Direct Lift Control for Approach and Landing

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Direct Lift Controllers for three large aircraft are designed by a computer program based on Kalman's linear state regulator theory. Demonstrated are controllers that maintain any desired pitch attitude, use feedbacks to a single control surface to eliminate response lag and reduce pitch rate overshoot while allowing conventional pitch attitude changes. The theoretical basis of the digital optimization program is presented coupled with a discussion of manipulation of the input cost matrices to satisfy performance and handling quality criteria. Strip chart recordings from a piloted analog simulation are shown to compare performance of the standard and DLC versions of each aircraft during a standard maneuver.

Introduction

THIS study has two main purposes: 1) demonstrate the flexibility of the digital optimization program (described in Ref. 3) in designing Direct Lift Control (DLC) systems for several large aircraft, and develop controllers displaying various flexible characteristics; 2) show, through analog simulation, the feasibility of applying DLC to the aircraft in question, and illustrate the improved handling qualities which result.

The aircraft included in this study are The Boeing 2707-200§ (SST), the Ames Large Transport (ALT) which is a C-5 class transport, and the Jumbo Jet Bus (JJB) which is typical of the incipient generation of large subsonic jetliners. In all cases, the coefficients used in the linearized equations of motion are for the approach and landing condition, corresponding to Load Alleviation and Mode Stabilization (LAMS)¶ flight condition 2 of Ref. 1. The coefficients are listed in Table 1, along with the LAMS B-52 data for comparison.

All controllers were designed with computer optimization program D (Ref. 3, p. 36) by merely reading in the proper aerodynamic coefficients for the aircraft in question. The strip chart recordings were obtained from a 2 degree-of-freedom analog simulation. A standard mission profile for independent or conventional attitude control is as follows:

1) Pitch over 2°.
2) Maintain 500 ft/min rate of descent. (Use pitch hold in DLC aircraft.)
3) Decrease rate of descent to 300 ft/min for 15 sec.
4) Increase rate of descent to 700 ft/min for 15 sec.
5) Maintain 500 ft/min rate of descent until flare.
6) Flare for touchdown after 1000 ft descent. (Turn off pitch hold in DLC aircraft.)

Received May 31, 1968; revision received December 9, 1968. This paper is based on the Air Force Institute of Technology (AFIT) report, "Direct Lift Control for Approach and Landing," by Captains Lorenzetti and Nelsen.[1] The study is a follow on to the work reported in Ref. 2. Lt. Colonel Johnson, Associate Professor of Electrical Engineering at Air Force Institute of Technology, served as editor for this article. We are indebted to P. Burris, J. Raisbeck, and C. Flora, all of The Boeing Company, who provided aerodynamic coefficients for use with the equations of motion presented in Ref. 3.

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§ This is the now-discarded variable sweep wing design.

¶ An Air Force Flight Dynamics Laboratory study of methods to increase the structural life of large flexible aircraft. Contractors are The Boeing Company and Honeywell, Inc.

Optimal Control Theory

The computer optimization program which selects the feedback gains is based on the linear state regulator theory originally advanced by R. E. Kalman.[4] The state equation for a *completely controllable linear time invariant system* is

$$\dot{\mathbf{X}}(t) = A\mathbf{X}(t) + B\mathbf{U}(t) \tag{1}$$

where A and B are time invariant matrices. Kalman's state vector $\mathbf{X}(t)$, represents an array of response variables. The aerodynamic surface array, $\mathbf{U}(t)$, is to be controlled to minimize a weighted sum of the squared errors of the response variables plus the squared surface deflections. The quadratic cost function, which is merely a mathematical statement of

