IN-FLIGHT ADAPTIVE PERFORMANCE OPTIMIZATION (APO) CONTROL USING REDUNDANT CONTROL EFFECTORS OF AN AIRCRAFT

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Abstract

Practical application of real-time (or near real-time) Adaptive Performance Optimization (APO) is provided for a transport aircraft in steady climb, cruise, turn descent or other flight conditions based on measurements and calculations of incremental drag from a forced response maneuver of one or more redundant control effectors defined as those in excess of the minimum set of control effectors required to maintain the steady flight condition in progress. The method comprises the steps of applying excitation in a raised-cosine form over an interval of from 100 to 500 sec. at the rate of 1 to 10 sets/sec of excitation, and data for analysis is gathered in sets of measurements made during the excitation to calculate lift and drag coefficients $C_L$ and $C_D$ from two equations, one for each coefficient. A third equation is an expansion of $C_D$ as a function of parasitic drag, induced drag, Mach and altitude drag effects, and control effector drag, and assumes a quadratic variation of drag with position $\delta_i$ of redundant control effector $i=1$ to $n$. The third equation is then solved for $\delta_{iopt}$ the optimal position of redundant control effector $i$, which is then used to set the control effector $i$ for optimum performance during the remainder of said steady flight or until monitored flight conditions change by some predetermined amount as determined automatically or a predetermined minimum flight time has elapsed.

6 Claims, 7 Drawing Sheets
Flight Data

Symmetric Aileron Command

Symmetric aileron excitation

APO Analysis

\[ \delta_{i opt} \]

FIG. 1a

FIG. 1b
FIG. 2

Amplitude

Period

Time = 0.0

Time = period

FIG. 3

Total thrust, lb

Symmetric outboard aileron command, deg

M = 0.83
H = 37,000 ft
W = 408,000 lb
FIG. 4

1. EXCITATION(S) (1 CYCLE)
2. COLLECT DATA
3. OPTIMIZATION ANALYSIS
4. POSITION EFFECCTOR(S)

T > 30 MIN
OR, H > 2000 FT
OR, M > 0.02

PREVIOUS OPTIMIZATION RESULTS

STORE RESULTS

i = 1
OR CONVERGENCE

YES
NO

POSITIVE EFFECCTOR(S)

TURN APO ON

YES
NO
FIG. 6

Aileron
--- Increasing
--- Decreasing

Drag coefficient

Symmetric outboard aileron command, deg

FIG. 7

Aileron
--- Increasing
--- Decreasing
--- Fit of increasing
--- Fit of decreasing

Change in drag coefficient

Symmetric outboard aileron command, deg
Aileron

Increasing

Decreasing

Fit of increasing

Fit of decreasing

Change in drag coefficient

Symmetric outboard aileron command, deg

FIG. 8

FIG. 9
FIG. 10

Total thrust, lb

- Data and linear fit
- Linear fit with 10 percent slope error
IN-FLIGHT ADAPTIVE PERFORMANCE OPTIMIZATION (APO) CONTROL USING REDUNDANT CONTROL EFFECTORS OF AN AIRCRAFT

ORIGIN OF INVENTION

The invention disclosed herein was made by an employee of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

TECHNICAL FIELD

The invention relates to using any or all redundant control effectors of an aircraft (subsonic or supersonic transports and fighters) to optimize actual in-flight performance of any specific aircraft configuration (particularly transport aircraft) during various flight conditions of different mission segments and while experiencing changes in flight conditions. The term “redundant control effectors” is defined as any control surfaces, such as modulation and vectoring control systems and control systems that are in addition to the very minimum effectors (surfaces and systems) required to make any specific aircraft configuration capable of flight during any specific flight condition.

BACKGROUND OF THE INVENTION

Aircraft efficiency is a critical factor for airline profitability. A one percent performance improvement (1% fuel use reduction) for a fleet of transport aircraft can result in great savings, as much as approximately $100 million per year for the United States fleet of wide-body aircraft at current fuel costs (55 cents per gallon) and an additional $20 million per year for each ten cents per gallon increase in fuel price.


A member of the Airbus Industries team performed preliminary design work and wind-tunnel testing for implementing variable camber as a redundant effector in the A330/A340 aircraft. Benefits of variable camber include improved aerodynamic efficiency through improved lift-to-drag ratio (L/D), increased Mach number (M) capability, improved buffet boundary, increased operational flexibility, reduced structural weight and reduced fuel burn. Variable camber has also increased aircraft development potential. However, the proposed use of a variable camber design as a redundant effector did not include development of a real-time adaptive performance optimization methodology.


The literature is replete with reports documenting trajectory optimization algorithms and their benefits relative to the economics of commercial transports. In fact, all large transports currently being produced have computer-based Flight Management Systems (FMS) that optimize the aircraft trajectory to minimize cost as a function of flight time and fuel price. However, the common basis for these algorithms are models of performance-related aspects of the particular aircraft model under specific flight conditions. As a result, the optimal trajectory is only as good as the onboard FMS models. In addition to the baseline onboard model having less than perfect accuracy, airframe and propulsion system degradation are factors which affect model accuracy.

NASA's Dryden Flight Research Center (DFRC), at Edwards, Air Force Base, California is active in transitioning performance improvement technology to transport aircraft (Glenn B. Gilyard and Martin D. Espana, “On the Use of Controls for Subsonic Transport Performance Improvement: Overview and Future Directions,” NASA TM-4605, 1994). Realizable performance benefits are smaller for transport aircraft than for high performance fighter aircraft. The designs of most transports have already been highly refined for good performance under a steady-state cruise flight condition. An algorithm developed on a Performance-Seeking Control (PSC) program was useful as an early demonstration of the benefits to be accrued on performance aircraft with detailed models available, though not suitable for implementing further performance optimization on transports primarily because of the fact that the algorithm was heavily based on a priori model data and absolute measurement accuracy (Glenn B. Gilyard and John S. Orme, “Performance Seeking Control: Program Overview and Future Directions,” NASA TM-4531, 1993). Consequently, DFRC is exploring the application of measurement-based APO for performance improvement on transports using redundant control effectors.

