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In-Flight Transport Performance Optimization: An Experimental Flight Research Program and an Operational Scenario

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October 1997

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IN-FLIGHT TRANSPORT PERFORMANCE OPTIMIZATION: AN EXPERIMENTAL FLIGHT RESEARCH PROGRAM AND AN OPERATIONAL SCENARIO*

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ABSTRACT

A flight research program exploring the practical application of real-time performance optimization based on aircraft measurements and calculation of incremental drag from forced-response maneuvers is presented. The outboard ailerons of the L-1011 test bed aircraft were modified to provide for symmetric deflections to permit a recambering of the wing in that localized area, which in turn modifies the entire wing load distribution. The National Aeronautics and Space Administration developed an onboard research engineering test station from which the flight experiments are conducted and all analyses, both qualitative and quantitative, are performed in a real-time or near real-time manner. Initial flight test results are presented that indicate real-time drag minimization is attainable. An approach to an operational implementation of adaptive performance optimization on current and future commercial and military transports is discussed with the goal of keeping the required modifications simple and the pilot interface minimal and user friendly.

NOMENCLATURE

AFTI	Advanced Fighter Technology Integration
APO	adaptive performance optimization
$A_{x_{fp}}$	acceleration along the flightpath, *g* (positive forward)
$A_{z_{fp}}$	acceleration normal to the flightpath, *g* (positive up)
C_D	coefficient of drag
C_{D_M}	coefficient of drag caused by Mach
C_{D_o}	coefficient of parasite drag
C_L	coefficient of lift
$C_{L_{@\mathrm{min}C_D}}$	C_L at minimum C_D
CDU	control display unit
EGI	embedded GPS/INS
FMS	flight management system
g	acceleration caused by gravity, ft/sec^2
GLA	gust load alleviation
GPS	global positioning system
H	altitude, ft
i	number of redundant control effectors
INS	inertial navigation system
K_1, K_2	drag equation coefficients
L/D	lift-to-drag ratio
M	Mach number
MADC	micro airdata computer
MAW	Mission Adaptive Wing
MLA	maneuver load alleviation
NASA	National Aeronautics and Space Administration
$N1$, $N3$	engine rotation speeds of the first and third spools, rpm
PCM	pulse code modulation
q	dynamic pressure, lbf/ft^2
RETS	research engineering test station
S	aircraft reference area, ft^2
t	time, sec
T	thrust, lbf
TE	trailing edge

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*Patent pending.

VME	versa module eurocard
W	aircraft gross weight, lbm
α	angle of attack, rad
δ_a	symmetric aileron position (positive = trailing-edge down), deg
$\delta_{a_{opt}}$	optimal (minimum drag) symmetric aileron position, deg
Δ	change
η	inclination of engine thrust relative to the fuselage, rad
ω	angular frequency, rad/sec

INTRODUCTION

Application of variable-geometry wing camber control to transport aircraft can reduce aircraft drag, a significant factor for improving airline profitability. A 1-percent drag reduction reduces fuel flow 1 percent which, for the U.S. fleet of wide-body transports, results in savings of approximately \$140 million each year.* [1–3].

A significant amount of transport efficiency technology was developed in the late 1970's and 1980's and has continued into the 1990's. The Advanced Fighter Technology Integration (AFTI)/F-111 Mission Adaptive Wing (MAW) program developed and demonstrated the potential of using variable-camber control to optimize cruise and maneuver flight conditions for fighter configurations [4, 5]. The program did not develop an operationally implementable algorithm for optimization of aerodynamic efficiency (maximizing the lift-to-drag ratio, L/D) but instead relied heavily on predetermined camber control scheduling. Recently, preliminary design work has been performed for implementing variable camber into transport aircraft [6–8]. The proposed variable-camber design did not include development of an L/D optimization methodology.

Numerous reports exist documenting trajectory optimization algorithms and their benefits relative to the economics of commercial transports [9–12]. In fact, all large transports currently being produced have an on-board flight management system (FMS) that “optimizes” the aircraft trajectory to minimize cost as a function of flight time and fuel price. However, the common theme or basis of all these algorithms is that a model of all the performance-related aspects of the aircraft is required. The “optimal” trajectory, therefore, is only as good as the on-board models. In addition to the baseline model having less-than-perfect accuracy, airframe and propulsion system degradation are additional factors that affect model accuracy.

Many issues enter into performance optimization for subsonic transport aircraft. Foremost, the potential for optimization must exist, which implies redundant control effector capability (for example, more than one means of trimming out the forces and moments to obtain a steady-state flight condition). Most transport aircraft have significant capability in this area. Controls or variables that can potentially play a role in performance optimization for current and future generation transport aircraft include elevators, horizontal stabilizers, outboard ailerons, inboard ailerons, flaps, rudders, center of gravity, thrust modulation, and differential thrust.

NASA has a flight research program, adaptive performance optimization (APO), that is currently addressing the key technological challenge of in-flight performance optimization for transport aircraft; namely, identification of very low levels of incremental drag. To provide an effective optimization algorithm, identification of incremental drag levels of 1 percent or less will be required.

Adaptive performance optimization is a new approach for improving aircraft performance without requiring extensive hardware modifications. This approach exploits existing redundant control-effector capability by automatically reconfiguring control-surface deflections to achieve a minimum drag trim condition [13–15]. Although this paper emphasizes drag minimization in the longitudinal axis, the methodology is equally and readily applicable to the lateral-directional axes. Currently, no commercial transport aircraft features an automated drag minimization system. The development and implementation of a system (using symmetric ailerons) is used to provide a practical example and is within the scope of current flight research activities at the NASA Dryden Flight Research Center. For fly-by-wire transports, the modification can be as simple as a new FMS and control display unit (CDU) software load. Transports with mechanical systems additionally require a simple control hardware modification.

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*Fuel cost of \$0.70/gal.

This paper addresses the practical application of a real-time performance optimization methodology using on-board measurements and calculation of incremental drag from forced-response maneuvers at cruise flight conditions. The experimental test aircraft is an L-1011 (Lockheed Corporation, Burbank, California) wide-body aircraft. The experimental system is described, including hardware and software features, test maneuvers, and analysis techniques. Preliminary flight test results are presented, and application to operational aircraft is discussed. Note that use of trade names or names of manufacturers in this document does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

BACKGROUND: TRANSPORT PERFORMANCE OPTIMIZATION

At cruise flight conditions, two control effectors are typically required for longitudinal flightpath control: the throttle and the horizontal stabilator (assuming a symmetric aircraft, with identical engines and a coupled elevator/horizontal stabilizer). Thus, in order to maintain a given flight condition, only one unique combination of the two control effectors exists.

