Computerized Design of Optimal Direct Lift Controller

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A direct lift controller (DLC) for large aircraft is designed using Kalman's linear state regulator theory. This application concerns a B-52 test aircraft, but the design method is directly applicable to other aircraft and aerodynamic surfaces. Spoilers, symmetric ailerons, and elevator form the three-dimensional primary flight controller which responds to pilot normal longitudinal column movement (interpreted as a rate of climb command), applying lift forces in the desired direction without pitching the aircraft. The controller permits changes in rates of climb and descent of up to 500 ft/min from trim condition without a change in aircraft pitch attitude. When larger control forces are applied, the DLC functions as a conventional control system, causing aircraft rotation. The pilot's ability to make precise changes in altitude or rate of climb is demonstrated by a moving-base cockpit simulation driven by a six-degree-of-freedom analog program. The controller reduces normal acceleration 50% during climb and descent maneuvers both in and out of turbulence and improves the pilot's ability to maintain constant airspeed. The closed-loop controller consists of an input command proportional to longitudinal stick movement plus fixed-gain normal acceleration, pitch angle, and pitch rate feedbacks to each of the three control surface servos. The associated feedback gains were selected by a digital optimization program using a linear plant with a quadratic cost function.

Introduction

DURING the past decade, the production of larger, heavier, higher-performance aircraft has required a rapid advance in flight control system technology to maintain acceptable handling qualities. Sophisticated stability-augmentation systems are currently standard in the century series as well as in many other aircraft. The F-111 has an even more advanced self-adaptive control system. In transport aircraft, increased size, weight, and airspeed have reduced the ratio of aerodynamic to inertial moments, producing a "sluggishness" of response. Precise control of these aircraft is difficult in certain flight regimes due to excessive pitch rate overshoot while controlling normal (vertical) acceleration. These regimes include approach and landing flare, in-flight refueling, terrain following, and cargo drop. Attempts to make small corrections in flight-path angle can result in undesirable transients. These problems exist because both lift and normal acceleration are controlled by pitching the aircraft. Thus, it is desirable to provide the pilot with a more direct control over lift without applying an undesirable pitching moment.

Direct Lift Control Defined

Within this paper, direct lift control (DLC) is defined as use of an independent, fast-response high-lift control surface(s) in conjunction with the elevator to achieve precision flight-path control. DLC decouples flight path and attitude control through lift modulation to improve handling characteristics during landing approach, terrain following, aerial refueling, and other precision maneuvering tasks. The pilot can change altitude or rate of climb without a change in pitch attitude and without the delay in lift build-up associated with conventional elevator control. This design accomplishes DLC by moving the elevator, spoilers, and (symmetrically operated) ailerons in response to longitudinal stick commands. Small stick movements produce lift without pitch to provide the desired precision maneuvering capability, whereas larger stick commands (for changes in rates of climb or descent in excess of 400–500 ft/min from trim) provide pitching moments, as in a conventional control system.

LAMS B-52

Many of the assumptions and limitations of this study are based on the ultimate goal of flight testing the resulting design on the LAMS B-52. Load Alleviation and Mode Stabilization (LAMS) is a current project of the Air Force Flight Dynamics Laboratory in conjunction with The Boeing Company and Honeywell Inc. Its objective is to determine methods of increasing the fatigue life of large airplanes by reducing vibrations and flexing of the airframe as a result of wind gusts and/or aircraft maneuvers.

The LAMS aircraft is a modified and heavily instrumented B-52E. The control surfaces themselves (ailerons, spoilers, and elevators) are standard; however, they have been fitted with new fast-responding broad-bandwidth actuators and symmetrically operated ailerons. Two transistorized analog computers (Electronics Associates Inc., EAI TR-48's) are installed in the aircraft to simulate a stability-augmentation system and to implement the LAMS controller (Ref. 1, p. 84). The LAMS controller is used only in three specific flight conditions, which can be described as terrain following, approach and landing, and high-altitude cruise (in-flight refueling). The direct lift controller is therefore designed for these same three flight conditions.

Direct Lift Controller Design

Three digital optimal control programs (quadratic criteria) were used to generate direct-lift controllers, demonstrating a limited choice in number and type of feedbacks. The linear state regulator theory advanced by R. E. Kalman and his associates (Ref. 7, pp. 35–45) was used.

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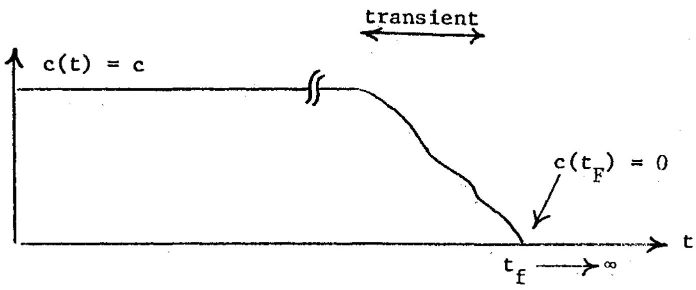

Fig. 1 Typical element of C matrix.

Linearized Equations of Motion

The LAMS equations are written for perturbations about three specific flight conditions. The digital optimization program is based on a short-period approximation of the LAMS B-52 (Ref. 3, pp. 40–44) with spoiler lift and moment coefficients linearized about a 20° trailing-edge-up bias position. This reduces the aircraft to a linear system capable of pitch and vertical movement at constant airspeed.