Table 1 D matrix: aerodynamic coefficients

Element	Coefficient	Alt	LAMS B-52[a]	SST
D(1,KS)	C_L (Clean)	2.03	.450	.716
D(2,KS)	$C_{L\alpha} + C_D$	7.94	3.890	3.29
D(3,KS)	$C_{L\delta e}$	.3660	.1578	1.145
D(4,KS)	$C_{M\alpha}$	-1.90	-.762	0
D(5,KS)	$C_{M\delta e}$	-2.119	-.517	-.265
D(6,KS)	$qS\bar{c}/I_{YY}$	.236	2.5750	1.89
D(7,KS)	qS/M	15.9	71.6	45.0
D(8,KS)	$C_{L_q}' = \frac{\bar{c}}{2U_o}\left[\frac{\partial c_L}{\partial(q\bar{c}/2U_o)}\right]$	0	.0876	0
D(9,KS)	$C_{L_{\dot{\alpha}}}' = \frac{\bar{c}}{2U_o}\left[\frac{\partial c_L}{\partial(\dot{\alpha}\bar{c}/2U_o)}\right]$	.029	.0212	0
D(10,KS)	$C_{M_q}' = \frac{\bar{c}}{2U_o}\left[\frac{\partial c_M}{\partial(q\bar{c}/2U_o)}\right]$	-1.90	-.383	-.111
D(11,KS)	$C_{M_{\dot{\alpha}}}' = \frac{\bar{c}}{2U_o}\left[\frac{\partial c_M}{\partial(\dot{\alpha}\bar{c}/2U_o)}\right]$	-.663	-.0622	-.0336
D(12,KS)	$C_{L\delta_{sp}}$	1.160	.1524	.410
D(13,KS)	$C_{M\delta_{sp}}$	0	.1496	0
D(14,KS)	U_o (fps)	194.0	429.4	236.0
D(15,KS)	$C_{L\delta_{ail}}$ (canard for SST)	0	.100	2.0
D(16,KS)	$C_{M\delta_{ail}}$ (canard for SST)	0	-.036	2.0

[a] JJB data is proprietary.

the above least squares requirement, is

$$J = \mathbf{X}^T F \mathbf{X} + \int_0^{t_F} (\mathbf{X}^T Q \mathbf{X} + \mathbf{U}^T R \mathbf{U}) dt \qquad (2)$$

If the final time t_F, is infinity, then the resulting optimal feedback system is linear and time invariant (Ref. 5, p. 751). The R matrix, the cost of control, must be positive definite; the Q matrix, the cost of nonzero states, need only be positive semidefinite, and F can be the zero matrix. $R(1, 1)$ weights the cost of using $U(1)$, the elevator, $R(2, 2)$ weights spoiler usage, and $R(3, 3)$ weights aileron (or canard) deflections. Similarly, $Q(1, 1)$ is the cost of nonzero $X(1)$, normal acceleration, while $Q(2, 2)$ and $Q(3, 3)$ weight pitch angle and pitch rate, respectively. Manipulation of the off-diagonal elements of the Q and R matrices, which are always zero in this study, is discussed in Ref. 2 and on pp. 47–51 in Ref. 3.

With $\mathbf{U}(t)$ not constrained, Kalman has shown (Ref. 5, p. 771) that an optimal control exists, is unique, is stable, and is given by

$$\mathbf{U}(t) = -R^{-1}B^T C \mathbf{X}(t) = [\text{controller matrix}][\mathbf{X}(t)] \qquad (3)$$

where C is the constant $n \times n$ positive definite matrix obtained by integrating the matrix Riccati equation

$$\dot{C}(t) = -C(t)A - A^T C(t) + C(t)BR^{-1}B^T C(t) - Q \qquad (4)$$

backwards in time with the boundary condition

$$C(t_F) = F = 0$$

As backward integration proceeds, the transient due to the initial condition $C(t_F) = 0$ dies out, and all elements of the C matrix become constant. The controller matrices in Tables 2–4 are then computed by Eq. (3).

Design Criteria

While all controllers produced by the digital computer program are optimal for the costs assigned in the Q and R matrices, they are not necessarily practical [$\mathbf{U}(t)$ is unconstrained], nor are handling qualities always acceptable to the pilot. After some experience with the program, two or three runs (one minute of IBM 7094 time each) usually suffice to achieve the desired aircraft response, with good handling qualities, at the desired gain levels.