Inclusion of symmetric outboard aileron as a longitudinal control effector adds redundancy to the set of longitudinal control effectors. (The three control effectors each produce pitching moment and drag/thrust changes to varying degrees.) With this one additional control effector, the set of three control effectors is redundant in that there no longer exists one unique set of control settings that will maintain a given flight condition. Instead, an infinite number of combinations of throttle, horizontal stabilator, and symmetric aileron deflections exists that can maintain the given flight condition. However, each of these combinations is not equally “good” in the sense of providing minimum aircraft drag; and over the range of small perturbations, only one pronounced minima is likely to exist that produces a minimum drag configuration. Adaptive performance optimization addresses this one unique combination of control effectors.

Adaptive performance optimization empirically determines the minimum drag configuration for the net aircraft and not just the wing. In this case, APO determines optimal settings for throttle, horizontal stabilator, and symmetric aileron deflection (a unique angle of attack is also determined implicitly). The APO methodology can be used to handle as many redundant control effectors as are available.

Most aircraft have significant capability in this area but are not currently taking advantage of it. Performance optimization from a condition that is already fine-tuned (based on wind-tunnel and flight testing) places increased demands on high-quality instrumentation to sense small differences in an unsteady environment.

A wide range of controls or variables can potentially play a role in performance optimization for current and future generation aircraft. These controls or variables include elevators, horizontal stabilizers, outboard and inboard ailerons, outboard and inboard flaps, rudder, center of gravity, thrust modulation, and differential thrust (fig. 1).

Preliminary design work, including wind-tunnel testing and some flight experiments, has been performed for implementation of variable camber on a transport aircraft. The benefits of full-span variable camber include the following [8]:

- Improved aerodynamic efficiency (improved L/D)
- Increased Mach number capability
- Improved buffet boundary
- Increased operational flexibility
- Reduced structural weight
- Reduced fuel burn
- Increased aircraft development potential

Figure 2 shows that, even at the design point of a state-of-the-art conventional wing, the variable-camber feature provides increased L/D ratios. This research involved using the entire trailing edge of the wing for variable-camber control with the variable-camber deflections being a function of span location. This system produced L/D increases of between 3 and 9 percent and a buffet boundary increase of 12 percent. The proposed full-span variable-camber design did not include development of a real-time adaptive optimization methodology.

TEST BED AIRCRAFT DESCRIPTION

An L-1011 aircraft was selected as the test bed for the APO flight experiment. This aircraft is representative of the general class of wide-body transports capable of

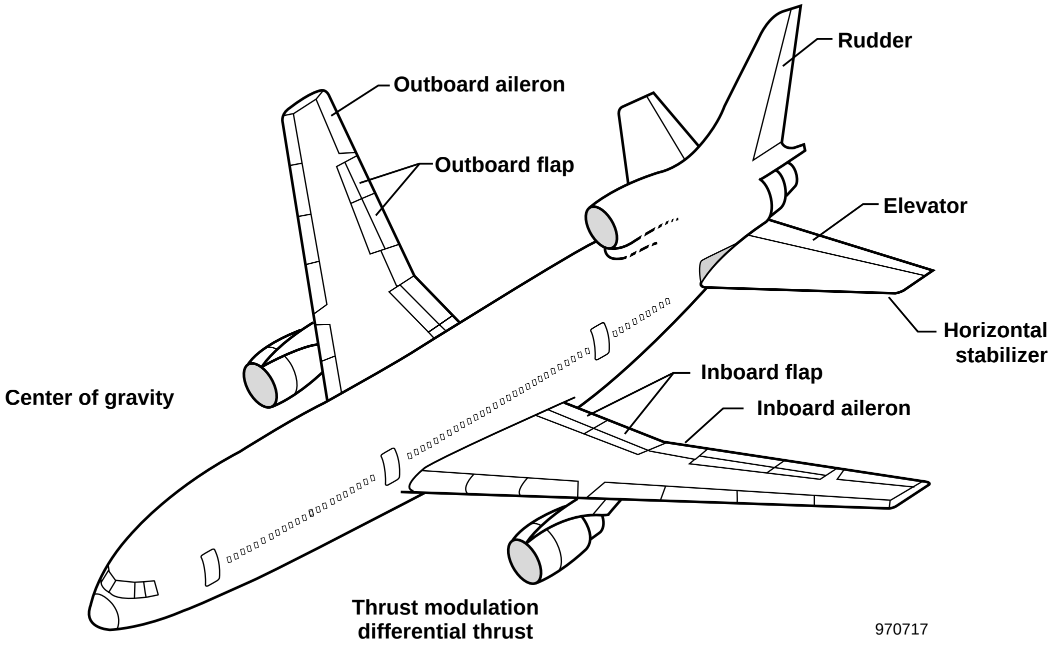

Figure 1. Potential redundant control effectors.

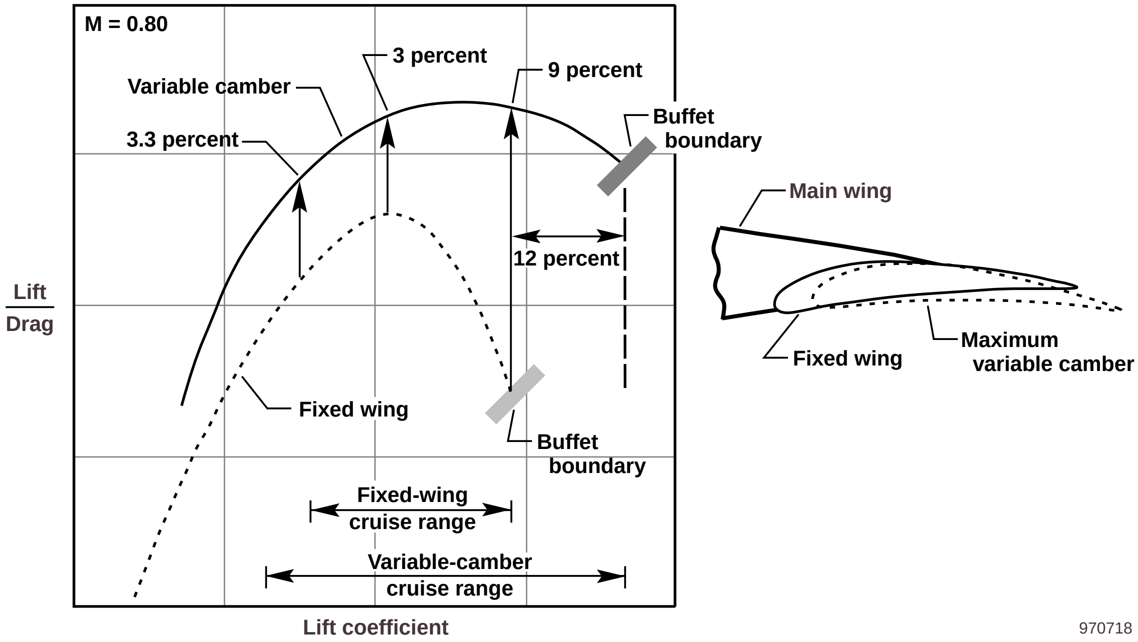

Figure 2. Benefits of variable camber for a transport configuration using a simple trailing-edge control surface system [8].

long-range cruise flight. Aircraft availability and cost dictated its selection over other wide-body transports.

