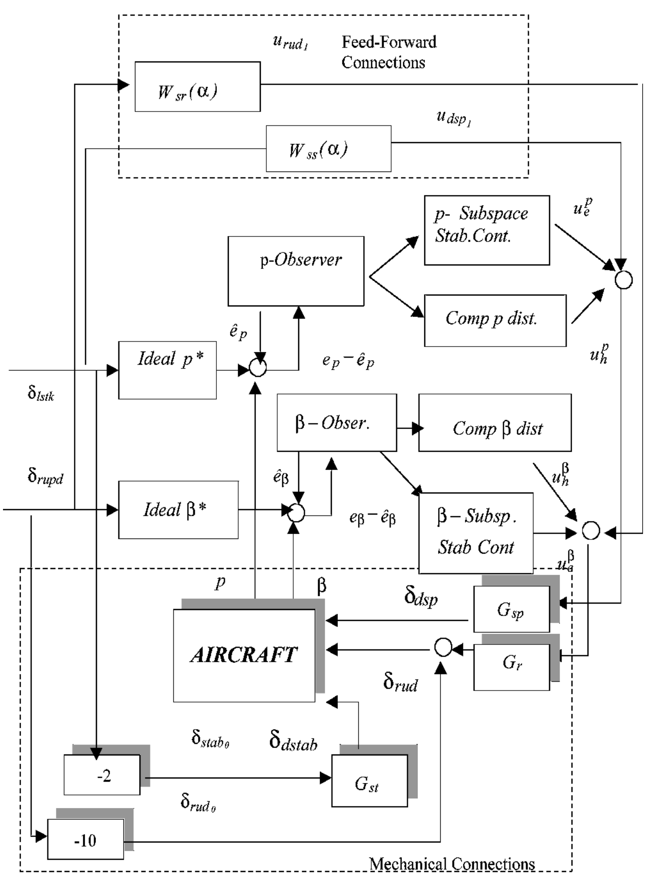

Fig. 1 Control architecture.

Disturbance Observers

A quadratic polynomial-spline waveform model, $z_k(t) = c_0 + c_1 t + c_2 t^2$; $k = \beta$, p, is used to represent the uncertain time variations of z_k. This leads to the differential equation model $\dddot{z}_k = 0$, almost everywhere. Thus, the associated dynamic model can be written[4]

$$\dot{e}_p = z_{1,p} + \bar{M}_{3,7}\delta_{\text{dsp}_2}, \qquad \dot{z}_{1,p} = z_{2,p} + \sigma_{1,p}(t)$$

$$\dot{z}_{2,p} = z_{3,\beta} + \sigma_{2,p}(t), \qquad \dot{z}_{3,p} = \sigma_{3,p}(t) \tag{11}$$

Here, $z_k = (z_1, \ldots, z_3)^T$, $k = \beta$, p, are the states of the quadratic-spline modeled disturbance term. The gain coefficients of the observers have been designed to set the estimation errors at $\lambda = -100$ rad/s. Corresponding observers have the form

$$\dot{\hat{e}}_p = \hat{z}_{1,p} + \bar{M}_{3,7}\delta_{\text{dsp}_2} + 400(p - \hat{p})$$

$$\dot{\hat{z}}_{1,p} = \hat{z}_{2,p} + 60{,}000(p - \hat{p}), \qquad \dot{\hat{z}}_{2,p} = \hat{z}_{3,p} + 4 \times 10^6 (p - \hat{p})$$

$$\dot{\hat{z}}_{3,p} = 10^8 (p - \hat{p}) \tag{12}$$

Subspace Stabilization Control Design

Introducing the actuators' first-order response[1] in Eqs. (9) and (10) yields

$$\ddot{e}_\beta = -\omega_\beta \dot{e}_\beta + \dot{z}_\beta + \omega_\beta z_\beta - \bar{M}_{6,6} u_{\text{rud}} \tag{13}$$

$$\ddot{e}_p = -\omega_p \dot{e}_p + \dot{z}_p + \omega_p z_p - \bar{M}_{3,7} u_{\text{dsp}} \tag{14}$$

