A Self-Organizing Adaptive Aircraft Control System

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An adaptive system which yields pitch-axis performance according to the C^*-Criterion is reconfigured to give self-organizing behavior. A feedback of normal acceleration, pitch rate and command input combined with variable gains is replaced by three distinct feedbacks of these signals summed with fixed gains. These are then added with variable gains. This allows signal blending from three accelerometers, three rate gyros, and three input transducers. The gain-changing mechanism is found by a gradient technique. Analog simulation shows that the structure provides inherent redundancy and compensates for simulated sensor failures.

Introduction

A SELF-ORGANIZING system may be defined as one which changes its basic structure as a function of its experiences and environment, to evolve toward some desired output behavior or mode of operation. Such a system can be described as having the ability to learn, and can therefore be designed to handle situations which rigidly programed systems are not particularly adept in handling. A report by Gibson, Fu, et al.,[1] gives a good introduction to learning control systems. A more recent introduction to the subject may be obtained from a report by Mendel.[2]

Almost all present aircraft use some type of air-data scheduling as the method of accommodating their automatic flight control systems to variations in the dynamic characteristics encountered over the full flight envelope of the aircraft. Such systems rely on measurements of dynamic pressure or Mach number. Also, each system must be tailored for the particular aircraft in which it will be deployed, with resulting extensive design changes from system to system, and expensive flight testing for final adjustments to ensure adequate performance.

With the rapid increase in technology in the field of electronics, many new electronic techniques have appeared and have proven to be almost indispensable in the safe operation of aircraft. These techniques, available and in use, can provide the necessary mechanization for an adaptive flight control system. Such a system would depend only on measurements of dynamic performance to provide the necessary gain-programing. This should give improved system performance compared to a scheduled-gain system. It should be possible to make such a system almost universally applicable, requiring only a change in the model and a few parameter adjustments for each different aircraft.

The method of approach used in this study is to extend that used for the North American SIDAC controller developed by Shipley and his associates.[3,4] This was modified by Rang,[5] from the observation that the equation for the handling qualities given by the C^*-Criterion, which was developed by Tobie, Elliot, and Malcom,[6] is very similar to the basic short-period equation of motion of the aircraft. A feedback system using variable gains was used to meet the C^*-Criterion requirements. The gain-changing mechanism is found by a gradient technique. In this paper the system is recast into one which has self-organizing properties. The development generalizes that given by Shipley.[4]

The system reported in Ref. 5 uses a feedback of normal acceleration, pitch rate and a feedforward of command input, combined with three variable gains to achieve an innerloop with invariant characteristics over the flight envelope. The approach taken here is to produce three linear combinations with fixed coefficients and then sum these signals with varying gains. This allows a blending of signals from three accelerometers, three rate gyros and three force transducers which hopefully yields a self-repairing redundant structure. Analog simulation shows that the system does have this property and will recover on simulated open or hard-over failures. A diagram of the organization is shown in Fig. 1.

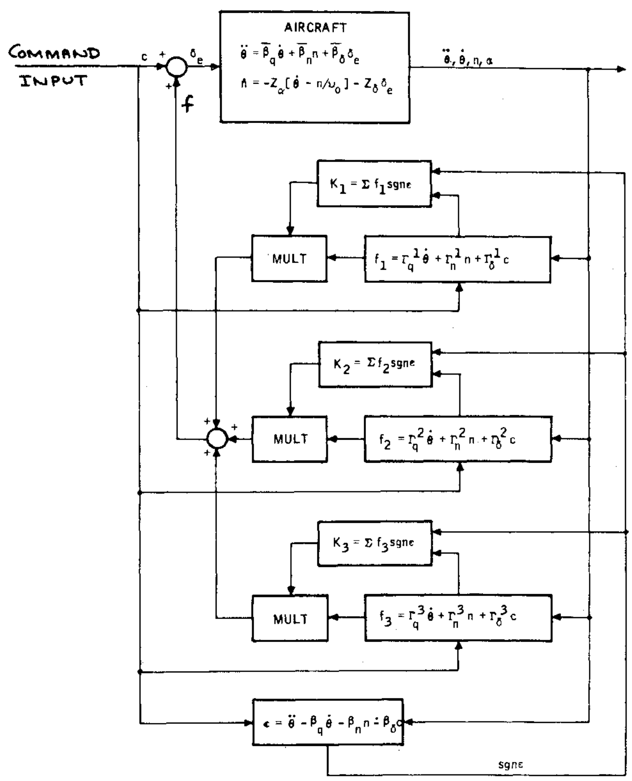

Fig. 1 Control unit configuration.