General Information

The test bed aircraft selected is owned and operated by Orbital Sciences Corporation (Dulles, Virginia) and was previously modified to launch satellites using various models of the Pegasus® rocket (Orbital Sciences Corporation, Dulles, Virginia). The modifications consisted of stripping the main cabin of seating and related passenger amenities, modifying the aircraft to carry and launch a rocket from the belly of the aircraft with support systems installed primarily in the lower galleys, and installing a launch panel control station in the forward cabin along with seating for approximately 10 engineers or observers. These rocket launch modifications do not affect the incremental drag measurements upon which APO is based.

The test aircraft is an L-1011-100 model and is powered by three RB-211-22B (Rolls Royce, Inc., Derby, England) high-bypass turbofan engines. The empty weight (without the Pegasus®) and maximum gross weight of the modified aircraft are 280,000 and 467,000 lbm, respectively. The empty weight of the Pegasus®-modified aircraft is approximately 20,000 lbm lighter than the production L-1011-100 model. The aircraft has a cruise range of approximately 4000 miles at Mach 0.84 and a maximum operating speed of Mach 0.90.

Adaptive Performance Optimization Test Bed Modifications

Aircraft modifications necessary to support the APO experiment consisted of the following:

- Adding a research engineering test station (RETS), which is the central feature of the APO modification
- Adding an actuator (one on each wing) to drive the outboard ailerons symmetrically
- Adding a trailing-cone system to obtain true static pressure
- Connecting into the basic aircraft system to obtain engine, control surface, and other measurements
- Adding an embedded global positioning system (GPS) and inertial navigation system (INS)
- Adding a state-of-the-art airdata computer
- Adding a pulse code modulation (PCM) data recording system

Figure 3 shows the APO system. The APO system does not rely on any uplink or downlink other than receiving normal GPS satellite signals.

Research Engineering Test Station—All aspects of the APO experiments are conducted from the RETS. At the top level, the RETS consists of four vertical racks that contain a SPARC 20 (Sun Microsystems, Inc., Mountain View, California) work station and three additional displays for presentation of time histories and related analysis results. The RETS is staffed by a flight test conductor and an analysis/systems engineer. The RETS also contains a computer based on versa module eurocard (VME) architecture to support real-time input and output requirements and related real-time calculations. The RETS was designed to be a flexible research tool and has many capabilities, which include the following:

- Generating excitation signals to drive the outboard ailerons: steps, ramps, sine waves, and raised-cosine waves
- Providing position control for the outboard aileron actuators
- Performing data collection, calibration, and storage on hard disk
- Performing real-time analysis
- Displaying data and analysis results
- Displaying variable or error signal to the cockpit to aid pilot control during test maneuvers
- Providing automatic feedback control and optimization of the outboard ailerons
- Monitoring system health
- Providing communications with the pilot station

Figure 4 shows the RETS console.

Symmetric Aileron Actuation—In order to achieve longitudinal-axis drag reduction, redundant control variables must be available. Although the wing has a number of control surfaces (inboard and outboard ailerons and flaps), symmetric control is not normally available in cruise flight with the exception of outboard ailerons for load control on a few transport aircraft types or models. A system modification was required to provide for symmetric deflections, but first a selection of the control surface to be used was required. Either or

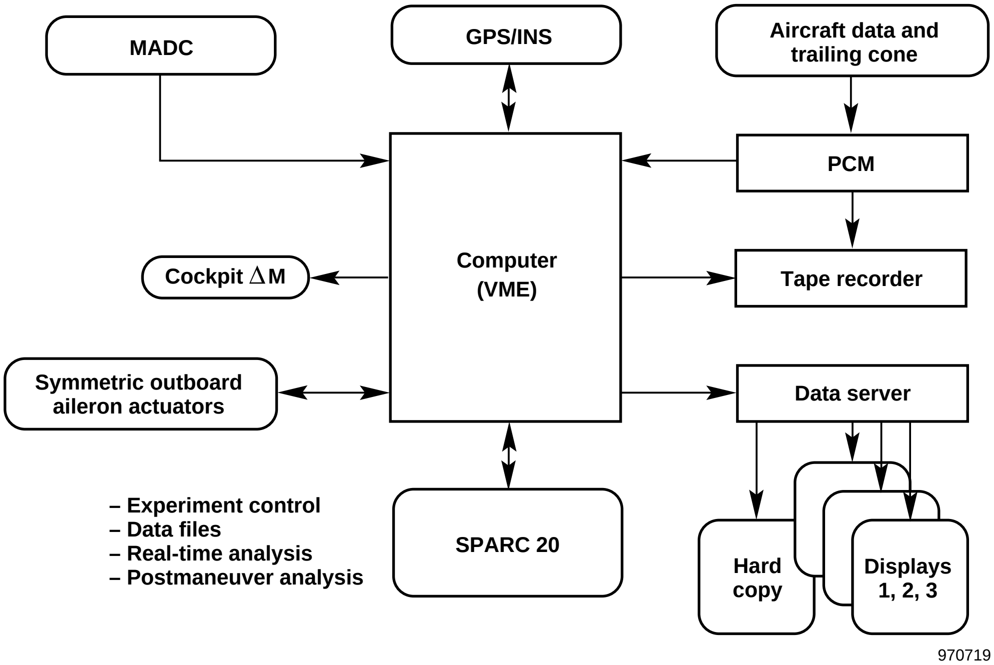

Figure 3. APO/L-1011 research system architecture.


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Figure 4. Research engineering test station.

both the inboard and outboard flaps might appear most desirable. However, because the flaps were designed solely for low-speed, high-lift operation, significant Fowler motion (translation) exists prior to and with flap rotation. In addition, the lower surfaces of the flaps normally develop significant gaps as the flap deflection increases, thus producing a significant drag increase. The inboard aileron has a short span relative to chord and therefore has significant edge effects, which leaves use of the outboard ailerons for modification.