In addition to the foregoing, the aircraft is assumed trimmed for straight and level flight with spoilers biased up before the direct lift controller begins operation. Thus, the equations of motion reduce to the following:

$$\dot{\alpha} = \left\{\frac{1}{AA}\right\}\left\{Q + \frac{qS}{mU_o}\left[-(C_{L_\alpha} + C_D)\Delta\alpha - C'_{L_q}Q - C_{L_{\delta_e}}\delta_e + C_{L_{\delta_{SP}}}\delta_{SP} - C_{L_{\delta_{ail}}}\delta_{ail}\right]\right\} \qquad (1)$$

where

$$q = \tfrac{1}{2}\rho U_o^2, \quad AA = 1 + \frac{qS}{mU_o}C'_{L_{\dot{\alpha}}}$$

$$C'_{L_q} = \frac{\bar{c}}{2U_o}\left[\frac{\partial C_L}{\partial(q\bar{c}/2U_o)}\right]; \quad C'_{L_{\dot{\alpha}}} = \frac{\bar{c}}{2U_o}\left[\frac{\partial C_L}{\partial(\dot{\alpha}\bar{c}/2U_o)}\right]$$

$Q = \dot{\theta}$ due to absence of lateral motion,

and

$$\dot{Q} = \frac{qS\bar{c}}{I_{yy}}\left[C_{M_\alpha}\Delta\alpha + C'_{M_q}Q + C'_{M_{\dot{\alpha}}}\dot{\alpha} + C_{M_{\delta_e}}\delta_e + C_{M_{\delta_{SP}}}\delta_{SP} + C_{M_{\delta_{ail}}}\delta_{ail}\right] \qquad (2)$$

$$C'_{M_q} = \frac{\bar{c}}{2U_o}\left[\frac{\partial C_M}{\partial(q\bar{c}/2U_o)}\right], \quad C'_{M_{\dot{\alpha}}} = \frac{\bar{c}}{2U_o}\left[\frac{\partial C_M}{\partial(\dot{\alpha}\bar{c}/2U_o)}\right]$$

The optimization program uses the state N_L, normal acceleration of the aircraft center of gravity. An equation for N_L was obtained by differentiating

$$N_L = U_o\dot{\theta} - \dot{W} \qquad \text{(Ref. 3, pp. 15–16)} \qquad (3)$$

Holding U_0 (airspeed) and all aerodynamic coefficients as constants, and ignoring surface rates,

$$\dot{N}_L = U_o\{\dot{Q}(1 - 1/AA) + AB[(C_{L_\alpha} + C_D)\dot{\alpha} + C'_{L_q}Q]\} \qquad (4)$$

where

$$AB = qS/[mU_o(AA)]$$

Optimal Control Theory

The state equation for a completely controllable, linear, time-invariant system is

$$\dot{\mathbf{X}}(t) = A\mathbf{X}(t) + B\mathbf{U}(t) \qquad \text{(Ref. 2, p. 750)} \qquad (5)$$

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 the preceding "least squares" requirement, is

$$J = \mathbf{X}^T F\mathbf{X} + \int_0^{t_F}(\mathbf{X}^T QX + \mathbf{U}^T R\mathbf{U})dt \qquad (6)$$

If the final time t_F is infinity, then the resulting optimal feedback system is linear and time invariant (Ref. 2, 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.

With $\mathbf{U}(t)$ not constrained, Kalman has shown (Ref. 2, p. 771) that an optimal control exists, is unique, is stable, and is given by

$$\mathbf{U}(t) = -R^{-1}B^T C\mathbf{X}(t) \qquad (7)$$

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

$$\dot{C}(t) = -C(t)A - A^T C(t) + C(t)BR^{-1}B^T C(t) - Q \qquad (8)$$

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 (see Fig. 1). C is $n \times n$ symmetric, therefore it represents $(n \times n + n)/2$ independent differential equations. The optimal system is always stable, even if one or more eigenvalues of A have nonnegative real parts.

Computer Program

Three optimal control programs were written using various states and three controls. The available B-52 control surfaces are

$U(1) = \delta_e$ (elevator)
$U(2) = \delta_{SP}$ (spoiler)
$U(3) = \delta_{ail}$ (symmetric ailerons)

Computer program A uses three states:

$X(1) = \alpha$ (angle of attack)
$X(2) = \theta$ (pitch angle)
$X(3) = \dot{\theta}$ (pitch rate)

Program B retains these, and adds a fourth state,

$X(4) = 0.01\ N_L$ (normal acceleration)

Note the use of 0.01 N_L rather than N_L itself. This makes all elements of the A and B matrices relatively equal in magnitude. When the program was run with N_L, the row four elements of the A and B matrices were two orders of magnitude greater than any other elements, giving an ill-conditioned set of differential equations which was virtually impossible to integrate, even with a variable step size Runge-Kutta routine. However, by simply using 0.01 N_L, backward integration of the C matrix proceeds rapidly without overflow or underflow. This is an important point that will eliminate much of the difficulty commonly associated with application of this theory. Simple conditioning of the equations, analogous to amplitude scaling on an analog computer, will save computer time by speeding integration while improving accuracy of the results.