As discussed earlier, actuator commands are split into components $u_h^\beta = (\omega_\beta \hat{z}_\beta + \dot{\hat{z}}_\beta)/\bar{M}_{6,6}$ and $u_h^p = (\omega_p \hat{z}_p + \dot{\hat{z}}_p)/\bar{M}_{3,7}$ compensating for the effects of disturbance terms and u_e^β and u_e^p, designed to obtain prescribed error responses. When additional integral error states are introduced, Eqs. (13) and (14) can be written in state format ($\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{Bu}$) as

$$\begin{bmatrix} \dot{e}_{0,p} \\ \dot{e}_{1,p} \\ \dot{e}_{1,p} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\omega_p \end{bmatrix} \begin{bmatrix} e_{0,p} \\ e_{1,p} \\ e_{1,p} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \omega_p \bar{M}_{3,7} \end{bmatrix} u_e^{\text{dsp}} \tag{15}$$

Subspace Stabilization

The linear-subspace stabilization problem is to find a feedback control, $u = \boldsymbol{Kx}$, so that all closed-loop solutions $\boldsymbol{x}(t)$ of the system $\dot{\boldsymbol{x}} = \boldsymbol{Ax} + \boldsymbol{BKx}$ asymptotically approach a chosen p-dimensional linear subspace S as $t \to \infty$. This subspace is designed to embody performance features such as rise time, settling time, damping, overshoot, and other requirements. When $\boldsymbol{x}(t)$ denotes the response error-state, the prescribed time-behavior of error components for a given control channel is

$$S_k = \left[\varpi^2,\ 1.4\varpi,\ 1\right] \times \begin{bmatrix} e_{0,k} \\ e_{1,k} \\ e_{2,k} \end{bmatrix} = 0, \qquad k = \beta, p \tag{16}$$

where

$$e_{0,k} = \int_0^t e_k \, \mathrm{d}\tau, \qquad e_{1,k} = k^* - k, \qquad e_{2,k} = \dot{e}_{1,k}$$

The main conceptual idea of the proposed approach is to separate the control problem into two subproblems. The first subproblem is to control the system in error state so that it promptly reaches the linear subspace S that embodies the specified model of behavior. The second subproblem is to control the error state so that it remains close to the subspace, in accordance with the specified model of behavior. In the second subproblem, the control must achieve invariance of the subspace S, which implies the motion of $x(t)$ toward the subspace should be independent of the motion parallel to the subspace. With the very simple structure of matrix $\boldsymbol{A}$ in Eq. (15), this leads to the following controller gains for the two channels:

$$K_{e\,0,\beta} = -\mu_\beta \varpi_\beta^2, \qquad K_{e\,1,\beta} = -1.4\mu_\beta \varpi_\beta - \varpi_\beta^2$$