Adaptive Control Background

Application of adaptive control to aircraft has been ongoing for more than 30 years with varying degrees of success. These applications have often centered on handling quality-related control system improvements, which often involve optimizing a very subjective, often ill-defined criteria typically involving handling qualities, for example, pilot ratings. Because of the subjective nature of handling qualities, adaptive control techniques are not necessarily well-suited to the problem. Also note that in many flight control applications, use of adaptive techniques has led to safety concerns about gain and phase margin reductions. Such reductions have contributed to stability and control problems.

As such, adaptive control, as applied to flight control, has not found wide acceptance within the aerospace community.
Lack of interest in adaptive control is partially caused by the satisfactory results that have been obtained using conventional design techniques and by lack of an overriding reason to obtain similar results by using more complex techniques.

Application of adaptive control is particularly advantageous when the optimization objective is well defined and there are significant unknowns about the aircraft and its operation. Application of adaptive optimal control to quasi-steady performance optimization has clear benefits that are not achievable in control design processes that are tailored to handling qualities issues. Quasi-steady performance optimization has well-defined objectives (i.e., minimize drag). For this reason, adaptive optimal control is well-suited to performance optimization. In addition, application of adaptive optimal control, using a measured performance metric, is insensitive to modeling inaccuracies and measurement biases. Because low frequency constrained maneuvers are proposed, stability- and control-related safety issues and performance optimization do not require accurate models or absolute measurements. The adaptive optimal approach is based on real-time estimation of gradients of performance measures to control variables. These gradients are based on flight measurements and not based on predictions, except as noted herein below. In addition, because gradients are used, the approach is insensitive to measurement biases.

An adaptive optimal approach is ideally suited for use on operational “fleet” aircraft where there is uncertainty in the aircraft model and absolute measurement accuracy. Likewise, adaptive performance techniques have a valuable role for commercial aircraft where small benefits over a 20-30 yr service life can produce significant cost savings.

Many issues enter into the performance optimization problem for subsonic transport aircraft. Foremost, there must be the potential for optimization, which implies redundant control effector capability (i.e., more than one means of camber control (J. Szodruch and R. Hilbig, “Variable Wing Camber for Transport Aircraft,” Progress in Aerospace Sciences, Vol. 25, No. 3, 1988, pp. 297–328). Application of adaptive optimal techniques to performance optimization does not require accurate models or absolute measurements. The adaptive optimal approach is based on real-time estimation of gradients of performance measures to control variables. These gradients are based on flight measurements and not based on predictions, except as noted herein below. In addition, because gradients are used, the approach is insensitive to measurement biases.

An adaptive optimal approach is ideally suited for use on operational “fleet” aircraft where there is uncertainty in the aircraft model and absolute measurement accuracy. Likewise, adaptive performance techniques have a valuable role for commercial aircraft where small benefits over a 20-30 yr service life can produce significant cost savings.

The present invention addresses the practical application of real time (or near real time) performance optimization and calculation of incremental drag from forced response maneuvers of redundant control effectors. The method is based on using an Inertial Navigation System (INS) which may include blending with Global Positioning System (GPS) information that can produce very accurate linear and angular displacement, velocity and acceleration measurements. Along with other more conventional measurements, such as true airspeed available from an Air Data Computer (ADC), some of this INS and GPS information is used to calculate winds and angle of attack, $\alpha$. Thrust, $T_e$, is estimated from a prepared map in the form of a table made from a representative engine as a function of $M$, $P$, and $\varphi$, where, $M$ is Mach number obtained from the ADC, $P$ is static pressure obtained from the ADC, and $\varphi$ is engine pressure ratio obtained from engine measurement. In other words, thrust is estimated from a representative engine model as a function of calculated variables ($M$, $P$) and engine measurement values of $\varphi$. While a thrust map may not be particularly accurate in absolute terms, it is typically very accurate in relative terms, i.e., it accurately reflects small changes about the trim (nominal) throttle position.

The following lift and drag equations are then used to calculate lift and drag coefficients, $C_L$ and $C_D$:

$$ C_L = \text{Lift/(qS)} = \left \{ W_{\text{aero}} + \Sigma \alpha \right \} \sin (\alpha - \eta) / (qS) \tag{1} $$

$$ C_D = \text{Drag/(qS)} = \Sigma \alpha \cos (\alpha - \eta) / (qS) \tag{2} $$

where: $q = \frac{M^2 P}{\rho}$, dynamic pressure, $\frac{\text{lb}}{\text{ft}^2}$ from ADC, $W$ - aircraft gross weight, $\frac{\text{slug}}{\text{s}}$, $\alpha$ - angle of attack, radians, from aircraft measurement or calculation, $\alpha$ - angle of attack, radians, from aircraft measurement or calculation, $\ldots A_g$ - acceleration normal to flight path, $g$, (positive upward $g$'s) from INS,
where CDₘₐₓ = minimum drag coefficient, vectoring, and propulsion system geometry and controls for equation (3) as follows:

\[ C_D = C_{D_{\text{min}}} + C_{D_{\text{m}}} \Delta M + C_{D_{\text{m}}} \Delta H_F + \Sigma K_{\text{opt}} (\Delta \theta - \Delta \psi)^2 \]