The controllers designed by computer programs A and B gave good results when tested on the two-degree-of-freedom analog simulation; however, angle of attack is difficult to measure accurately in flight, so α feedback was reduced as much as possible through manipulation of the Q matrix. The analog simulation still showed noticeable performance degra-

$$\underline{x}^T Q \underline{x} = [N_L\ \theta\ \dot{\theta}] \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{bmatrix} \begin{bmatrix} N_L \\ \theta \\ \dot{\theta} \end{bmatrix}$$

$$\begin{aligned} \underline{x}^T Q \underline{x} = {} & Q_{11} N_L^2 + Q_{12} N_L \theta + Q_{13} N_L \dot{\theta} \\ & + Q_{21} N_L \theta + Q_{22} \theta^2 + Q_{23} \theta\dot{\theta} \\ & + Q_{31} N_L \dot{\theta} + Q_{32} \theta\dot{\theta} + Q_{33} \dot{\theta}^2 \end{aligned}$$

Similarly:

$$\begin{aligned} \underline{u}^T R \underline{u} = {} & R_{11} \delta_e^2 + R_{12} \delta_e \delta_{SP} + R_{13} \delta_e \delta_{ail} \\ & + R_{21} \delta_e \delta_{SP} + R_{22} \delta_{SP}^2 + R_{23} \delta_{SP} \delta_{ail} \\ & + R_{31} \delta_e \delta_{ail} + R_{32} \delta_{SP} \delta_{ail} + R_{33} \delta_{ail}^2 \end{aligned}$$

Fig. 2 Expansion of quadratic cost function. (Letters with bars beneath are in boldface type in text.)

Q MATRIX

0.5	0	0
0	40	0
0	0	20

R MATRIX

.04	0	0
0	.04	0
0	0	.04

@ feedback gain in $\frac{\text{ft/sec/sec}}{100}$ per radian control surface movement.
# feedback gain in radians per radian surface movement.
¢ feedback gain in rad/sec per radian surface movement.

ABOVE SCALING USED THROUGHOUT PAPER.

CONTROLLER 41* FEEDBACKS

to \ of	N_L	θ	$\dot{\theta}$
δ_e	-.9859@	30.29 #	21.24¢
δ_{sp}	.1192	-8.648	-6.213
δ_{ail}	.0586	1.811	1.379

CONTROLLER 42* FEEDBACKS

to \ of	N_L	θ	$\dot{\theta}$
δ_e	-1.0055	30.35	21.53
δ_{sp}	.0804	-8.384	-6.118
δ_{ail}	.1056	1.783	1.407

CONTROLLER 43* FEEDBACKS

to \ of	N_L	θ	$\dot{\theta}$
δ_e	-1.0200	30.44	21.61
δ_{sp}	.0461	-7.972	-5.896
δ_{ail}	.0638	2.243	1.742

Fig. 3 4X series controllers.

dation when the remaining α feedback was removed, and the roots of the system characteristic equation changed significantly with α feedback eliminated.

Optimization program C was written to overcome these difficulties. The states are

$$\begin{aligned} X(1) &= 0.01\ N_L \text{ (normal acceleration)} \\ X(2) &= \theta \text{ (pitch angle)} \\ X(3) &= \dot{\theta} \text{ (pitch rate)} \end{aligned}$$

Note that 0.01 N_L is again used. No difficulties were encountered with this program, and the two-degree-of-freedom analog results were good. Since the absence of α feedback makes program C controllers more practical, they were used exclusively in the six-degree-of-freedom piloted simulation at the AFFDL computer facility.

Manipulation of Q and R Matrices

Figure 2 expands the integral portion of Kalman's quadratic cost function. Optimization program C states are used for illustration. Two points should be kept in mind throughout the following discussion.

1) Every controller produced by the digital computer programs is optimal for the costs assigned in the Q and R matrices. Manipulation of the cost matrices is required only to find the costs that also exhibit good flying qualities. Flying qualities must be determined on the (two-degree-of-freedom) analog simulation.

2) Since there are no constraints on controls in the optimization programs, the controllers are not necessarily practical.

Clearly, Q_{11} weights the cost of nonzero normal acceleration, Q_{22} weights pitch angle, and Q_{33} weights pitch rate. For the controls, R_{11} weights the cost of elevator usage, R_{22} weights spoiler cost, and R_{33} weights aileron usage. These main diagonal elements of the Q and R matrices are the most important and are often the only ones used.

Good handling qualities are easily provided through manipulation of the main diagonal elements of the Q matrix. For instance, if the aircraft "fights" a commanded change in rate of climb, N_L feedback must be reduced by decreasing Q_{11}. If the constant-attitude feature proves undesirable in some DLC applications, θ feedback can be reduced or eliminated by reducing Q_{22}. In this case, stick movement will be interpreted essentially as a C^* command. In fact, the computer program could be used to design optimal C^* systems by substituting $\ddot{\theta}$ for θ in the equation set.

If lower gain magnitudes are required, they are easily obtained (still in an optimal ratio) by increasing the values in the R matrix. Preliminary studies show this can be done with little sacrifice in DLC performance.