First the designer chooses $Q(2, 2)$ based on the desirability of a constant-attitude DLC system (Table 4). $Q(1, 1)$ is manipulated to produce a normal acceleration feedback that provides adequate gust alleviation and smooth rate of climb traces without fighting pilot command inputs. Examination of the controller matrices shows that the magnitude of normal acceleration feedback is quite small to best accomplish these conflicting objectives. $Q(1, 1)$ must be about one order of magnitude smaller than the other Q's to accomplish this. $Q(3, 3)$ is manipulated to obtain a pitch rate feedback that provides good stabilization, eliminates excessive pitch rate overshoots, and results in good handling qualities.

The main diagonal elements of the R matrix can be made equal unless control surface effectiveness varies greatly (as in the SST canards) or feedbacks to one or both auxiliary surfaces are not desired. Controller ALT/2C (Table 3) uses open-loop spoilers for DLC, while $R(1, 1)$ is made small to allow elevator use in maintaining the constant attitude dictated by the large $Q(2, 2)$. With $R(2, 2)$ and $R(3, 3)$ large in relation to $R(1, 1)$, the program specifies no feedbacks to spoilers or the nonexistent ailerons. The gain level of the entire controller is conveniently controlled through the R matrix. For instance, if lower gains than those obtained are required due to structural mode or other considerations, they are easily obtained, still in an optimal ratio, by increasing the R matrix values.

Equation (2) could be used to compute a cost of responding to some initial disturbance with various controllers. This information might be interesting, but it has no practical value. The ultimate design criteria are that the system: a) provide acceptable stabilization of the aircraft. This is accomplished by the feedback loops to the elevator just as in an ordinary stability augmentation system; b) provide the unique advantages of the auxiliary direct lift surface... elimination of normal acceleration reversal, thus speeding aircraft response, and reduction of pitch rate overshoot to a desirable level; c) provide superior handling qualities as evaluated by a pilot on an analog simulation. The relationship between pitch rate and normal acceleration is unalterable in a conventional elevator control system, placing a basic limit on performance and handling qualities. Direct Lift Control removes these limitations. These criteria are common to all closed-loop DLC systems. The digital computer program is merely a means of satisfying the criteria in

Table 2 Jumbo Jet Bus controller feedbacks

Q MATRIX

1	0	0
0	30	0
0	0	5

R MATRIX

.04	0	0
0	20	0
0	0	.04

CONTROLLER JJB/2C FB

to \ of	$.01\ N_L$ @	θ #	$\dot{\theta}$ †
δ_e	−.9935	27.04	13.26
*δ_{sp}	0	0	0
δ_{ail}	−.1580	4.300	2.109

*Spoilers used open-loop

@Feedback gain in 0.01 ft/sec/sec per radian surface movement.

#Feedback gain in radians per radian control surface movement.

†Feedback gain in rad/sec per radian control surface movement.

ABOVE SCALING USED THROUGHOUT PAPER

Table 3 Ames Large Transport controller feedbacks

Q MATRIX

1	0	0
0	20	0
0	0	20

R MATRIX

.04	0	0
0	10	0
0	0	10

CONTROLLER ALT/2C FB

to \ of	N_L	θ	$\dot{\theta}$
δ_e	−.2468	22.27	23.04
δ_{sp}	0	0	0
δ_{ail}	0	0	0

Table 4 Supersonic transport controller feedbacks

Q MATRIX

.1	0	0
0	15	0
0	0	15

R MATRIX

.1	0	0
0	15	0
0	0	30

CONTROLLER SST/7A FB

to \ of	$.01\ N_L$	θ	$\dot{\theta}$
δ_e	.0374	11.20	12.47
δ_{sp}	0	0	0
δ_{can}	0	−.2818	−.3137