in the following equation

\[ C_D = C_{D_{\text{min}}} + C_{D_{\text{m}}} \Delta M + C_{D_{\text{m}}} \Delta H_F + \Sigma K_{\text{opt}} (\Delta \theta - \Delta \psi)^2 \]

where CDₘₐₓ = minimum drag coefficient, Cₜₐₘᵦ = Cₜ₋ₐₘᵦ at minimum CD, Cₜₐₘᵦ = coefficient of drag caused by Mach number, Cₜₐₘᵦ = coefficient of drag caused by altitude, \( \Delta M \) = change in Mach number from the time of turning on the APO, \( \Delta H_F \) = change in altitude from the time of turning the APO on, \( K_{\text{opt}} \) and \( K_{\text{opt}} \) are drag equation coefficients, \( \Delta \theta \) and \( \Delta \psi \) are optimal position of redundant control effector i, where i is an integer from 1,2, \ldots, n, \( \Delta \theta \) and \( \Delta \psi \) are optimal position of redundant control effector i, \( \Sigma \) summation over the number n of redundant control effectors in use from i=1 to n.

Equation (3) is a mathematical expression for \( C_D \) that is a function of aircraft parasite drag, induced drag, Mach and altitude drag effects, and aileron drag. That equation assumes a quadratic variation of \( C_D \) with \( \Delta \theta \) and \( \Delta \psi \) can include one or more redundant control effectors of the aircraft, such as symmetric ailerons, flaps, slats, spoilers, stabilizer, elevator, thrust, center-of-gravity and thrust vectoring, and propulsion system geometry and controls for longitudinal effectors and rudder, ailerons (normal or differential) and differential thrust lateral or directional effectors, so long as the designated effectors satisfy the definition of a redundant control effector for the condition of the specific flight segment to be optimized, such as but not limited to ascent, cruise, and descent.

If tables for estimating thrust as a function of EPR are not available, equations (1) and (2) can be expanded as follows:

\[ T = T_e + K_{T_e}(EPR) \text{ at Mach } \text{ and altitude } \text{ constant} \]

\[ T_e \text{ to be identified} \]

\[ K_{T_e}(C(T)/EPR) \text{ constant to be identified} \]

\[ C_{L} = \text{Lift}(\Delta \gamma) = (W)A_{\text{ramp}} - 2(T_e + K_{T_e}(EPR)) \sin (\Delta \gamma) (\Delta \gamma) \]

\[ A_{\text{ramp}} = \text{Engine}^{\text{EPR}} (\Delta \gamma) \cos (\Delta \gamma) - (W)A_{\text{ramp}} (\Delta \gamma) \]

\[ C_l \text{ and } C_{D_{\text{min}}} \text{ are new algebraic expressions which are included in the expansion of the expression for } C_D \text{ in equation (3) as follows:} \]

The novel features that are considered characteristic of this invention are set forth with particularity in the appended claims. The invention will best be understood from the following description when read in connection with the accompanying drawings.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1a illustrates a multiengine wide-body aircraft having many control effectors, a number n of which may be employed as redundant control effectors as the term is defined, depending upon what flight condition in steady state has been established.

FIG. 1b illustrates how the Adaptive Performance Optimization (APO) feature of this invention is functionally applied to one redundant effector in one example.

FIG. 2 illustrates a raised-cosine excitation form preferred to be used for forced-response maneuvers of selected redundant control effectors in the APO methodology of the present invention.

FIG. 3 is a graph of variation of thrust required for trimmed flight as a function of symmetric aileron displacement and shows a thrust of 24.03\times10^4 lb, an improvement of 364 lb (1.5%) at approximately 4.5\° symmetric aileron deflections.

FIG. 4 is a flow chart on an operational implementation of the APO algorithm.

FIG. 5 presents a time history of forced excitation response cycle with both altitude- and velocity-hold turns on
produced a trimmed flight condition (level flight at constant Mach and altitude), each combination having a unique angle of attack. However, each of these combinations is not equally good in the sense of providing minimum aircraft drag. Even though there can theoretically be multiple drag minima, it is more likely that there is only one pronounced minimum over a range of small changes in the combinations which can produce a minimum drag configuration. A method for finding this one unique combination of redundant control effectors and resulting angle of attack \( \alpha \) that the present invention addresses, namely an Adaptive Performance Optimization (APO) algorithm using at least one redundant control effector while in a steady flight condition, such as a climb, cruise or descent condition.

Of course instead of there being only one additional redundant control effector there can be many, in which case a minimum drag for each may be sought by separate sequential excitations, each in accordance with the methodology of this invention described herein with reference to equations (1), (2) and (3), but the set of minima, although good in the sense of providing a better “minimum” drag than without the methodology, would not guarantee a true optimal configuration. It would be preferable to integrate the excitations (forced response of redundant effectors) in the methodology using combinations of small perturbations affected simultaneously as stated in equation (3).

The following describes the general sequence of events to obtain the optimal control effector combination, but first it should be noted that since the performance optimization method described is best suited to steady flight, the following autopilot and navigation modes should be engaged: altitude-hold, Mach- (or velocity-) hold, and heading-hold.

In the event that the aircraft is not equipped for any of these modes, the pilot must perform the functions necessary for steady flight in the best he can, although the latter case could result in less than true optimal \( \delta_{\text{opt}} \) being determined due to degraded quality in the forced response maneuver and analysis of the redundant control effector(s) resulting from less than perfect steady flight. The methodology will now be described.