$$K_{e\,2,\beta} = -\mu_\beta - 1.4\varpi_\beta - \omega_\beta \tag{17}$$

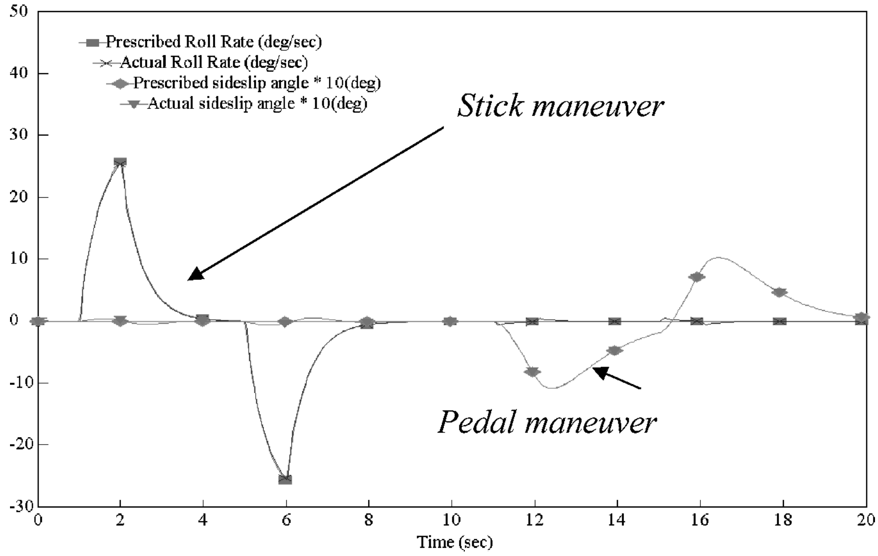

Fig. 2 Roll rate and sideslip responses.

$$K_{e0,p} = -\mu_p \varpi_p^2, \qquad K_{e1,p} = -1.4\mu_p \varpi_p - \varpi_p^2$$

$$K_{e2,p} = -\mu_p - 1.4\varpi_p - \omega_p \tag{18}$$

The motion to the subspace is chosen faster than the motion on the subspace because it is essential to achieve prescribed error response as quickly as possible. Values of $\mu_\beta = 15$ and $\mu_p = 25$ were chosen for the F-14 simulation.

F-14 Simulation Results

The scenario used in the previous work of Fialho et al.[1] was chosen to test the proposed controller design. Figure 2 shows the two simulated maneuvers. Two pairs of 1-s, 1-in. (2.54-cm) stick inputs to the left and then to the right are applied at 1 and 5 s followed by two pairs of pedal inputs at 11 and 15 s. The comparison of the roll rate response to the stick input with the "ideal" closed-loop response in Fig. 2 shows tracking performance slightly superior to the already very good result shown in Ref. 1. The very small peak sideslip error of 0.06 deg is far better than the 0.8-deg error obtained in Ref. 1. The response to pedal inputs achieved almost perfect tracking of the sideslip angle and a limited residual roll rate response of only 0.35 deg/s. This is much better than the 1 deg/s roll rate error presented in Ref. 1.

Conclusions

A linear-adaptive controller has been designed where disturbance estimators/observers provide a real-time estimate of the effects of all terms except the nominal control effects. The compensation of the generalized disturbance terms, based on real-time estimates provided by the observer, transforms the coupled and uncertain time-varying MIMO control problem into a pair of SISO control problems. The prescribed roll rate and sideslip responses for an F-14 were almost perfectly tracked with a nearly total decoupling of the two channels. This approach significantly extends the results obtained in Ref. 1.

References

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Employing Soft Computing Techniques to Study Stability and Control in Aircraft Design

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Nomenclature

$C_{Lh\alpha}$	=	a_t-lift curve slope of horizontal tail
$C_{L\alpha}$	=	lift curve slope of aircraft
$C_{m\alpha}$	=	$\mathrm{d}C_m/\mathrm{d}\alpha$
C_{m0}	=	coefficient of moment at zero angle of attack
$(C_{L\alpha})_{A-h}$	=	a_w-lift curve slope of aircraft without horizontal tail
$\bar{c}$	=	mean aerodynamic chord
$\mathrm{d}\varepsilon/\mathrm{d}\alpha$	=	downwash effect induced by the wing
l_t	=	horizontal tail arm, m
N_β	=	$\mathrm{d}N/\mathrm{d}\beta$
S	=	gross wing area, m^2
S_t	=	gross tail area, m^2
V_h	=	horizontal tail volume
W_0	=	gross weight, N
η_t	=	ratio of dynamic pressure at tail to the freestream dynamic pressure

Introduction

IT may be argued that one of the most well-known evolutionary algorithms is the genetic algorithm (GA) developed by Holland and his colleagues in the early 1970s (see Ref. 1). The GA capabilities of searching a vast search space using a population of search points, with multiple mixed parameter types, and at the same time

Received 24 April 2001; revision received 1 July 2002; accepted for publication 1 August 2002.

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