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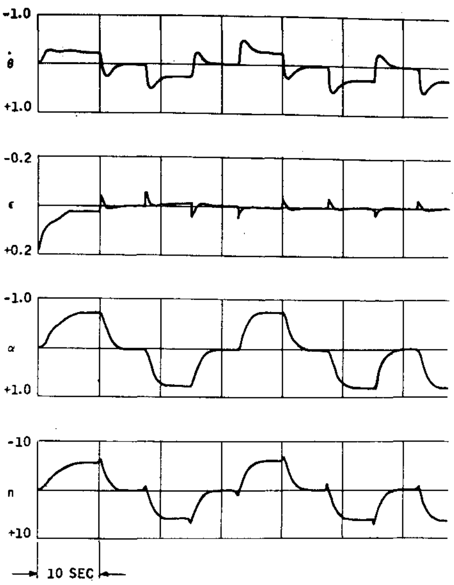

Fig. 2 Plot for flight condition 0002, showing the change in response as the K's go from zero toward their steady-state values.

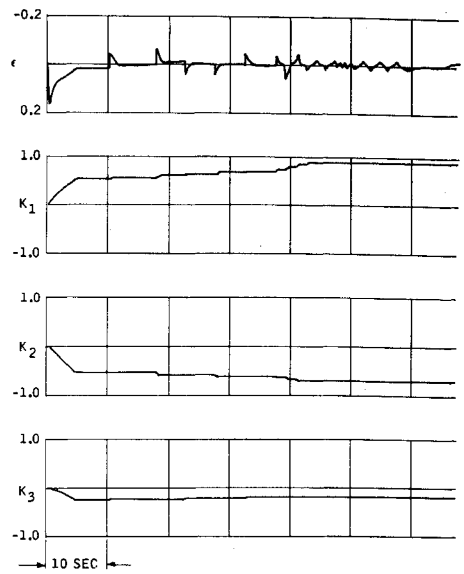

Fig. 3 Plot for flight condition 0002, showing K's driving toward their steady-state values.

Analytical Derivation

Shipley, Ref. 3, begins with the short-period perturbation equations for straight-and-level flight, written as

$$\ddot\theta = M_q\dot\theta + M_\alpha\alpha + M_{\dot\alpha}\dot\alpha + M_\delta\delta,$$
$$n = U_0(\dot\theta - \dot\alpha) = -Z_\alpha\alpha - Z_\delta\delta \tag{1}$$

Angle-of-attack α is eliminated because it is difficult to measure accurately and its measurement is affected by gusts and air turbulence. Eq. (1) may then be written in terms of normal acceleration n and pitch rate $\dot\theta$ for elevator inputs δ

$$\ddot\theta = \bar\beta_q\dot\theta + \bar\beta_n n + \bar\beta_\delta\delta, \quad \dot n = -Z_\alpha(\dot\theta - n/U_0) - Z_\delta\dot\delta \tag{2}$$

where the coefficients are calculated as

$$\bar\beta_q = M_{\dot\alpha} + M_q, \quad \bar\beta_n = -M_\alpha/Z_\alpha - M_{\dot\alpha}/U_0,$$
$$\bar\beta_\delta = M_\delta - Z_\delta M_\alpha/Z_\alpha \tag{3}$$

These are negative for all flight conditions. The constants M_α, $M_{\dot\alpha}$, M_q, M_δ, Z_α, Z_δ are stability derivatives characteristic of the particular flight condition. Values for a typical fighter-type aircraft are listed in Table 1. The first equation in Set (2) becomes

$$(-1/\bar\beta_n)\ddot\theta + (\bar\beta_q/\bar\beta_n)\dot\theta + n + (\bar\beta_\delta/\bar\beta_n)\delta = 0 \tag{4}$$

It is a fundamental relation.

The C^*-Criterion requires that the time response of the quantity

$$C^* = n + l\ddot\theta + U_c\dot\theta \tag{5}$$

should be relatively invariant over the flight envelope.