**FIRST**

Forced response excitation must be provided for each of the redundant control effectors, \( i=1,2 \ldots n \). In the case of only one redundant control effector \( i=1 \), as in the example of the symmetric outboard ailerons used as one redundant effector discussed above with reference to Fig. 1b, that effector must be excited (moved to a new position) using the smooth raised-cosine excitation form shown in Fig. 2 and in Fig. 1b sufficiently for the resulting aircraft and control surface motion to provide sets of information (typically 100 to 500 sets at the rate of one to ten sets per second for raised-cosine excitation of a time interval equal to 100 to 500 sec. from which the optimal position \( \delta_{\text{opt}} \) is to be determined.

A passenger ride quality constraint is that the motions resulting from the forced response excitation be imperceptible (less than -0.02 g) to the average passenger. This requires both a smooth and slow excitation such that the autopilot (or pilot) can respond to the excitation in an effort to control a steady altitude, Mach (velocity) and heading. The raised-cosine excitation form of Fig. 2 satisfies the smoothness requirements for excitation periods (intervals) of 100 to 500 seconds. An interval in that range should allow for ride quality constraints to be satisfied while collecting data sets required by the methodology of equations (1), (2) and (3) at rates of from one to ten sets per second. The raised-cosine excitation function of Fig. 2 is defined by the following equation:

\[
\delta_{\text{exc}}(A) = (1.0 - \cos(\frac{1}{\pi} \delta_{\text{opt}} \text{TIME}))/2
\]
where: $A =$ maximum amplitude of the forced response ($\alpha$ or $\gamma$) maneuver, 
$P =$ period (duration) of the maneuver,

TIME $=$ starts at 0 and runs until the end of the period is reached, 

$\pi = 3.141592654$ 

Other excitation forms may, of course, be used to effectively obtain the optimal solution through analysis of all of the sets of data. However, the smooth raised-cosine form insures the smoothness that is required for passenger aircraft applications and for all other aircraft as well. Thus, depending on the application, other excitation forms may be used.

In any case, the excitation form for the maximum amplitude, $A$, of the forced response must be selected to cover the point of optimality, i.e., minimum drag which translates into minimum thrust required as a function of symmetric outboard ailerons at $\delta_{a\text{pper}}$ shown in Fig. 3 as equal to 4 to 5$^\circ$ for the example under discussion of optimizing cruise at 37,000 ft. That maximum excitation amplitude needed may be determined empirically.

If there are multiple redundant control effectors, each must cycle through an excitation forced response maneuver. Analytically, the best means of determining the optimal for more than one redundant control effector ($n > 1$) is to provide simultaneous excitation of the $n$ redundant control effectors, as noted hereinafore. However, the excitation of each of the redundant control effectors must be independent (i.e. different) in some way to insure identifiability of the separate control effectors.

To achieve separability, the excitation signals used for each effector $i=1,2, \ldots n$ may have a different form such as one having a sine wave form and the other a square wave form. However, as already noted, a raised-cosine form is well suited given the passenger comfort constraints. Consequently, to have independence and still use a raised-cosine excitation form, the excitation signal for each redundant control effector may be applied with different periods. This technique can allow two or more redundant control effectors to be excited in order to provide for sets of data to be gathered from all effectors for a joint optimal solution with only one APO algorithm sequence.

For multiple redundant surfaces, sequential optimization could also be used to avoid an identification problem by performing the excitation and optimization of each control effector first, then set that control effector to its optimal position and repeat the procedure for each additional redundant control effector. Because this will not provide a “joint optimal” solution, iteration of this multiple-effectors procedure should continue for all redundant effectors until convergence is achieved. The results would then not be achieved in what may be considered real time, but near enough to real time to be good APO control.

SECOND

Data is collected during the excitation of forced response maneuver of each one or more redundant control effectors at a nominal rate, for example one set of response data per second, such that for a raised-cosine excitation of, for example, 300 sec., about 300 separate sets of data can be acquired, although data acquisition of ten sets per second would be preferable for assurance of better optimization.

THIRD

For analysis of the sets of response data, the thrust estimation is first made for use in equations (1) and (2) above in the STATEMENT OF THE INVENTION to calculate the values of the lift and drag coefficients in those equations for each set of data. These sets of data are then used to form 300 drag coefficient expansion equations using equation (3), which are then solved for the $5+2(n)$ unknowns in equation (3) (where $n$—the number of redundant control effectors), namely

$$C_{D_\text{eff}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}, C_{D_{\text{a\text{pper}}}}$$

Solutions can be obtained by regression analysis or other comparable techniques.

FOURTH

Apply the optimal solution (s) to the control effector(s) in a smooth fashion. Use of the first-half of a raised-cosine form to reach the optimal value is satisfactory.

Repeat the optimization algorithm either continuously at fixed flight time intervals or only as needed, i.e., when need is determined by changes in flight conditions specified as criteria.

The flow chart of Fig. 4 illustrates the sequence of operations for the APO algorithm which recurs under control of the programmed APO with elapsed time $\Delta T$ or change in either altitude $\Delta H$ or Mach number $\Delta M$. The algorithm comprises four steps described above and represented by blocks 1 through 4 in the flow chart. Once the optimal $\delta_{\text{pper}}$ is identified and the redundant control effector is positioned accordingly, the aircraft can then take advantage of the optimal (minimum drag) configuration with any number of objectives such as but not limited to:

Minimize Fuel Flow: Trim the aircraft at the same Mach and altitude the APO algorithm determined $\delta_{\text{pper}}$; this will result in minimum fuel flow.

Maximize Mach Number: Trim the aircraft at the same altitude the APO algorithm determined $\delta_{\text{pper}}$ and at the steady-state fuel flow recorded just prior to the APO algorithm being requested to determine $\delta_{\text{pper}}$; this will result in maximum Mach number.