The L-1011-100 aileron control system is fully mechanical. Although use of a servocontroller (to sum both electrical and mechanical inputs) at the outboard actuator would be ideal, the servounit as well as the analysis and testing required to flight-qualify the unit would have been prohibitively expensive. Normal outboard aileron operation is commanded from the inboard aileron using pushrods and cables. The approach taken to provide symmetric control of the outboard ailerons was to modify the rod coming from the inboard aileron, which in turn positions the outboard aileron actuator. The modification consisted of replacing the rod with a low-bandwidth, linear, electric actuator with end fittings identical to the rod being replaced. This modification provides for an adjustable rod length that permits independent commands to be summed for each outboard aileron.

Figure 5 shows a diagram of the outboard aileron control system and a photograph of the modified rods with actuators. This modification allows for both normal (asymmetric) and symmetric commands to be sent to the outboard aileron simultaneously.

The approach described was taken to minimize aircraft changes and maintain the aircraft safety characteristics. In addition to the mechanical rate and position limits of the inline actuator, additional limits on rate and position can be placed in the position controller software.

Trailing-Cone System—Precise, absolute drag measurements require the use of a trailing-cone system to obtain accurate, absolute static-pressure measurements for research purposes. The trailing-cone system consists of 250 ft of tubing running from the main cabin through a pressure fitting in the aft bulkhead, up the conduit in the leading edge of the vertical fin, and out the top of the vertical fin.

Figure 6 shows a diagram of the trailing-cone system. The trailing cone is only for research purposes; an operational aircraft will not need one. A selector valve is used to switch between static pressure of the aircraft and trailing-cone static pressure to compare results between aircraft and research sensors.

Standard Aircraft Data—Because the APO research is directed toward operational implementation in transport aircraft, the basic aircraft instrumentation was used to the maximum degree possible. Access to the aircraft data was obtained through tee connectors with a large impedance on the instrumentation output side of the tee to preclude research instrumentation electronic problems from affecting aircraft systems.

The following aircraft data were recorded:

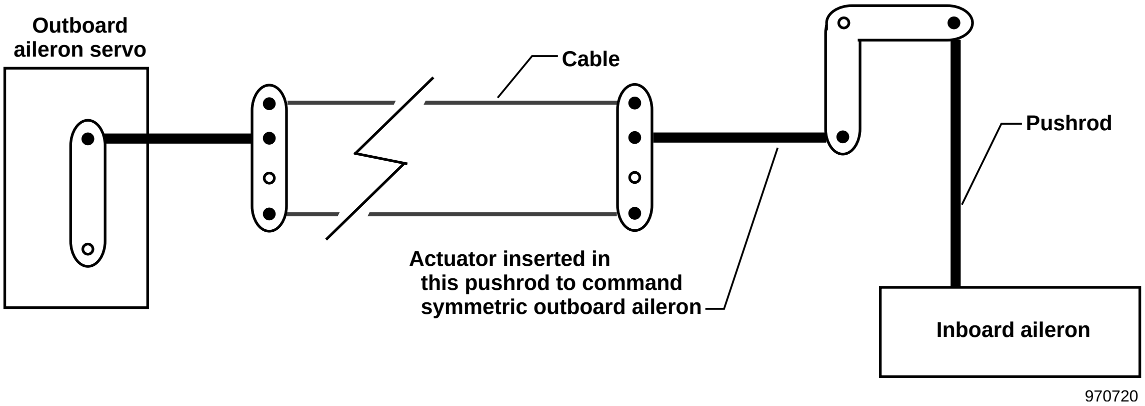
- Airdata: total and static pressure and angle of attack
- Engine parameters: engine pressure ratio, fuel flow, and first and third spool speeds (*N1* and *N3*)
- Surface positions: inboard and outboard ailerons, inboard and outboard flaps, horizontal stabilator, and rudder

In addition, sideslip sensor and throttle position transducers were installed, and fuel burn counters were added to the instrumentation system.

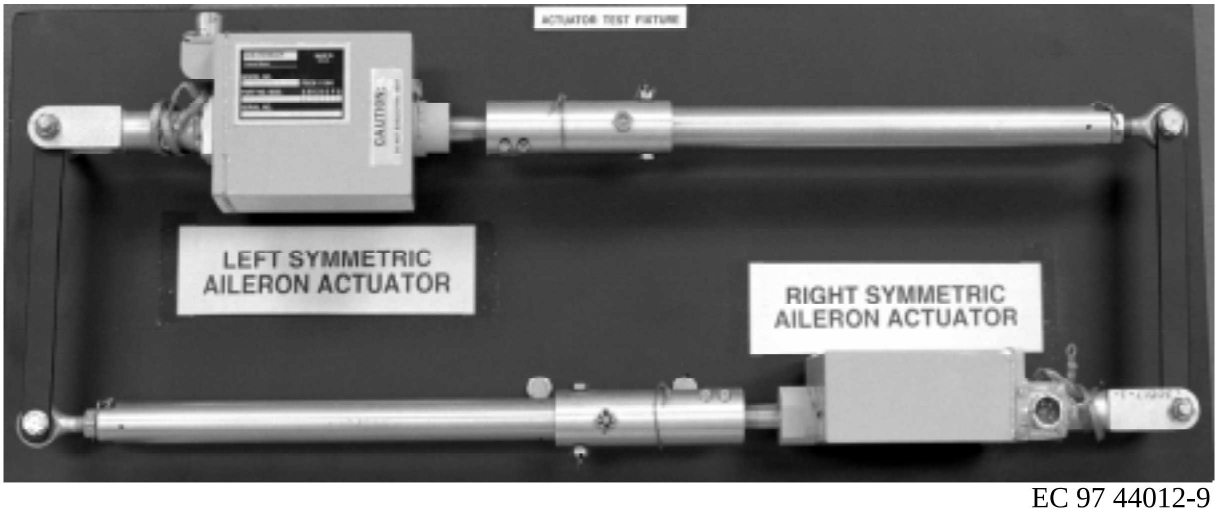
Embedded GPS/INS System—An embedded GPS/INS (EGI) system typical of current production aircraft was added to the instrumentation data base to provide highly accurate measurements of very small changes in flightpath axis accelerations and velocities. These measurements are critical to the determination of very small changes (less than 1 percent) in incremental drag. The EGI system data, along with airdata, are also used to compute wind estimates and angle-of-attack and sideslip estimates.

Airdata Computer—A state-of-the-art micro airdata computer (MADC) was added to the instrumentation data base to provide accurate measurements and calculation of very small changes in Mach number, true airspeed, and altitude. The unique construction of the MADC provides for more accurate airdata calculations than independent measures of total and static pressures.