If C^* is required to be a multiple of the command input C, then Eqs. (4) and (5) are of the same form. Deviation from this exact proportionality is allowed by the Criterion and results from actuator dynamics and effects due to higher derivatives.

Let a system error be defined as

$$\epsilon = \ddot\theta - \beta_q\dot\theta - \beta_n n - \beta_\delta C = \ddot\theta + 3.0\dot\theta + 0.02n + 20.0C \tag{6}$$

for a fixed set of constants β_q, β_n, β_δ chosen in the range of values of $\bar\beta_q$, $\bar\beta_n$, $\bar\beta_\delta$, respectively. If the system responds so this error is small, the C^*-Criterion will be easy to satisfy, possibly by adding an outerloop, and the performance will be invariant over the flight envelope. Thus, the equations of motion of the system are

$$\ddot\theta = \bar\beta_q\dot\theta + \bar\beta_n n + \bar\beta_\delta\delta, \quad \delta = C + f$$
$$f = K_1f_1 + K_2f_2 + K_3f_3, \quad \epsilon = \ddot\theta - \beta_q\dot\theta - \beta_n n - \beta_\delta\delta \tag{7}$$

with three feedbacks

$$= \Gamma_q{}^1\dot\theta + \Gamma_n{}^1 n + \Gamma_\delta{}^1 C, \quad f_2 = \Gamma_q{}^2\dot\theta + \Gamma_n{}^2 n + \Gamma_\delta{}^2 C,$$
$$f_3 = \Gamma_q{}^3\dot\theta + \Gamma_n{}^3 n + \Gamma_\delta{}^3 C \tag{8}$$

of fixed gains, in matrix form

$$\Gamma = \begin{bmatrix} \Gamma_q{}^1 & \Gamma_n{}^1 & \Gamma_\delta{}^1 \\ \Gamma_q{}^2 & \Gamma_n{}^2 & \Gamma_\delta{}^2 \\ \Gamma_q{}^3 & \Gamma_n{}^3 & \Gamma_\delta{}^3 \end{bmatrix} = \begin{bmatrix} 0.895 & 0.00213 & 6.75 \\ -0.0187 & 0.000107 & -0.626 \\ 0.258 & -0.00331 & 1.083 \end{bmatrix} \tag{9}$$

Table 1 Aircraft parameters[a]

Flight condition	Altitude	Mach no.	U_0	$-M_\alpha$	$-M_{\dot\alpha}$	$-M_q$	$-M_\delta$	$-Z_\alpha$	$-Z_\delta$	$-\bar\beta_\delta$	$-\bar\beta_q$	$-\bar\beta_n$	$\Gamma_q{}^*$	$\Gamma_n{}^*$	$\Gamma_\delta{}^*$
0002	0	0.2	223	1.3	0.26	0.43	2.8	83	13.2	2.58	0.69	0.0146	90	0.0021	6.75
0009	0	0.9	1005	38	1.38	2.61	58.4	2420	313	53.5	4	0.0143	−0.019	0.0001	−0.63
1504	15,000	0.4	423	2.93	0.33	0.56	6.3	228	31.5	5.90	0.89	0.0121	0.36	0.0013	2.39
3006	30,000	0.6	597	3.6	0.27	0.51	7.5	262	38.2	6.93	0.78	0.0133	0.32	0.0010	1.88
4509	45,000	0.9	872	4.35	0.20	0.34	6.52	277	35.8	3.78	0.54	0.0158	0.65	0.0011	4.29
5020	50,000	2	1938	42.4	0.04	0.48	14.9	817	102	9.61	0.52	0.0519	0.26	0.0033	1.08

[a] Units in radians, feet and seconds.

Values for these were chosen corresponding to the single feedbacks which would make the system error zero at three different flight conditions. The three feedbacks are combined with varying gains, abbreviated as a vector as

$$K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \end{bmatrix} \tag{10}$$

to give the final form of the input into the elevator channel

$$f = K_1 f_1 + K_2 f_2 + K_3 f_3 \tag{11}$$

To facilitate the derivation, vector-matrix notation, is used. Let

$$x = \begin{bmatrix} \dot{\theta} \\ n \\ C \end{bmatrix}, \quad \bar{\beta} = \begin{bmatrix} \bar{\beta}_q \\ \bar{\beta}_n \\ \bar{\beta}_\delta \end{bmatrix}, \quad \beta = \begin{bmatrix} \beta_q \\ \beta_n \\ \beta_\delta \end{bmatrix}, \quad \gamma = \begin{bmatrix} \Gamma_q \\ \Gamma_n \\ \Gamma_\delta \end{bmatrix}$$

The set of equations from (7) then yields

$$\ddot{\theta} = \bar{\beta}'x + \bar{\beta}_\delta f = \bar{\beta}'x + \bar{\beta}_\delta \gamma' x, \; \epsilon = (\bar{\beta}' - \beta' + \bar{\beta}_\delta \gamma')x \tag{12}$$

where the prime denotes the transpose of the matrix.