Maximize Altitude: Trim the aircraft at the same Mach number the APO algorithm determined $\delta_{\text{pper}}$ and at the steady-state fuel flow recorded just prior to the APO algorithm being requested to determine $\delta_{\text{pper}}$; this will result in maximum altitude.

Maximum Loiter Time at a Fixed Altitude: Trim the aircraft at the same flight condition the APO algorithm determined $\delta_{\text{pper}}$; this will result in reduced fuel flow at that flight condition. Trim the aircraft to a fixed increment lower Mach number (e.g., $\Delta M - 0.02$) by reducing throttle position (fuel flow). Since this is a new flight condition, request the recurrence of the APO algorithm to determine a new $\delta_{\text{pper}}$ which may be imperceptibly small since the flight condition change was relatively small. Repeat these two procedures (reduce Mach number and request the recurrence of the APO algorithm for a new $\delta_{\text{pper}}$) until fuel flow begins to increase, thus locating a $\delta_{\text{pper}}$ for a minimum Mach number. There will be that minimum since as Mach is reduced and the angle-of-attack increases to maintain lift (in order to maintain altitude), a point is reached where drag to angle-of-attack is going to be dominant.

Once the optimal $\delta_{\text{pper}}$ is identified and the redundant control effector is moved to the optimal position (minimum drag), the APO algorithm (program) can be placed in an idle mode until either automatic or crew monitoring of elapsed time or change in altitude or Mach number requests a recurrence of the APO algorithm.

On an operational flight mission, the APO is turned on by the flight crew during any steady-state segment of the mission. In any instance of turning on the APO algorithm,
the program of the algorithm will first check on whether there are any previous optimization results stored. If not, as in the case of the APO algorithm being turned on for the first time for this particular segment of the mission (e.g., climb, cruise, descent or other), the algorithm proceeds to the first phase. If the check is positive (YES), the previously stored optimal results of the redundant control effector(s) will be used as a priori values. This procedure of storing previously determined optimal redundant control effector values and using the stored values as a starting point when the APO algorithm is turned on again will maximize benefits of the APO algorithm by utilizing representative optimal values to arrive at new optimal values more quickly than starting without any priori values.

There is a separate 4-dimensional table for each redundant control effector(s) value of Mach, altitude, gross weight and center of gravity, e.g., as follows:

<table>
<thead>
<tr>
<th>DATA TABLE</th>
<th>Mach</th>
<th>Altitude</th>
<th>Gross Wt.</th>
<th>C.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>min delta</td>
<td>0.02</td>
<td>2,000</td>
<td>10,000</td>
<td>0.5</td>
</tr>
<tr>
<td>max interp.</td>
<td>0.10</td>
<td>10,000</td>
<td>50,000</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Data is stored to the nearest min delta. The maximum interpolation allowed to determine an a priori position is max interp. The values in the above table are only representative; actual values depend on the aircraft in question. Note: The redundant control effector(s) can include but is not limited to designated effectors of the aircraft such as symmetric ailerons, flaps, slats, spoilers, horizontal stabilator, elevator, thrust, center of gravity, variable inlet and/or engine geometry (for propulsion systems with that capability), and/or engine geometry (for propulsion systems with that capability), and thrust vectoring for longitudinal effectors and rudder, ailerons, (normal or differential) and differential thrust for lateral and directional effectors.

Although the above process may infer a post-maneuver, the analysis can be performed in real time with the data acquired to that point in time. In certain applications this may provide some benefits. This analysis processing then continues for the last part of the raised-cosine excitation during which the maneuver is completed and then the entire process is repeated until a criteria has been met to assure that optimal conditions have been reached (e.g. the criteria that the estimated \( \delta_{opt} \) remains constant over two or more passes through the process).

It would be well to note at this point that the raised-cosine excitation form need not begin to immediately diminish in amplitude once the maximum amplitude is reached. Instead the form may be flat at maximum amplitude for say 200 sec. to extend the period of a 300 sec. raised-cosine excitation to 500 sec. This has the benefit of smoothing the maneuver more and allowing more time for the analysis of the data gathered during the first part of increasing amplitude since new sets of data during the flat part need not be processed at the times that there is not some significant change from the last point of significant change. This is a particularly useful benefit as the number n of redundant effectors increases beyond a few.

For normal transport operation in cruise flight, continuous optimization is not necessary and in fact would tend to increase drag since ideally, once you are at the optimal control position of a redundant effector, all other maneuvers would be away from that optimal position and therefore increase drag. Thus, the optimization algorithm should be performed only when either a certain change in flight condition criteria is met or a certain time interval has elapsed. For both of these, subjective but reasonable criteria would be the following incremental changes: a) \( \Delta \text{Mach}=0.02 \); b) \( \Delta \text{Altitude}=2000 \text{ ft.} \); and \( \Delta \text{time}=30 \text{ min.} \)

Algorithm solutions can range from continuous to batch operation. In either case, all unknown coefficients of equation (3) are identified including the optimal aileron position, \( \delta_{opt} \).

Values of \( K_a \) and \( C_{L_{max}} \) are assumed to be independent of the symmetric aileron position for small deflections. In actuality, symmetric aileron deflection would result in a small change to spanwise lift distribution and, in turn, to induced drag characteristics of the wing. This effect would cause a small variation in the value of \( K_a \), as a function of symmetric aileron position. Sensitivity of the APO algorithm to this variation has been left for future studies.