Figure 3 shows the 4X series controllers (X indicates flight condition) which were used for the run shown in Fig. 9 and most of the other data runs. Feedbacks are essentially the same for the three LAMS flight conditions, which vary widely in speed, altitude, and gross weight. Thus, there is a possibility that a single fixed-gain direct lift controller could be used in the entire B-52 flight envelope.

Aileron/Elevator Controllers

By increasing R_{22} from 0.04 to 10, the spoiler feedbacks were reduced essentially to zero. These aileron/elevator controllers provided a measure of DLC benefits, and would be suitable for long-term usage. Because of the increased drag, a controller that uses spoilers biased up 20° can only be used for short periods such as during refueling and landing approach. These aileron/elevator controllers were not pursued extensively, because of the limited simulator availability and the small size of the B-52 ailerons. However, the design method for aileron/elevator controllers has been demonstrated, and this scheme could be very useful on a different aircraft, possibly for gust alleviation during cruise.

Off-Diagonal Elements of Q and R Matrices

All the controllers discussed are variations of controller 61 as shown in Fig. 4. They are labeled Y61 for identification,

Q MATRIX

1	0	0
0	40	0
0	0	20

R MATRIX

.04	0	0
0	.04	0
0	0	.04

CONTROLLER 61 FEEDBACKS

to \ of	N_L	θ	$\dot{\theta}$
δ_e	-.7777	30.35	21.23
δ_{sp}	-.0892	-8.464	-6.200
δ_{ail}	.1791	1.670	1.368

CONTROLLER 62 FEEDBACKS

to \ of	N_L	θ	$\dot{\theta}$
δ_e	-.7904	30.51	21.60
δ_{sp}	-.2155	-7.689	-5.884
δ_{ail}	.2074	2.058	1.734

Fig. 4 6X series controllers.

to \ of	N_L	θ	$\dot\theta$
	CONTROLLER 61/361 FEEDBACKS		
δ_e	-.7777/-.4252	30.35/34.59	21.23/24.39
δ_{sp}	-.0892/-.1470	-8.464/-7.511	-6.200/-5.512
δ_{ail}	.1791/ .1907	1.670/1.461	1.368/1.218

Fig. 5 Controller 61/361 comparison.

as all incorporate flight condition one (low-altitude, high-speed) data. Computer optimization program C was used exclusively. In each case, all off-diagonal elements except those mentioned are zero. All comparisons are to controller 61.

Controller 361 was designed with $R_{12} = 0.04$, which encourages elevator and spoiler movements of opposite sign in order to produce negative cost. (Normal movements are opposite in sign to cancel pitching moments.) Controllers 61 and 361 are compared in Fig. 5. They are very similar, and flying qualities are the same.

Controller 461 was designed with $R_{21} = -0.02$, discouraging the normal elevator and spoiler movements of opposite sign. Controllers 61 and 461 are compared in Fig. 6. Note sign reversals in spoiler feedbacks. The response of 461 to an 0.1 radian θ step input is slower, and flying qualities (as evaluated on the analog simulation) are poorer.

Controller 561 was designed with $Q_{23} = 40$. This element weights the cost of θ multiplied by $\dot\theta$. If θ is positive and a negative $\dot\theta$ is commanded (the normal situation), the cost is negative. This controller is identical to controller 61. If $Q_{23} = Q_{32} = 40$, the controller is still unchanged. However, only 1 sec of real-time backward integration is required before the C matrix becomes constant. All other runs of program C required 2.5 sec of backward integration.

Controller 661 was designed with $Q_{31} = -5$. This element weights N_L multiplied by $\dot\theta$ and encourages these states to be of like sign. Since $N_L = U_o(\dot\theta - \dot\alpha)$, a negative Q_{31} does no harm to the controller's normal function, and 661 is identical to 61. On the other hand, when Q_{13}, the other $N_L\dot\theta$ weight, is made plus ten, the controller is radically changed and becomes nearly unflyable.

In summary, the use of the off-diagonal elements is straightforward. Some, such as the positive Q_{13}, specify ludicrous requirements; however, if there are legitimate reasons for restricting certain combinations of controller usage or vehicle motions, the proper elements of the Q and R matrices to be weighted are easily determined.

Digital Running Time

In a normal run, an optimization program was used to design a controller for each of the three LAMS flight conditions using the same Q and R matrices. The average IBM 7094 time required by program C was 77 sec. Average (real) backward integration time for the C matrix was 2.5 sec.

Normal Acceleration Reduction

Normal acceleration of the direct lift controlled aircraft is significantly less than that of the basic aircraft (see Fig. 7). This is true for the climb and descent maneuvers both with and without turbulence. When this effect was noted in the 4X controllers, the 6X controllers were designed by Q_{11}, cost of N_L, increased from 0.6 to 1.0. This reduced N_L mean absolute values another percentage point or two, and made it easier to maintain a specified rate of climb or descent. This reduction in N_L is an indication of the pilot's ability to hold a steady rate of climb, as seen in comparing the $\dot h$ traces of Figs. 8 and 9. Reference 6 (Vol. II, p. 57) also concludes that DLC will demonstrate "a more stable platform (with reduced normal acceleration and pitch rate response to disturbances) for weapon delivery." The reduction in N_L does not necessarily mean reduced structural mode excitation, and an investigation was beyond the scope of the study. However, DLC is one of the techniques used by the LAMS controller.