Other Modifications—An independent PCM data pallet was installed to collect and record on tape all of the standard aircraft data that is required for the flight experiment parameters previously discussed. This PCM data stream is also sent to the RETS for use in displays and algorithm analysis. In addition, a unit was added to the cockpit to display one variable and an error



(a) Original outboard aileron control linkage.



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(b) Control rod and linear actuator assemblies.

Figure 5. Outboard aileron control system.

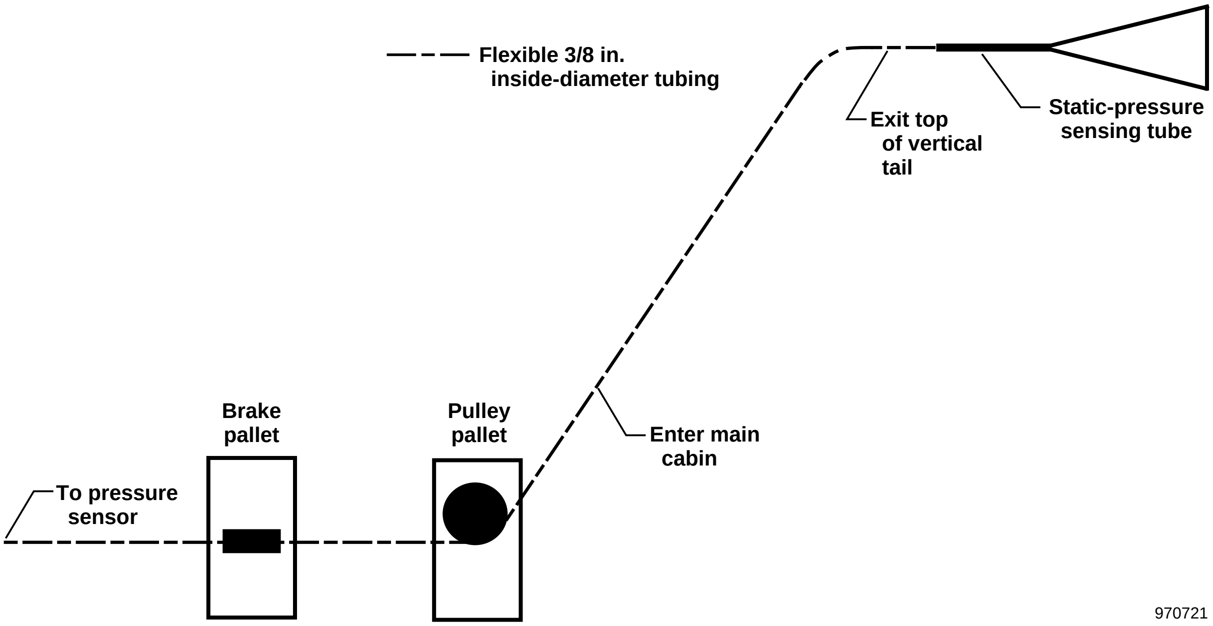


Figure 6. Static-pressure trailing-cone system.

signal to aid the pilot in performing precise control. The symmetric aileron actuator power switch was added to the cockpit.

REAL-TIME TEST OPERATIONS

Forced excitation of redundant control effectors is required to identify incremental drag effects. The requirement for forced excitation must be tempered by the additional requirement that neither handling nor ride qualities are noticeably impacted, which in turn dictates the range of excitation frequencies and amplitudes. These trade studies were conducted using a high fidelity simulation of the test aircraft.

The APO flight experiment modifications discussed previously only allow for direct control of the outboard ailerons; throttle, stabilator, and angle-of-attack changes are controlled indirectly. When the pilot applies power to the APO actuators, the test conductor has control over the actual surface position of the outboard ailerons. The experimental APO system has the following capabilities:

- An independent bias can be added to either or both outboard ailerons.
- Normal (asymmetric) aileron commands from the pilot and autopilot can be removed from the outboard aileron command, thus providing for only symmetric outboard aileron deflections. (In the situation where roll control is required, inboard aileron deflections are increased so as to account for the “loss” of asymmetric outboard aileron control.)
- Step, ramp, sine, or raised-cosine excitation commands are available. The magnitude, frequency, and maneuver duration is selectable as required.
- Maximum commandable position and rate sent to the outboard aileron is selectable and controlled in software.
- Relay characteristics that control commands sent to the actuator for position feedback control of the actuator are selectable in software.

Real-Time Flight Experiment Operation at Stabilized Cruise Conditions

The test conductor selects the excitation parameters and variables described in the previous section. The desired flight condition is stabilized by the pilot and/or autopilot. When the test conductor determines flight conditions have stabilized, the excitation function is commanded. The APO algorithm (described in the next section) requires the pilot and/or autopilot to control Mach number and altitude as accurately as possible through use of the throttles and stabilator. The excitation causes small drag and pitching-moment changes in the aircraft configuration. The net aircraft drag changes are anticipated to be both positive and negative over the range of the excitation.

As previously noted, APO determines the control effector positions to yield a net aircraft minimum drag condition. Although only symmetric ailerons are excited explicitly, maintaining approximate flight conditions during the maneuver requires throttle and horizontal stabilator changes (by the pilot or autopilot), thus providing information relative to their pitching-moment and thrust or drag effects. Flight conditions are not required to be maintained exactly because small deviations can be compensated for in the analysis.

Data are collected throughout the maneuver, and upon maneuver completion, a drag-minimization analysis is performed. The outboard ailerons are then commanded to that optimal position. Probably the most obvious way to take advantage of the drag reduction is to continue flying at the same desired flight conditions but at reduced fuel flows. An alternate use of the reduced drag is to increase the cruise speed at the same fuel flow setting; other variations on reduced drag benefits are also possible. The operation of APO at other than stabilized cruise is possible and is the subject of follow-on research. Long-range cruise flight is where most of the drag reduction (fuel saving) benefits will be accrued.

Drag-Minimization Algorithm

To provide an effective optimization algorithm, estimation of incremental drag to levels of 1 percent or less will be required. Although absolute drag measurements of this accuracy are only obtainable with very detailed analysis and precise engine modeling, incremental drag values in this range are more readily achievable [16, 17].

Previously discussed APO feasibility studies [13, 14] (using a first-generation jet transport) have practical difficulties in an operational flight scenario because of measurement bias and resolution characteristics. The optimization approach presented in this paper is directed at identifying unknown drag characteristics (including the minimum-drag symmetric aileron position) from a forced-response, smooth, low-frequency maneuver and then setting the symmetric aileron to the estimated minimum-drag position.