The formulation of equation (3) is not unique; the important element being that the first-order effects of aileron-induced drag be represented in the \( C_D \) equation in a plausible manner. Care should be taken not to over parameterize the problem; independence of the various estimates must be maintained to provide meaningful results. The actual drag reduction is

\[ \Delta \text{Drag}=\eta K_a (A h)^2 \]
demanding, the optimization problem only places demands on perturbation accuracy, which is not affected by biases. Maximizing velocity for constant altitude and fuel flow requires accurate perturbation measurements of velocity, flightpath acceleration, or both.

Real-Time Drag Minimization

Preferably, performance optimization could be accomplished using responses to pilot or autopilot and FMS commands. However, with tight pitch-rate, pitch-attitude, and altitude- and Mach-hold control laws, external environment-based disturbances and associated responses would, generally, be small. As a result, forced response of redundant controls by unique excitation is required to ensure identifiability. The requirement for forced excitation must be tempered by the additional requirement that neither handling nor ride qualities are noticeably impacted. In turn, this requirement dictates the range of excitation periods and amplitudes.

Aircraft Simulation Model

The APO algorithm was evaluated using a simulation of a first-generation wide-body transport. The simulation is high fidelity and covers the full aircraft envelope. The primary control system has simple rate feedback, while the altitude- and Mach-hold autopilot modes were designed with feedback to the stabilator and throttle, respectively. The aileron drag characteristics were modified (based on simulation and flight data of similar configurations) to provide a quadratic drag variation with symmetric aileron displacement. All the simulation runs were initiated at Mach 0.83, at an altitude of 37,000 ft, and at a weight of 408,000 lb. Fuel burn was simulated as a function of thrust. Low-order thrust versus throttle-lever dynamics are in the simulation. Light turbulence was used for all runs to provide a realistic signal-to-noise ratio. FIG. 3 shows the variation of thrust required for trimmed steady-state flight as a function of symmetric aileron displacement. The maximum drag reduction of 364 lb (1.5 percent) occurs at approximately 4.5° symmetric aileron deflection.

Results and Discussion

FIG. 5 presents the forced excitation response, with altitude- and Mach-hold modes on, to a raised cosine (1.0–cos (o)t) symmetric aileron command with a 300-sec duration. (The o is the angular frequency.) The simulated responses used in the analysis are flightpath axes accelerations, angle of attack, thrust, weight, and symmetric aileron deflection. For this analysis, it was assumed that the angle of attack is calculated from pitch attitude INS velocities and true airspeed. In addition, the flightpath accelerations are calculated from body-axes accelerations rotated through angle of attack, and thrust is obtained as a function of EPR and flight condition. The variation of C_D with δ_a does not present a clear picture of the minimum drag point (FIG. 6).

FIG. 7 presents CDp = C_Dp - K_Cp(δ_a - C_Dp_min)^2 with δ_a being the sole symmetric aileron, the sole redundant control effector. Correcting for the C_Dp variations produces a much clearer picture of the drag minimization process. The quadratic variation of C_Dp is clear, but there still is a significant difference between increasing and decreasing δ_a commands. (Note that the C_Dp and C_Dp incremental scales are the same for FIGS. 6–9 for ease of comparison.)

A close look at the time histories reveals that Mach number variations exist which could, in turn, contribute a change in drag as a function of Mach number via a C_Dp effect. To improve the accuracy of the analysis, a linear C_Dp AM term was added to Equation 3 with C_Dp added to the list of variables to be estimated. FIG. 8 presents the C_Dp variation (including the Mach number effect correction) with δ_a = δ_a (for symmetric aileron) and the quadratic variation is now well-defined and agrees with the minimum drag point of FIG. 4.

The variation of drag with the δ_a variation can be modeled as a quadratic function for the purposes of locating the local minimum of even a potentially complex function. It is not required that the true drag associated with the δ_a variation be quadratic but only that a quadratic representation of the local minima be reasonably representative of the true minima. This modeling will assure that the local minima is found.

Sensitivity to Baseline Data

The good results presented in FIG. 8 may not be all that surprising in view of the fact that the simulation output variables are perfect with, at most, some white noise effects manifested from the turbulence. Assurance of analysis insensitivity to all known effects must be verified.

To minimize the variation or inaccuracy of the estimates, or both, a priori values of K_c and C_L/minC_D are used. These parameters characterize the quadratic nature of the C_L/C_D variation. Separate parametric variations of these a priori parameters of ±25 percent and ±50 percent on K_c and C_L/minC_D, respectively were performed. These variations produced less than 0.1° variation on the optimal symmetric aileron value (4.5°). As a result, the optimal solution appears insensitive to these a priori parameters.

Measurement Bias Effects

For absolute performance analysis, measurement bias is a limiting factor on analysis accuracy. However, the formulation of this APO analysis algorithm is designed to be insensitive to measurement bias. The following biases (applied one at a time) produced less than 0.1° variation on the optimal symmetric aileron value:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Attack</td>
<td>0.5°</td>
</tr>
<tr>
<td>Acceleration along the flightpath</td>
<td>0.02 g</td>
</tr>
<tr>
<td>Acceleration (upward) normal to the flightpath</td>
<td>0.02 g</td>
</tr>
<tr>
<td>Net aircraft thrust</td>
<td>1500 lb</td>
</tr>
<tr>
<td>Aircraft gross weight</td>
<td>30,000 lb</td>
</tr>
</tbody>
</table>

A bias on the symmetric aileron measurement produces an equivalent change on the optimal solution, but in true terms, the solution is unaffected. Bias insensitivity is significant relative to the analysis because measurement biases are common. Note also that these findings apply in spite of the fact that the equations are nonlinear.