Other Design Considerations

The controllers consist of first-order servo approximations, $K/(s + K)$ where $K = 1/\text{time constant}$, fed by stick output and the feedback specified by the digital optimization program. The time constants were varied from 0.1 sec to as much as 6 sec with good results. The only requirement is that the three control surface actuators have reasonably equal time constants.

Crossfeeds

The original controller design used crossfeeds between elevators and spoilers, etc., based on a literature study of conventionally designed direct lift control systems. Experimentation with a two-degree-of-freedom simulation soon[7] showed that these feedbacks degraded system performance. This is logical, since the N_L, θ, and $\dot\theta$ feedbacks provide an optimal ratio of control surface movements. Any additional items such as crossfeed only destroy the optimality of the controllers. The Q and R matrices were easily manipulated to achieve good handling characteristics without crossfeeds.

Stick-to-Elevator Gain

Stick output is fed directly to the spoiler and aileron servos. However, stick output to the elevator servo is fed through a potentiometer set at 0.3700. This gain was established by adding the aileron and spoiler pitching-moment coefficients and dividing by the elevator pitching moment coefficient.

Six-Degree-of-Freedom Analog Simulation

Complete Airplane Equations of Motion

The following equations were used to simulate airplane dynamics with the AFFDL moving-base cockpit simulator:

X equation:

$$\dot U = RV - QW - g\theta + \frac{qS}{m}\left[\frac{T}{qS} - C_{D_{\text{clean}}} - C_{D_{\delta_{SP}}}\delta_{SP} + (C_{L_{\text{clean}}} - C_{D_\alpha})(\Delta\alpha + \alpha_{\text{gust}}) + C_{X_u}\Delta U\right] \quad (9)$$

Y equation:

$$\dot V = PW - RU + g\sin\phi + \frac{qS}{m}\left[C_{Y_\beta}\beta + \frac{185}{2U_o}C_{Y_P}P + C_{Y_{\delta_{SP}}}\delta_{SP}\right] \quad (10)$$

Z equation:

$$\dot W = QU - PV + g\cos\phi + \frac{qS}{m}\Big[-C_{L_{\text{clean}}} - (C_{L_\alpha} + C_D)(\Delta\alpha + \alpha_{\text{gust}}) + C_{Z_u}\Delta U + C_{L_{\delta_{SP}}}\delta_{SP} - C_{L_{\delta_e}}\delta_e - C_{L_{\delta_{\text{stab}}}}\delta_{\text{stab}} - C_{L_{\delta_{\text{ail}}}}\delta_{\text{ail}} - \frac{\bar c}{2U_o}(C_{L_q}Q + C_{L_{\dot\alpha}}\dot\alpha)\Big] \quad (11)$$

to \ of	N_L	θ	$\dot\theta$
	CONTROLLER 61/461 FEEDBACKS		
δ_e	-.7777/-.7847	30.35/32.51	21.23/22.80
δ_{sp}	-.0892/-.4792	-8.464/7.148	-6.200/4.738
δ_{ail}	.1791/ .1784	1.670/1.818	1.368/1.475

Fig. 6 Controller 61/461 comparison.

P equation:

$$\dot{P} = QR\frac{(I_{ZZ} - I_{YY})}{I_{XX}} + \frac{qSb}{I_{XX}}\left[C_{l_\beta}\beta + \frac{185}{2U_o}(C_{l_r}R + C_{l_p}P) + C_{l_{\delta_{ail}}}\delta_{ail} + C_{l_{\delta_{SP}}}\delta_{SP}\right] \quad (12)$$

The cross product of inertial terms and the effect of spinning rotors were assumed to be negligible in the P, Q, and R equations.

Q equation:

$$\dot{Q} = RP\frac{(I_{ZZ} - I_{XX})}{I_{YY}} + \frac{qS\bar{c}}{I_{YY}}\left[C_{M_0} + C_{M_{stab}}\delta_{stab} + C_{M_{\delta_e}}\delta_e + C_{M_{\delta_{SP}}}\delta_{SP} + C_{M_{\delta_{ail}}}\delta_{ail} + \frac{T_{\epsilon_T}}{qS\bar{c}} + \frac{\bar{c}}{2U_o}(C_{M_Q}Q + C_{M_{\dot\alpha}}\dot{\alpha}) + C_{M_\alpha}(\Delta\alpha + \alpha_{gust})\right] \quad (13)$$

R equation:

$$\dot{R} = -PQ\frac{(I_{YY} - I_{XX})}{I_{ZZ}} + \frac{qSb}{I_{ZZ}}\left[C_{n_\beta}\beta + \frac{185}{2U_o}(C_{n_r}R + C_{n_p}P) + C_{n_{\delta_{SP}}}\delta_{SP}\right] \quad (14)$$

Spoiler Equations

The spoilers are actuated by wheel position for roll control in the basic aircraft and by wheel position and/or stick position in the direct lift controlled aircraft. The effect of spoiler deflection was included in all six equations of motion using a nonlinear spoiler attenuation-constant curve supplied by Boeing. DLC spoiler authority was limited to allow roll control.