Q MATRIX

.01	0	0
0	.05	0
0	0	20

R MATRIX

.1	0	0
0	15	0
0	0	30

CONTROLLER SST/7B FB

to \ of	$.01\ N_L$	θ	$\dot{\theta}$
δ_e	.0387	.0282	12.62
δ_{sp}	0	0	0
δ_{can}	0	0	−.3175

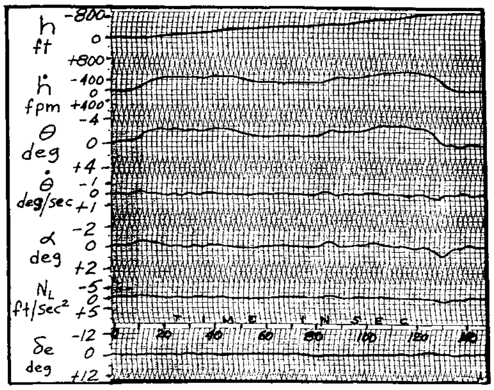

Fig. 1 JJB/basic aircraft.

an optimal manner. The required manipulation of the Q and R matrices is an easily learned art.

Stick to Control Surface Gains

In theory, the digital optimization program could be expanded to select these gains along with the feedbacks. This has not been done as equal gains to the surfaces work well for the aircraft in this report. When the DLC surface generates appreciable pitching moment, as the B-52 spoilers in Refs. 2 and 3, the ratio of stick gains to the spoilers and elevator can be made the inverse of the pitching moment ratios.

Control Surfaces

For all three airplanes, Boeing stated that the spoiler coefficients could be considered constant for $\pm 10°$ movement in the approach and landing condition. For ease of recording, spoilers are always shown with $\pm 10°$ authority from a 10° bias position. Maximum elevator and canard deflection on the SST is $\pm 10°$, while the elevators of the other two craft and the JJB ailerons can move $\pm 17°$.

In this study, all servo time constants were set at 0.167 sec to reasonably simulate the actual aircraft equipment. However, Ref. 6 shows that the auxiliary DLC surface (flaps in this case) can provide significant reductions of aircraft normal acceleration in turbulence with a time constant as large as 1 sec, and a 0.4 sec time constant for the DLC surface represents a good compromise between performance and actuator power requirements.

Sign Conventions and Equations of Motion

N_L is acceleration of the aircraft center of gravity and $\dot{h}$ is rate of climb, both positive in the up direction. Note that the stability derivatives are stated in the sub-L convention. Positive θ is pitch up.

Elevator, canard, and symmetric aileron trailing edge deflection down from neutral is positive. Spoiler trailing edge deflection up from the wing surface is positive, so negative spoiler does not exist.

Linearized two degree of freedom perturbation equations were used for both the digital optimization program and the analog simulation. Thus, all recorded strip chart parameters are changes from equilibrium conditions. Work in Ref. 3 showed good correlation of DLC capabilities and handling qualities between 2 and 6 degree-of-freedom simulations.

Pitch Hold Control

In Refs. 2 and 3, all controllers were designed to hold θ to 0°. To add flexibility to the DLC system, the simulation for this report was changed to allow the pilot to maintain any desired pitch attitude. This was done by simply adding a $\Delta\theta$ integrator fed through a switch (labeled pitch hold) by $\dot{\theta}$, and using the output as the controller pitch angle feedback. With this system, the pilot can rotate the aircraft to any desired attitude in a normal manner, turn on the pitch hold switch, and then use DLC to vary his rate of climb about the nominal value established by his pitch attitude. The pitch rate and normal acceleration feedbacks are not affected by the pitch hold system and the auxiliary control surfaces are still in use. Thus, the pilot can make a change in pitch attitude without pitch rate overshoot and without the reversal of normal acceleration and pitch rate which may be present in the basic aircraft.

All DLC controllers presented here are operated by the pilot's normal longitudinal stick or column movements. When pitch hold is used, column movement is interpreted as a rate of climb command. Otherwise, the pilot commands a blend of pitch rate and normal acceleration as in the C^* system.