Resolution Effects

Operating near or at the resolution limits of instrumentation is potentially a serious problem, and the analysis procedure must be insensitive to these quantization effects. Formulation of this APO analysis algorithm is not overly sensitive to resolution resulting, in part, from the regression technique employed. The results of FIG. 8 are repeated in FIG. 9 but with the following resolution set:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aileron position</td>
<td>0.10</td>
</tr>
<tr>
<td>Angle of Attack</td>
<td>0.10</td>
</tr>
<tr>
<td>Acceleration along the flightpath</td>
<td>0.002 g</td>
</tr>
<tr>
<td>Acceleration (upward) normal to the flightpath</td>
<td>0.002 g</td>
</tr>
<tr>
<td>Net aircraft thrust</td>
<td>350 lb</td>
</tr>
<tr>
<td>Mach number</td>
<td>0.001 lb</td>
</tr>
</tbody>
</table>
The analysis with resolution produced less than 0.2° variation from the optimal symmetric aileron value case of FIG. 8. The algorithm appears to be most sensitive to thrust resolution. An increase in the thrust resolution to 300 lb changes the optimal symmetric aileron value by 0.4°. In general, however, the optimal solution is relatively insensitive to these resolution effects.

**Thrust Accuracy**

Although thrust is not measured, it is determined based on EPR and flight condition measurements and a representative engine model. The thrust calculations will tend to be the least accurate of all inputs to the analysis process. Constant errors in the thrust level are not a problem. However, thrust is based on interpolation of steady-state thrust tables; hence, inaccuracies caused by lack of modeled engine dynamics, whether they accrue from throttle lever motion or atmospheric effects, will occur. A cursory evaluation of this effect was conducted by calculating a thrust value to be fed into the analysis as a linear variation with throttle lever. FIG. 10 shows the variation of thrust with throttle lever for the data of FIG. 5 along with a linear fit of the data. Using this relationship in the analysis produces an error of less than 0.1° in the optimal aileron solution. Because aircraft specific variations play a significant role in the actual amount of performance improvement achievable, using previous optimality results as initial conditions can speed up optimality convergence for subsequent flights.

**Thrust Accuracy**

Minimizing fuel flow at constant Mach number and altitude conditions requires accurate fuel-flow indications, such as fuel flow, fuel valve position, throttle position, or thrust. In lieu of direct fuel-flow measurements, EPR measurements combined with a representative engine model, which is a function of flight condition, will provide sufficiently accurate incremental fuel-flow or thrust estimates.

A more realistic and interesting situation is the sensitivity of the solution to an error in the slope of the thrust as a function of the throttle of the linear fit (FIG. 10). A bias of the linear relationship is addressed above under the Measurement Bias Effects heading. An error in the slope (in addition to a bias error) would be representative of a miss-modeling of the engine characteristics via a table look-up process. FIG. 10 also shows a linear thrust-throttle lever variation with a 10-percent increase in slope and with the constant adjusted so that the linear relationship has the correct thrust level at the trim flight condition. The constant has the same effect as a bias error and, therefore, is a reasonable assumption. The 10-percent error in slope produced a negligible (less than 0.1°) difference in the optimal aileron solution. A 20-percent error produces a 0.4° difference in the optimal aileron solution. In referring back to FIG. 5, even a 0.5° error in the optimal solution is insignificant because the variation of drag with aileron is shallow.

**Hardware Implementation**

Selected aircraft have the hardware (symmetric aileron trim deflection capability) required to perform onboard performance optimization and, therefore, would only require a relatively simple set of optimization software. Algorithm redundancy is not required because the algorithm is a nonsafety-of-flight system. This nonsafety-of-flight aspect can be assured by having APO in a discretionary mode with very limited rate and position authority. The algorithm can be a completely independent set of code and, therefore, avoid the issues of integration with the FMS. The algorithm can be thought of as a slow, limited authority trimmer.

For aircraft that do not currently have the hardware capability of moving the outboard ailerons symmetrically, a relatively simple modification consisting of adding a low frequency, limited authority, trim actuator in series with the mechanical command to the outboard aileron actuator would suffice. The slow actuator rate plus limited authority minimizes safety-related issues.
Although particular embodiments of the invention have been described and illustrated herein, it is recognized that modifications may readily occur to those skilled in the art. Consequently, it is intended that the claims be interpreted to cover such modifications and equivalents thereof.

What is claimed is:

1. A method for providing in-flight adaptive performance optimization of an aircraft in a steady climb, cruise, turn, or descent flight condition that uses autopilot and navigation modes in a normal manner or by the pilot’s direct control, where said optimization is based on real-time measurements and calculations of incremental drag from a forced response maneuver of one or more redundant control effectors that affect aircraft drag defined as those control effectors that are in excess of the minimum set of control effectors that affect aircraft drag required to maintain said steady flight condition in progress, comprising the steps of first applying excitation to said one or more redundant control effectors simultaneously in a smooth raised-cosine form over a finite interval, concurrently gathering sets of measurements made during said excitation, next calculating lift and drag coefficients \( C_L \) and \( C_D \) from two equations, one for each coefficient, and then calculating an optimum position \( \delta_{i_{opt}} \) of said one or more redundant control effectors from a third equation which is an expansion of \( C_D \) as a function of parasitic drag, induced drag, Mach, altitude drag effects, and control effector control effector, said third equation comprising a quadratic variation of drag with positions \( \delta \) of redundant control effectors \( i = 1, 2, \ldots, n \), solving said third equation for \( \delta_{i_{opt}} \) in a separate step, and finally using the value \( \delta_{i_{opt}} \) to set the position of each control effector \( i \) for optimum performance of said aircraft throughout the remainder of said steady flight condition, unless monitored flight conditions change by some predetermined minimum amount, or a predetermined minimum flight time lapses, or flight conditions have changed an amount perceptible by a flight crew monitoring instruments in the cockpit of said aircraft, in response to any one of which occurs, said method for providing in-flight adaptive performance optimization is repeated.