Quasi-Elastic Perturbation Equations

The simulation is quasi-elastic rather than of the normal rigid-body type. This means that the aerodynamic coefficients have been modified to account for body bending and fin torsion. Constant coefficients were used (except for the spoilers) so that the equations are for perturbations about the three LAMS flight conditions summarized in Table 1.

Table 1 LAMS flight conditions

Flight condition	Altitude, ft	Weight, lb	Speed, KEAS
1) Terrain following	4,000	350,000	370
2) Approach and landing	4,000	350,000	254
3) In-flight refueling	32,000	270,000	448

Results

All of the flight tasks were devised to hold θ as close as possible to zero. With slightly different mechanization in later tests, θ was held to any desired value. For instance, if one wants to fly a glide path, it is advantageous to trim the aircraft for the proper glide-path angle and use DLC to make corrections back to the glide path. This was done easily by feeding back a $\Delta\theta$ in place of θ. Controller gains did not change.

Figure 7 shows that N_L (normal acceleration) is reduced in the DLC aircraft when compared to the basic aircraft. It was less for all the pilots in all flight conditions, with and without turbulence, reflecting the ability to maintain a desired rate of climb. The average reduction in N_L varied from 52% in flight condition three to 65% in flight condition one. Airspeed control (ΔU) was also improved with DLC.

Effect of Varying Servo Time Constants

Direct lift control does not depend on any particular actuator speed; servo time constants were varied from 0.1 to 6 sec (which is probably too slow for other aircraft control requirements). Thus, actuator speeds can be chosen based on considerations such as stability, available hydraulic power, cost, etc. Of course, the DLC mission must also be considered ...gust alleviation, for instance, can be improved by using faster-acting control surface actuators.

Piloted Simulation

Over one hundred runs were made by eight pilots in the six-degree-of-freedom moving-base simulator. Runs were made with the basic and DLC aircraft, with and without turbulence, in all three LAMS flight conditions. Results of a typical climb and descent maneuver are shown in Fig. 8 (basic aircraft) and Fig. 9 (DLC aircraft).

Pilot comments and evaluations were obtained at the end of each run. The basic B-52 received Cooper ratings of three (satisfactory) in early runs. This was soon improved to 2.8 when stick sensitivity problems were corrected with the help

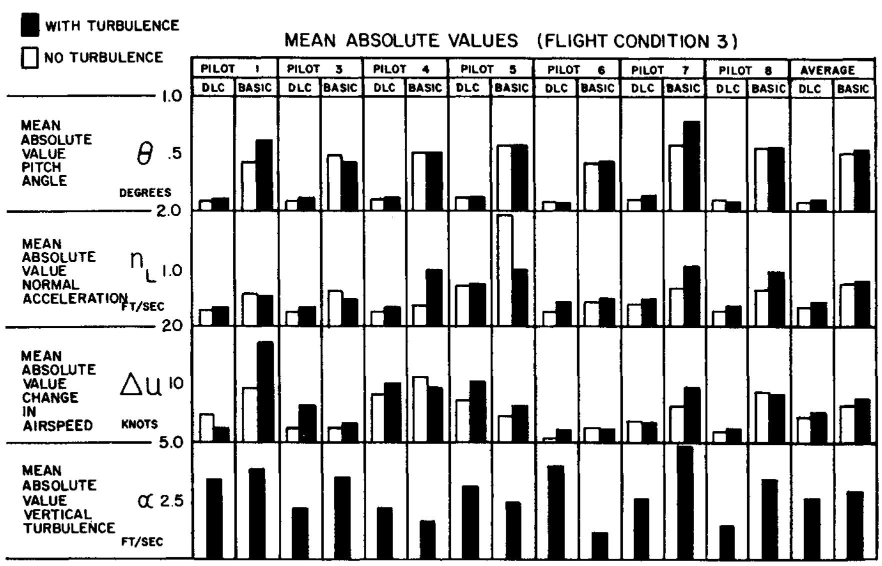

Fig. 7 Mean absolute values (flight condition 3).