The analysis procedure follows the general methodology used for standard postflight performance analysis with simplifications for the determination of incremental drag. The process is based on the availability of accurate linear and angular displacement, velocity, and acceleration measurements, such as from an INS, along with accurate airdata information. These data can be used to calculate winds and then angle of attack. Transformations are then performed to produce flightpath-axes accelerations. Thrust, T, is estimated from a representative steady-state engine model as a function of measured variables. The lift and drag equations are then used to calculate the coefficient of lift, C_L, and the coefficient of drag, C_D.

$$\text{Lift} = qSC_L = WA_{z_{fp}} - T\sin(\alpha - \eta) \tag{1}$$

$$\text{Drag} = qSC_D = T\cos(\alpha - \eta) - WA_{x_{fp}} \tag{2}$$

where α is angle of attack and η is the inclination of the engine thrust relative to the fuselage. Aircraft gross weight, W, is calculated based on takeoff weight and fuel flow. Thrust-related ram effects are assumed aligned with the gross-thrust axis and are included in the other terms.

The following is an expression for C_D that is a function of parasite drag, induced drag, Mach-induced drag, and symmetric aileron drag.

$$\begin{aligned} C_D = {} & C_{D_o} + K_1\left[C_L - C_{L_{@\min C_D}}\right]^2 \\ & + C_{D_M}\Delta \mathrm{M} + K_2(\delta_a - \delta_{a_{opt}})^2 \end{aligned} \tag{3}$$

Equation (3) is then solved from forced-response excitation data. Algorithm solutions can range from continuous to batch operation (the variables K_1 and $C_{L_{@\min C_D}}$ can be selected from previous baseline aircraft flight data). Estimates of the parasite drag coefficient (C_{D_o}), curvature of the aileron drag variation (K_2), and the optimal symmetric aileron position ($\delta_{a_{opt}}$) are produced. The optimal settings of throttle and horizontal stabilator are not determined explicitly but rather are determined from the fact that when one of the three redundant control-effector positions is fixed, no redundancy is left for the remaining two effectors and thus they will seek their unique position based on the flight condition being constrained. The algorithm can be considered a slow, limited-authority trimmer.

The formulation of equation (3) is not unique; the important concept is that the primary effects of symmetric 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.

Simulation results confirm that the analysis procedure is insensitive to a wide range of algorithm variables such as *a priori* estimates of K_1 and $C_{L_{@\min C_D}}$, measurement bias effects, measurement resolution effects, and thrust model accuracy [15]. Other performance-related calculations such as changes in specific fuel consumption and range can be calculated.

PRELIMINARY FLIGHT RESULTS

A functional flight of the research-modified aircraft was flown, and the research systems operation was evaluated at Mach 0.84 and an altitude of 35,000 ft. With the altitude-hold autopilot on, the pilot trimmed the aircraft throttles before maneuver initiation (throttles were not used during the excitation portion of the maneuver). The maneuver consisted of a 5° amplitude raised-cosine $(1.0–\cos(\omega t))$ forced excitation of the symmetric outboard ailerons with a 300-sec duration.

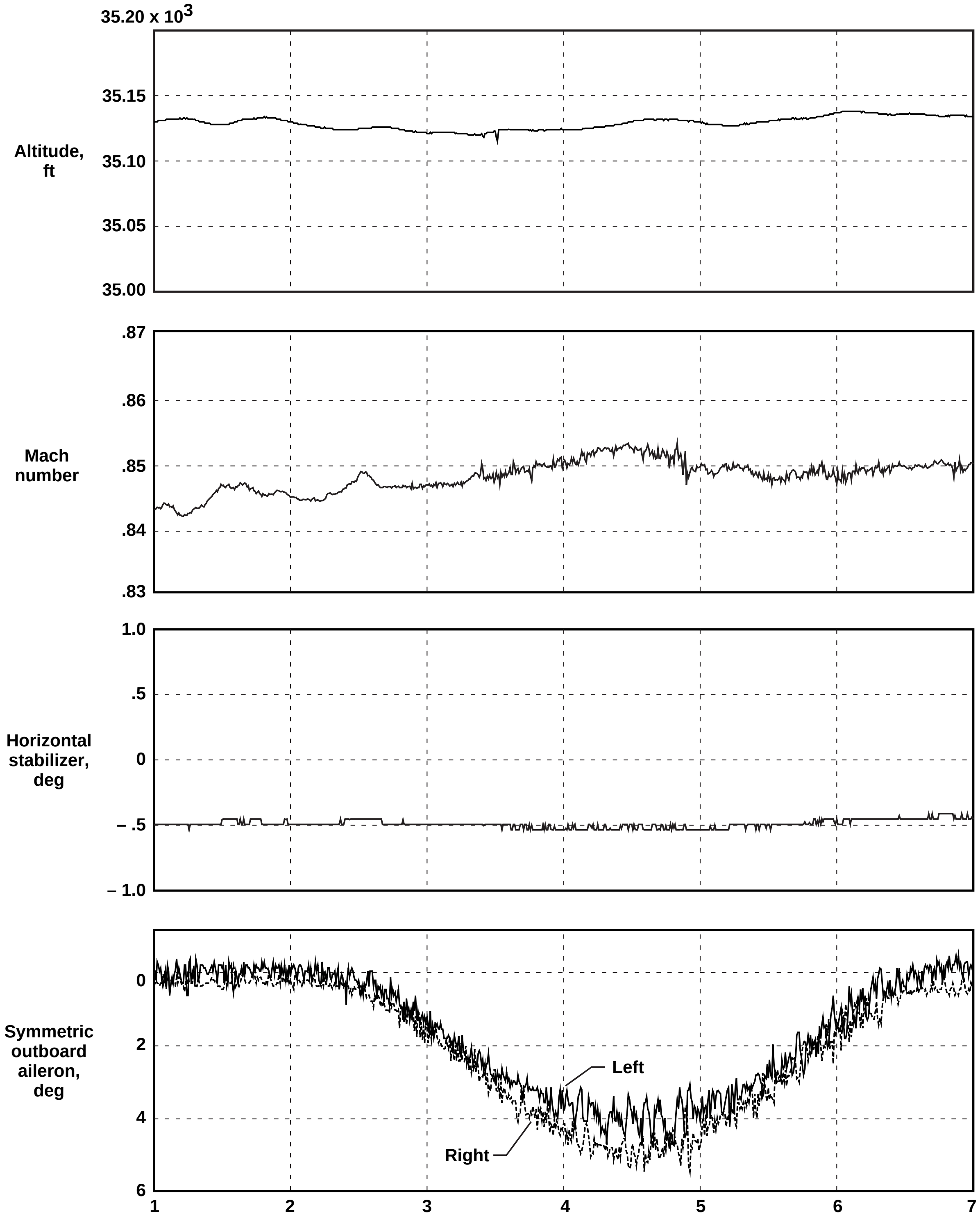
Figure 7(a) shows altitude, Mach number, and stabilizer response variables to the forced excitation. Altitude is held within 10 ft over the maneuver duration, and Mach number apparently increases during the initial portion of trailing-edge-down outboard aileron deflection and begins decreasing as the deflection reaches its peak value. Mach number-hold through the throttles was not used during this maneuver. Although in an operational scenario, Mach number would be constrained by an autothrottle mode. It is clear from the maneuver response characteristics that neither handling qualities nor ride qualities are affected.