Independent Attitude Control

This is another easily implemented DLC refinement that is used in conjunction with pitch hold. A rate-controlled integrator fed through a switch by a thumbwheel potentiometer is used to slowly produce a false pitch angle error signal which is summed with the output of the $\Delta\theta$ integrator described previously. The Direct Lift Controller responds by pitching the aircraft to cancel the false θ error. Note that this is a closed loop system, and the thumbwheel can be calibrated in degrees change from existing attitude. Figures 2 and 4 show that this system changes the aircraft attitude smoothly and without overshoot. The pilot could use this independent control to establish the proper attitude for glide-slope or flare, then use stick-controlled DLC to capture the glide-slope or touch down.

JJB Simulation

The basic aircraft was flown with results shown in Fig. 1. All JJB flying was done by Captain Lorenzetti, who is not rated, demonstrating that the JJB's longitudinal characteristics are not difficult to handle in this mode. (His attempts to fly the basic SST resulted in chaos, while the DLC/SST was easy to fly.) For DLC, the JJB uses elevator, biased spoilers, and symmetrically operated ailerons. Controller JJB/2C (Table 2) was designed with a high cost for spoiler usage (large R_{22}) and a high θ cost (large Q_{22}). The

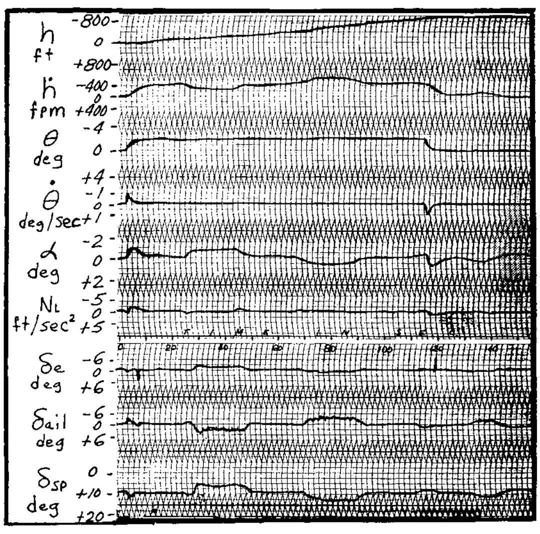

Fig. 2 JJB/2C (independent attitude control).

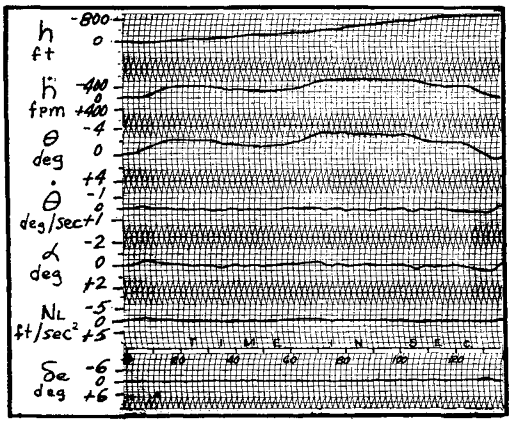

Fig. 3 ALT/basic aircraft.

spoilers were used open loop, simplifying the controller. Figure 2 shows the DLC aircraft's ability to change rate of climb without changing attitude.

ALT Simulation

Recordings for the Ames Large Transport are shown in Figs. 3 and 4. All ALT flying was done by Captain Nelsen, a U. S. Air Force Senior Pilot. This aircraft showed noticeable normal acceleration reversal when a climb was commanded, and the generally sluggish response made it harder to fly than the JJB.

For direct lift, the ALT uses elevator and biased spoilers only. Coefficients for symmetrically operated ailerons were not readily available. They could have been chosen arbitrarily, but their absence demonstrates DLC with a single auxiliary control surface and the flexibility of the digital optimization program. The cost of aileron usage (R_{33}) was made high, and the computer program operated without problems or modifications. Computed aileron feedbacks were zero in all runs.