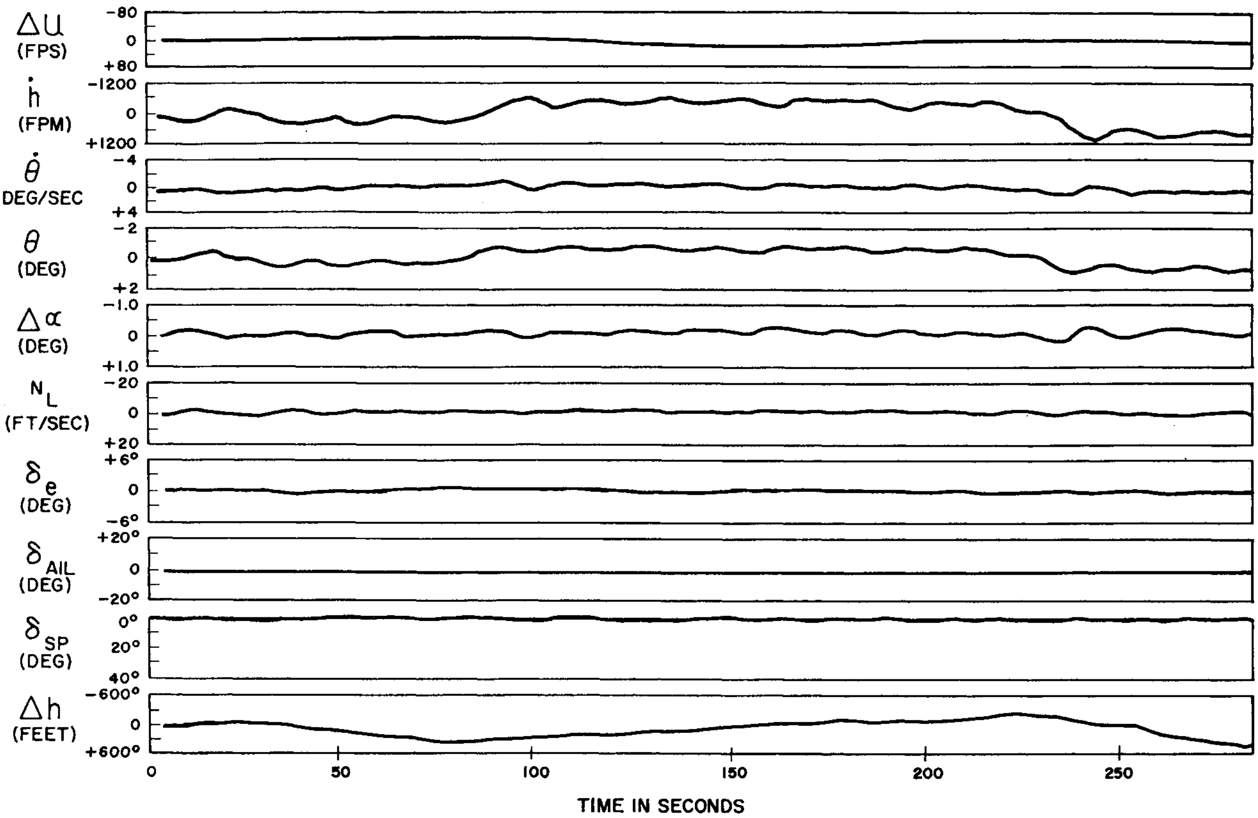

Fig. 8 Basic aircraft, climb and descend, no turbulence, flight condition 3.

of a B-52 pilot who then said the simulation "flew like a real B-52." (Cooper rating of two is "good, pleasant to fly" whereas one is "excellent, includes optimum.") The DLC aircraft averaged a Cooper rating of 1.8 for all runs. In other words, DLC significantly improved an aircraft whose performance was already satisfactory. In addition, the majority of the pilots thought the workload in performing a given task was markedly reduced by the addition of the direct lift controller. In short, the pilots felt that direct lift control increased their ability to perform precision maneuvers and improved