Figure 7(b) shows the variation of ΔC_D with δ_a. The ΔC_D parameter is estimated from equations (1), (2), and (3) using flight data measurements. The smooth, solid line is the "best fit" of the flight data using estimates of the unknown parameters of equation (3). Although the variation is "noisy," a minimum clearly exists (≈4°, trailing-edge-down, symmetric aileron deflection) that indicates a more optimal flight configuration than the baseline aircraft (0° symmetric aileron deflection). From this one example, it is clear that small incremental drag changes can be estimated and that the aircraft can be reconfigured to reduce drag.

OPERATIONAL IMPLEMENTATION

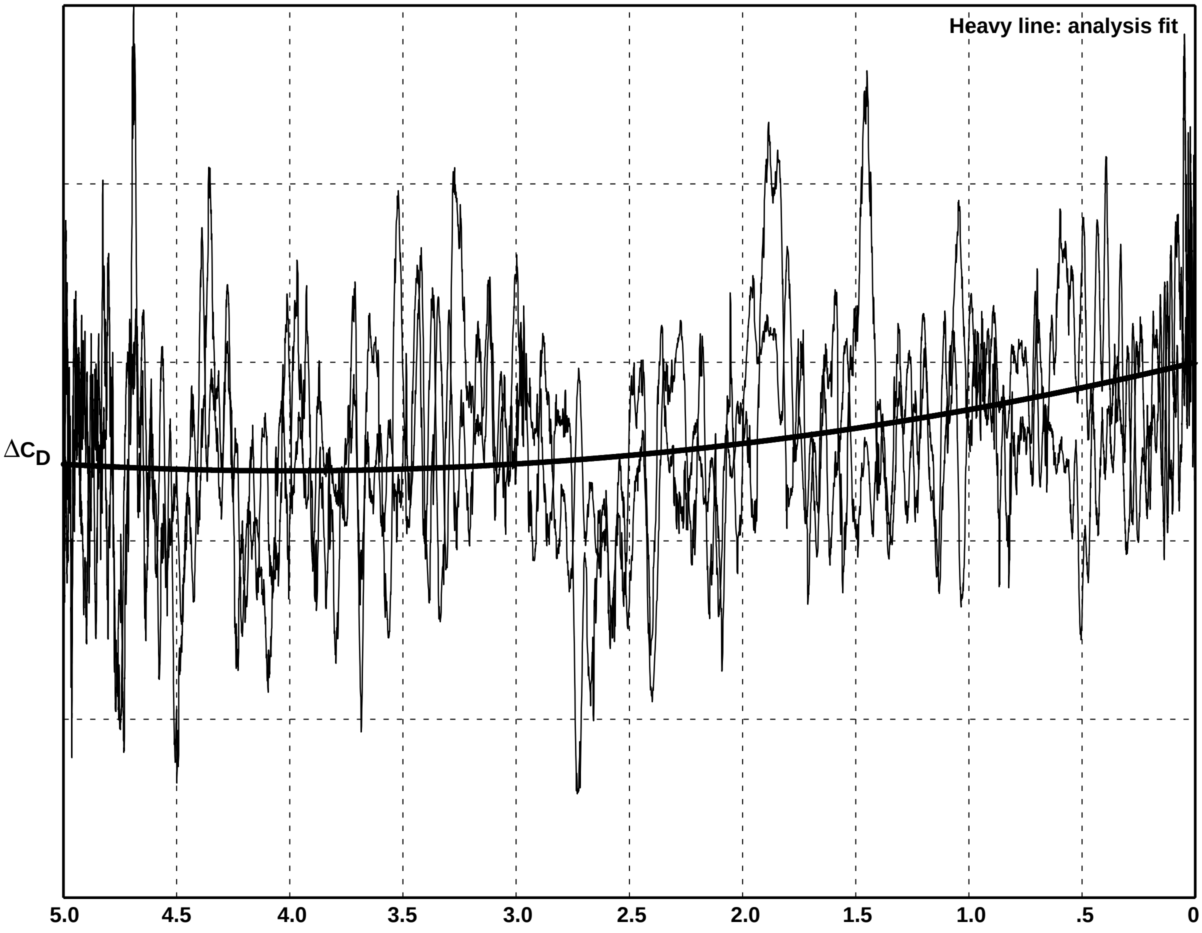
Application of APO to fly-by-wire aircraft is straightforward and theoretically only requires software additions that could be placed in the FMS. The pilot would interface with the APO software through the CDU. For aircraft with mechanical control systems, application of APO would require the additional modification of the installation of electrically commanded actuators (or equivalent) somewhere within the system controlling the particular control surface of interest.

Redundancy is not required because the APO system is not a safety-of-flight item. This aspect can be assured by having APO in a discretionary mode with very limited rate and position authority. In a situation where the aircraft has an active control mode using the outboard ailerons (for example, maneuver load alleviation, MLA, or gust load alleviation, GLA), the APO optimal position would be summed with the active signals. In the GLA situation, APO provides a new reference condition about which the GLA commands operate. The MLA command is similar to the APO command and obviously has priority; the APO command needs to be "washed out" as the total outboard aileron deflection exceeds predetermined levels.



(a) Aircraft response to forced-excitation maneuver.

Figure 7. Preliminary APO flight test results.



(b) Variation of incremental drag with symmetric aileron deflection.

Figure 7. Concluded.

Operational Algorithm Operation

Figure 8 shows an approach to an operational implementation of the APO algorithm. (A proposed pilot interface with the APO system will be discussed later.) After APO is engaged, storage arrays are searched for previous APO results. If applicable results are located, the control surfaces will be positioned beforehand to this value based on the assumption that the previous optimal position is, in all likelihood, better than the baseline aircraft configuration. The forced-excitation signal is then applied. A raised-cosine excitation with a period of approximately 300 sec is preferred because of its smooth characteristics and long duration during which the autopilot maintains steady flight conditions. (Autopilot modes are assumed to exist for all practical operational implementations to maintain constant flight conditions.)