Consider the function

$$2V = (\bar{\beta}' - \beta' + \bar{\beta}_\delta \gamma')Q(\bar{\beta} - \beta + \bar{\beta}_\delta \gamma) \tag{13}$$

where Q is a positive definite matrix to be chosen later. Differentiation gives

$$dV/dt = (\bar{\beta}' - \beta' + \bar{\beta}_\delta \gamma')Q\bar{\beta}_\delta(d\gamma/dt) \tag{14}$$

Since V is to be driven to zero, which in turn means ϵ is driven to zero, the requirement is

$$dV/dt \leqq 0$$

Thus, choose

$$d\gamma/dt = Q^{-1}xG \tag{15}$$

so that

$$dV/dt = \bar{\beta}_\delta \epsilon G$$

Since the parameter $\bar{\beta}_\delta$ is always negative, taking

$$G = \operatorname{sgn}\epsilon = \begin{cases} 1, & \epsilon \geqq \epsilon_0 = 0.02 \\ 0, & -\epsilon_0 < \epsilon < \epsilon_0 \\ -1, & \epsilon \leqq -\epsilon_0 \end{cases}$$

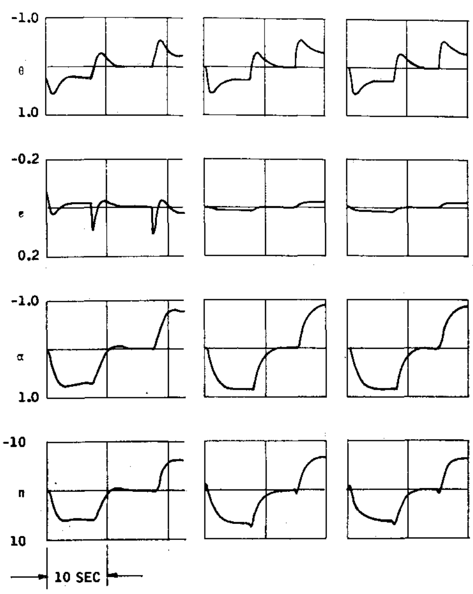

Fig. 4 Plots for flight condition 0002, with the value of $\Gamma_q{}^1, \Gamma_q{}^2$, and $\Gamma_q{}^3$, respectively, set to zero.

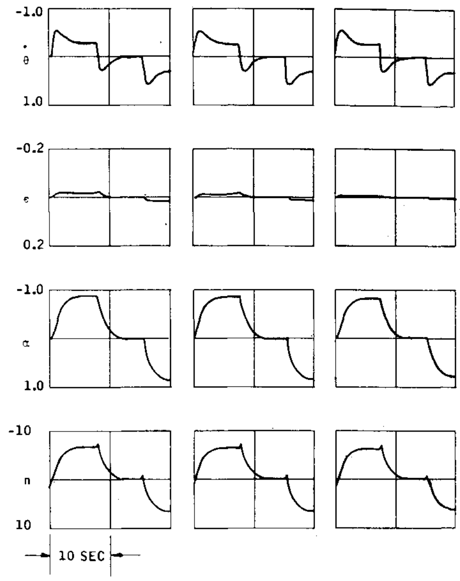

Fig. 5 Plots for flight condition 0002, with the value of $\Gamma_n{}^1, \Gamma_n{}^2$, and $\Gamma_n{}^3$, respectively, set to zero.

makes

$$dV/dt = \bar{\beta}_\delta |\epsilon| \leqq 0$$

The choice

$$Q^{-1} = \begin{bmatrix} K_q & 0 & 0 \\ 0 & K_n & 0 \\ 0 & 0 & K_\delta \end{bmatrix}$$

yields the same system discussed in Ref. 5.