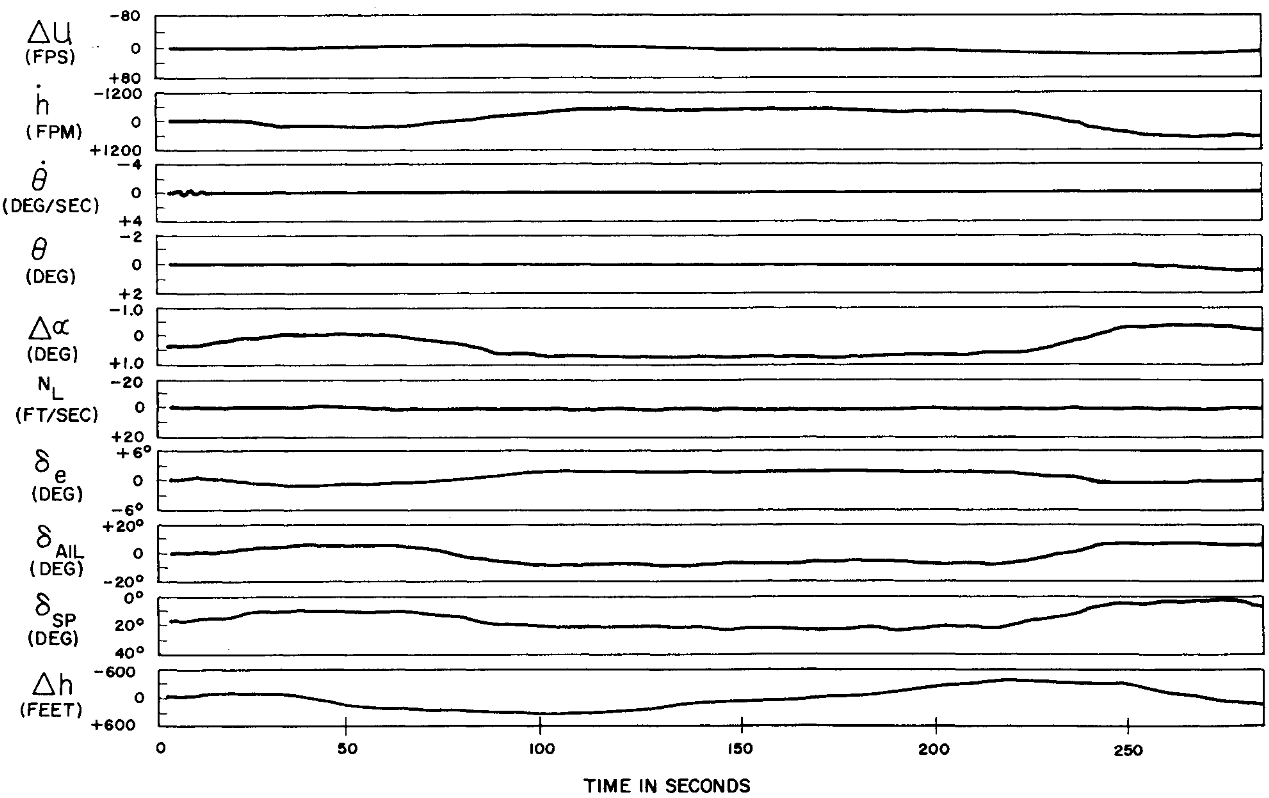

Fig. 9 Controller 63, climb and descend, no turbulence, flight condition 3.

aircraft handling qualities while reducing pilot workload. Reference 6 reports similar performance improvements with DLC.

Discussion and Conclusions

Direct Lift Control Feasibility

This paper, together with the work reported in Refs. 4–6, establishes beyond reasonable doubt the feasibility of direct lift control. Control surfaces such as spoilers, symmetric ailerons, flaps, or canards can be used in conjunction with the elevator to apply lift forces to the airplane without changing the pitch attitude. Although the B-52 does not have this undesirable characteristic, direct lift control can eliminate the long heave crossover time and normal acceleration reversal associated with large and/or short coupled aircraft. The authors have since demonstrated this with C-5 and SST class aircraft (to be published at a later date).

LAMS B–52 DLC Capability

The direct lift controllers described in this paper employ the full B-52 spoiler bank with ±20° authority from the 20° bias position and full aileron and elevator authority. The controllers improve precision maneuvering capability in short-term tasks such as terrain following, approach and landing, and in-flight refueling. The pilot's ability to make precise corrections in rate of climb or altitude is increased because DLC does not excite the phugoid mode, and visual cues are disturbed by continually changing pitch attitude.

In addition, DLC reduces normal acceleration of the airplane center of gravity by an average of 50%, both in and out of turbulence. This suggests an improvement in riding qualities and a DLC application for gust alleviation in civilian as well as military aircraft.

Optimization Theory

Kalman's optimal control theory for a linear plant with quadratic cost function (Ref. 2, pp. 750–780) proved well suited to DLC design. Optimization theories are often criticized for producing complex controllers with an excessive number of feedbacks, some of which may not be readily available. This paper demonstrates the opposite. The controllers consist simply of fixed-gain stick input plus feedbacks of normal acceleration, pitch angle, and pitch rate to each of the control-surface servos. The system is operated by the pilot's normal longitudinal stick or column movements. Control-surface crossfeeds, washout circuits, etc. are nonexistent. They serve only to degrade DLC performance.

The digital optimization program is extremely flexible and can be used to design a continuous duty controller which uses ailerons and elevators to improve ride and provide gust alleviation during cruise. Some choice in the number and nature of the feedbacks also has been demonstrated.

DLC feasibility studies for other aircraft have been accomplished by reading the proper aerodynamic coefficients into computer program *C*. The two-degree-of-freedom analog simulation provides a cheap and easy, but surprisingly accurate, method of testing the digitally designed controllers.

Controller *C* was used for all data runs because of the difficulty of measuring angle of attack in an actual aircraft, desire to reduce N_L, and the obvious preference for three feedbacks rather than four. Nevertheless, the three types of controllers are capable of comparable performance if the specified feedbacks are readily available.

Appendix: LAMS B-52 Flight Test of DLC

Several LAMS B-52 flight tests were arranged with the Boeing Flight Test Division through P. Burris of the Boeing Company. A LAMS flight was scheduled for May 7, 1968 for the purpose of gathering additional data on LAMS system performance as well as testing DLC capability. A KC-135 Strategic Air Command tanker was supported out of Altus Air Force Base, Oklahoma, for the period of the DLC refueling hook-ups.

A series of three actual hook-ups and several alignments behind the tanker were made to evaluate the merits of DLC. The closed-loop system provided good pitch stability in spite of the turbulence created by the tanker. The pilots were very favorably impressed with DLC as a refueling aid, rating it superior to the existing refueling autopilot. Small changes in altitude were easy to achieve.

Later DLC flight tests involved the approach and landing task. The pilots reported that the airplane was extremely easy to fly along the ILS beam and speed stability was excellent.

The controllers flown were not optimal, nor were the gains as high as those discussed previously. N_L feedback was not used; this was taken care of by the LAMS‡ controller. These changes were due to lack of prior simulation experience at Boeing, due in turn to the unfunded nature of the DLC tests.

All previous DLC flight tests have used open-loop controllers with fixed DLC surface-to-elevator interconnects. The important point of these LAMS B-52 flight tests was demonstration of a closed-loop, blended, constant-attitude DLC system. Re-optimization of this system, easily accomplished as described earlier, should provide even more dramatic performance improvements.

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‡ The technology used for DLC and LAMS system definition is about the same. A single computer optimization program could be written to satisfy both objectives; however, the systems as designed are compatible enough for the present flight demonstration phase.