Controller ALT/2C, shown in Table 3, demonstrates the simplest possible constant attitude DLC system. Figure 4 shows the spoilers operating open loop, while the elevator does a good job of maintaining the attitude commanded by the independent thumbwheel controller. Except for the absence of symmetrically operated ailerons, this controller is similar to that actually flight tested on the LAMS B-52 (Ref. 1, Appendix). A comparison of Figs. 3 and 4 confirms the pilot's comments that a specified rate of descent could be established faster and maintained easier with DLC.

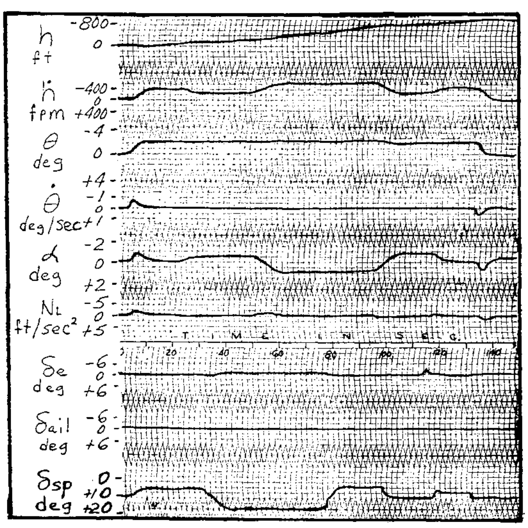

Fig. 4 ALT/2C (independent attitude control).

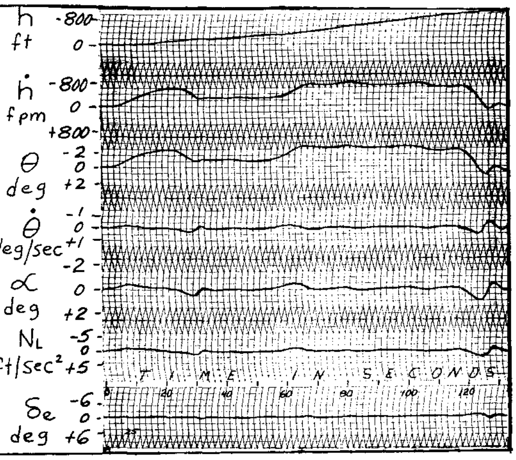

Fig. 5 SST/basic aircraft.

SST Simulation

Here, basic SST means a vehicle without canards. There was some difficulty in determining the designer's thinking on canard usage, and obtaining accurate canard lift and pitching moment coefficients. The values used (Table 1) represent a compromise between C_L values ranging from 0.4 to 4.0. The analog recordings show maximum canard deflection of less than 3° vs maximum 10° authority, so some variance from these coefficients can be tolerated.

Recordings for the basic SST are shown in Fig. 5. With a step stick input, this simulation (2 degrees of freedom) shows very noticeable reversal of normal acceleration and rate of climb, with a heave crossover time of 2 to 3 sec. Longitudinal response is very sluggish.

Direct Lift Controller design for the SST considers use of elevator, biased spoilers, and canards. The two controllers selected for presentation are listed in Table 4.

Controller SST/7A uses moderate θ feedback and low N_L feedback, since high N_L feedback tends to excite the structural modes of a very flexible aircraft such as the SST. Results are shown in Fig. 6, which also demonstrates pitch attitude control with the pilot controlling the canards and spoilers only. There is no stick input to the elevator. This and other SST controllers were flown both with and without stick input to the elevator with no discernable difference in performance.