2. A method as defined in claim 1 for providing in-flight adaptive performance optimization of an aircraft after said steady flight condition has been reached wherein, while applying forced response excitation to said one or more redundant control effectors simultaneously, collecting sets of data during the forced response excitation, performing optimization analysis to determine lift and drag coefficients \( C_L \) and \( C_D \) for each set of data by solving the following equations:

\[
C_L = \frac{\text{Lift}(\phi \theta)}{\text{W} \cdot S \cdot \sin(\alpha - \eta)} \\ \text{(8)}
\]

\[
C_D = \frac{\text{Drag}(\phi \theta)}{\text{W} \cdot S \cdot \cos(\alpha - \eta)} \\ \text{(9)}
\]

where: \( \phi \) = dynamic pressure, \( \text{lb} \cdot \text{ft}^{-2} \), \( S \) = wing reference area, \( \text{ft}^2 \), \( \alpha \) = angle of attack, radians, \( W \) = aircraft gross weight, lbs, at the start of said method \( A_y \) = acceleration normal to flight path, (positive upward), \( A_x \) = acceleration along the flight path (positive forward), \( \alpha \) = inclination of engine thrust relative to aircraft fuselage, radians, \( \Sigma \) = summation of the bracketed quantity over the number of engines of the aircraft from \( i = 1 \) to \( N \), solving for estimates of \( \delta_{i_{opt}} \) for each redundant control effector \( i \) by calculating unknown variables

5. where the equation for \( C_D \) in the following equation:

\[
C_D = C_D + K_v (C_L + \delta_{i_{opt}} C_D)^2 + C_D \cdot \Delta M + C_D \cdot \Delta H_p + \Sigma K_i (\delta_i - \delta_{i_{opt}})^2
\]

where \( C_D \) = minimum drag coefficient, \( \delta_{i_{opt}} = \) optimal position of redundant control effector \( i \), \( C_L\) = lift coefficient, \( \delta_{i_{opt}} = \) position of redundant control effector \( i \), and \( \Sigma \) = summation over a number \( n \) of redundant control effectors from \( i = 1 \) to \( n \) and finally solving for \( \delta_{i_{opt}} \).

3. A method as defined in claim 2 wherein the equation for \( C_D \) is a quadratic variation of \( C_D \) with \( \delta_{i_{opt}} \).

4. A method as defined in claim 2 wherein said one or more redundant control effectors of said aircraft comprise symmetric ailerons, flaps, slats, spoilers, stabilizer, elevator, thrust, center-of-gravity and thrust vectoring, all for longitudinal effectors, and rudder, normal or differential ailerons and differential thrust, all for lateral or directional effectors.

4. A method as defined in claim 3 wherein the number of redundant control effectors is equal to 1, said method comprising using a forced response maneuver of said redundant control effector to collect aircraft response data to forced maneuvers of limited extent to search for the optimal redundant control effector position that minimizes drag by solving the following lift and drag equations:

\[
C_L = \frac{\text{Lift}(\phi \theta)}{\text{W} \cdot S \cdot \sin(\alpha - \eta)} \\ \text{(10)}
\]

\[
C_D = \frac{\text{Drag}(\phi \theta)}{\text{W} \cdot S \cdot \cos(\alpha - \eta)} \\ \text{(11)}
\]

where: \( \phi \) = dynamic pressure, \( \text{lb} \cdot \text{ft}^{-2} \), \( S \) = wing reference area, \( \text{ft}^2 \), \( \alpha \) = angle of attack, radians, \( W \) = aircraft gross weight, lbs, at the start of said method \( A_y \) = acceleration normal to flight path, (positive upward), \( A_x \) = acceleration along the flight path (positive forward),
\( \eta \) = inclination of engine thrust relative to aircraft fuselage, radians.

\( \Sigma \) = summation of the bracketed quantity over the number of engines of the aircraft from \( i = 1 \) to \( N \), solving for an estimate of \( \delta_{\text{opt}} \) for a redundant control effector by calculating the other unknown variables

\[
C_{D_\infty}, K_0, C_{\text{inc},\infty}, C_{D_\infty} + C_{D_{\text{opt}}}, K_1
\]

in the following equation:

\[
C_D = C_{D_\infty} + K_0(C_L - C_{\text{inc},\infty})^2 + C_{D_{\text{opt}}} \Delta M + C_{D_{\text{opt}}} \Delta H_p + K_1(\delta_1 - \delta_{\text{opt}})^2
\]

where \( C_{D_\infty} \) = minimum drag coefficient,

\( C_{\text{inc},\infty} \) = \( C_L \) at minimum \( C_D \).

\( C_{D_{\text{opt}}} \) = coefficient of drag caused by Mach number,

\( C_{D_{\text{opt}}} \) = coefficient of drag caused by altitude,

\( \Delta M \) = change in Mach number from the time of turning the APO on,

\( \Delta H_p \) = change in altitude from the time of turning the APO on,

\( K_0 \) and \( K_1 \) are drag equation coefficients,

\( \delta_1 \) = position of said redundant control effector,

\( \delta_{\text{opt}} \) = optimal position of said redundant control effector,

said aircraft response data collected for analysis using the above equations being acquired at a steady flight condition comprising relatively constant Mach number, altitude and heading accomplished by any combination of autopilot and pilot control.

* * * * *