Equation (11) combined with (8) is

$$f = K'\Gamma x$$

But also, from Eq. (7)

$$f = \gamma' x$$

Therefore,

$$\gamma = \Gamma' x$$

Equation (15) is then

$$d\gamma/dt = \Gamma'(dK/dt) = Q^{-1}xG$$

or

$$dK/dt = (Q\Gamma')^{-1}xG$$

Now choose

$$(Q\Gamma')^{-1} = Q_0{}^{-1}\Gamma$$

so that

$$dK/dt = Q_0{}^{-1} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} G \tag{16}$$

With

$$Q_0{}^{-1} = \begin{bmatrix} K_q & 0 & 0 \\ 0 & K_n & 0 \\ 0 & 0 & K_\delta \end{bmatrix}$$

Eq. (16) becomes

$$dK_1/dt = K_q f_1 G; \qquad dK_2/dt = K_n f_2 G; \qquad dK_3/dt = K_\delta f_3 G$$

These produce the variable gains used in the self-organizing system. Since

$$Q = \Gamma^{-1}Q_0(\Gamma^{-1})'$$

if Γ is nonsingular and Q_0 is positive definite, then Q is positive definite, which is necessary for concluding that ϵ goes to zero as V goes to zero.

Analog Simulation

The system, for all flight conditions tested, drove its gains to values such that the system error remained in its zero range. The time required for this system adjustment varied with flight condition, frequency, and amplitude of the input commands, and the number of commands given. The flight characteristics did not vary significantly during this transient time. Figures 2 and 3 illustrate this for the flight condition of a landing approach at sea level and Mach 0.2. We note from Fig. 3 that the gains make the majority of their adjustments during the transient period after the first step input and then approach the steady-state values at a much slower pace. However, from Fig. 2 we see that the shapes of the responses of the dynamic variables do not change significantly after the first step input. (Since we had only a four-channel recorder, the two figures are from different runs, which start with the same initial state and have essentially the same command input history.)

Simulated failures were compensated by variations in the gains. The plots in Figs. 4 and 5 are typical results. These show little change in aircraft flight characteristics as pitch-rate feedbacks are dropped in the first set of curves and as the normal acceleration feedbacks are deleted in the second group of traces. In some cases, the value of the error signal could not be made to remain in its deadband, but always quickly drove toward zero. A failure at one of the flight conditions which were used to define the three feedbacks showed no effect if it was in one of the two nonessential paths. This is as expected, since the design element should handle the flight condition by itself. When the failure was simulated in the design feedback element, there was usually a big change in the variable gains, and a slight change in performance. The flight characteristics were still satisfactory.

When multiple failures of the zero input type were simulated, the system was still able to function adequately. There was some deterioration in the amplitude of response and the time-response characteristics. The system error usually did not stay in its zero range when command signals were given, but always went rapidly to zero. The system was able to handle combinations of up to six simulated failures in inputs, as long as at least one each of the $\dot{\theta}$, n, and C inputs remained.

When multiple failures were simulated using erroneous input signals, system reaction was not as good as with the zero input failure simulation. The system was still able to reach a semi-steady-state condition in which the error would drive to zero, but response was generally poorer. The poorest results were obtained when the error simulation involved two of the same quantities, such as two $\dot{\theta}$'s. In such cases, the system could not tell which input was the correct one, and the resulting performance plots were quite bad. Similar results were obtained by mixing the modes of failure together. The system was able to handle failures simulated by setting one feedback equal to a nonzero constant value very well. No limit cycles were observed after simulated hard-ever accelerometer signals.

The response time required to give acceptable dynamic performance appears to be adequate even though the tracking to the steady-state values of the gains is slow. Previous studies of the system with a single set of feedbacks[5] showed there is a marked tolerance to noise, a superimposed primary system, fuselage bending, actuator hysteresis, and other disturbances. We conjecture that the system will not be disturbed by the phugoid mode or the lateral degrees of freedom although these simulations were not made.

Conclusions

A self-organizing adaptive control scheme can handle gain scheduling within a control system in such a way that the system response is relatively invariant as required by the C^*-Criterion. The ability to alter system gains as necessary to meet the response criterion gives the system better response than can be realized with a fixed-gain schedule system. The system is also able to accommodate sensor failures, thus providing a built-in backup.

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