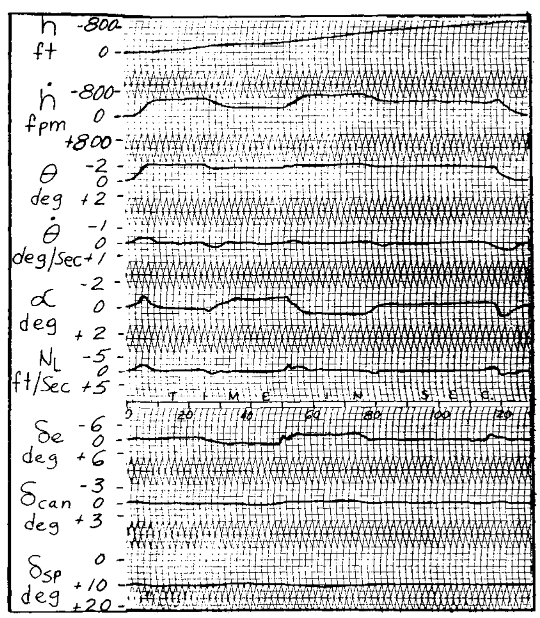

Fig. 6 SST/7A, no stick to δ_e (independent attitude control).

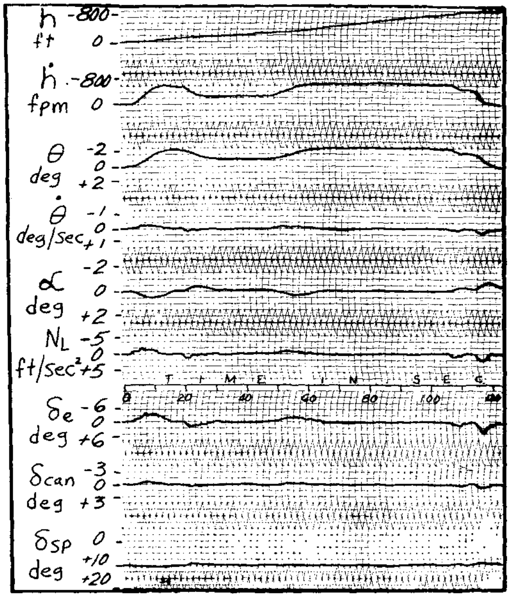

Fig. 7 SST/7B, no stick to δ_e (conventional attitude control).

For controller SST/7B, the Q matrix has been manipulated to reduce N_L and θ feedbacks essentially to zero. Thus, Fig. 7 shows a normal aircraft pitch response. However, the pitch rate feedback to the elevator stabilizes the plane, and use of the DLC canard makes the rate of climb response more rapid and precise, as seen by comparing Figs. 5 and 7. The small $\dot{\theta}$ feedback to the canards was later eliminated with little effect. Again, there is no stick input to the elevator, and spoiler movement is negligible.

If spoilers are not used, and full $\pm 10°$ elevator authority is allowed in the DLC feedbacks; controller SST/7A can change its rate of climb about 400 ft/min without changing pitch attitude.

Summary and Conclusions

This follow-on study has demonstrated the flexibility of the digital optimization program developed in Ref. 3. By merely changing the input data, approach and landing controllers have been designed for three aircraft with widely varying characteristics and additional DLC features have been demonstrated. The near-automatic computerized design coupled with the simple pilotable analog simulation allows rapid and economical DLC capability studies for various aircraft and/or control surfaces.

For brevity, a given type of controller has usually been demonstrated on a single aircraft. However, except for use of the SST-peculiar canards, comparable controllers can be designed for the other aircraft. In fact, controllers with any desired features and gain levels are easily produced by proper variations of the Q and R matrices.

The authors personally prefer controllers such as ALT/2C or SST/7A for the approach and landing tasks. Restricting the feedbacks to a single control surface simplifies the hardware, while the open-loop use of spoilers or symmetric ailerons provides the normal DLC benefits. The θ feedback is high enough to allow use of an independent attitude control and maintain any desired pitch attitude while rate of climb is varied up to 400 ft/min. On the other hand, the pilot can disengage pitch hold at will without adversely affecting aircraft stability or DLC's other performance features. These controllers also allow use of a simple altitude hold circuit (Ref. 3, p. 56).

The success of the false θ error in the independent attitude control system suggests another possible auxiliary feature for DLC. If a fighter or bomber aircraft is required to do a constant g pull up maneuver, a "false N_L error" (with no θ feedback) should achieve the desired results.

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