Data are collected during the course of the maneuver. When the maneuver is complete, the optimization analysis is performed. These results are available essentially instantaneously. The control surface is then smoothly commanded to the newly determined optimal position by using the first one-half of the raised-cosine command shape. If it is determined that the excitation signal range did not encompass the optimal position, the algorithm is assumed not to have converged, and the process is repeated with the range of the excitation signal changed. (This issue should not exist when a set of APO optimal conditions have been determined for a particular aircraft.) In the situation where more than one redundant controller is available, repetition of the excitation for a different control surface may be required. When the optimal APO conditions have been determined, the results update the storage arrays. Because aircraft-specific variations play a significant role in the actual amount of performance improvement accruable, using previous optimality results as initial conditions can speed up optimality convergence for subsequent flights.

When an optimal set of control positions have been determined, the APO system goes into a standby mode because continuing the excitation process will only serve to introduce drag increases at the optimal condition. A new excitation cycle is required when aircraft or flight conditions have changed sufficiently such that a new optimization cycle could provide a new optimal result. Although the criteria for starting a new APO cycle are somewhat aircraft-dependent, a reasonable set of criteria could be the exceedence of any one of the following: 30 min since the last APO cycle, an altitude change of 2000 ft, or a Mach number change of 0.02. Of course, the flight crew would always have the option of initiating a new APO cycle.

Flight Crew Operation

Figure 9 shows one possible APO system interface display from the flight crew's perspective. The required software would be implemented in an FMS revision. As a first-generation implementation, the proposed interface has some limited interactive features. The proposed operations relative to the panel illustrated are as follows:

ON	ON window lights; EXCITE and ENTER remain dark OLD Optimal Value control position is displayed if a valid set of interpolation points are available; if not, display reads 0.0
ENTER	ENTER window lights Sends displayed value to the surface; light stays on to indicate optimal value is on the control surface Optimal value is entered in the data table Succeeding excitations and analyses place a new value in the window and turn the ENTER window light off
EXCITE	EXCITE window lights and stays on during forced excitation Commanding EXCITE initiates a new excitation signal (must be dark/off to initiate) When an optimal value is determined, the excitation function goes into a standby mode After a fixed period of time or upon exceedence of predetermined flight parameters (for example, ΔM, ΔH), the excitation repeats automatically Upon completion of forced excitation, analysis is performed and result displayed (for example, NEW –1.8) Excitation will be referenced to previous ENTER position

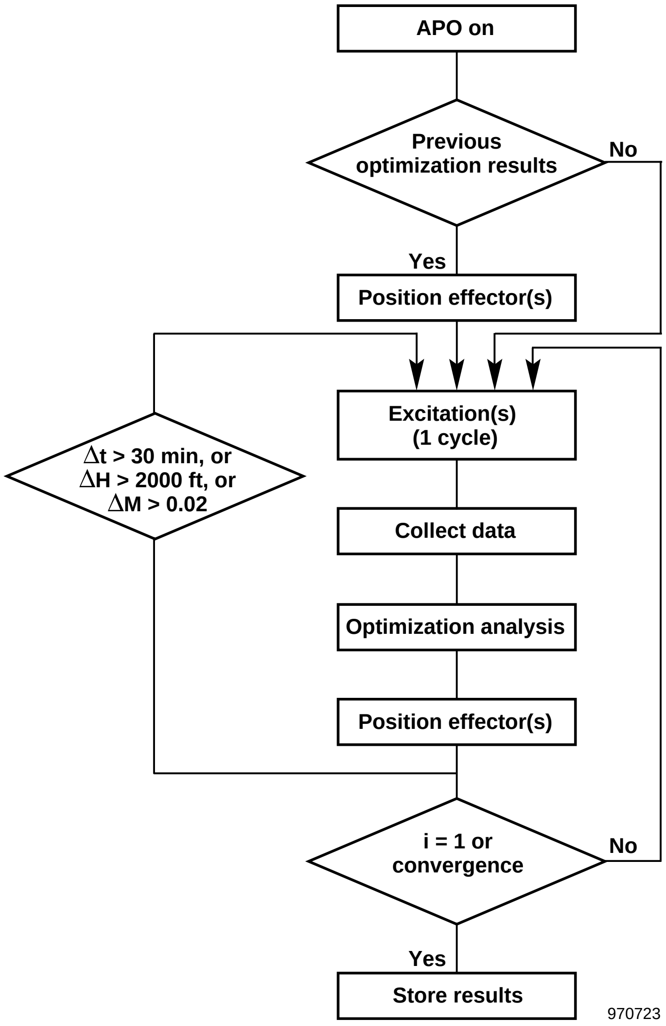


Figure 8. APO algorithm flow chart.

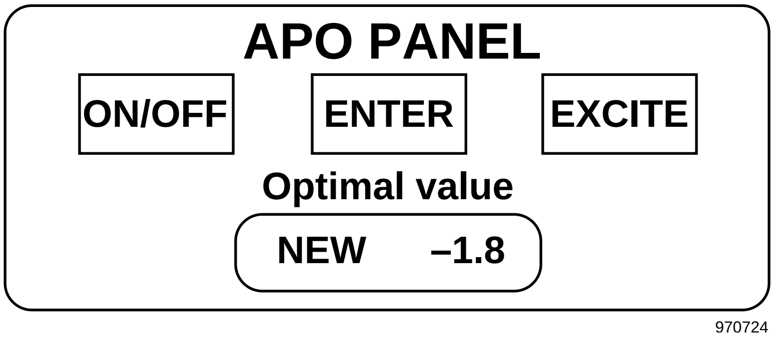


Figure 9. Crew interface display.

Optimal Value	Window flashes until the optimal value is entered (surface is then commanded to the optimal position)

The described APO system keeps the flight crew apprised of optimal positions as the positions become available; the crew then has the option of accepting those optimal positions. It is presumed that when experience has been gained with the system described, even this minimal interactive capability will not be required. The elements of the display (described above) presumably would be integrated into one or more CDU display pages so that no hardware changes to either the FMS or the flight station are required.

CONCLUDING REMARKS

The NASA Adaptive Performance Optimization (APO) flight research program, which is directed at exploring the practical application of real-time performance optimization based on aircraft measurements, has been described. The experiment has been implemented on an L-1011 wide-body transport. The outboard ailerons of the test bed aircraft were modified to provide for symmetric deflections, and an onboard research engineering test station was developed by NASA. Incremental drag variations are calculated in response to a forced excitation of the redundant control surface being optimized. An example flight maneuver has been presented that illustrates the real-time character of the maneuver and its minimal effect on flying or ride qualities.

An approach to an operational implementation of APO on current and future commercial and military transports is proposed with the goal of keeping the required modifications minimal. Application of APO to fly-by-wire aircraft theoretically requires only software additions that could be placed in the flight management system. Aircraft with mechanical control systems would additionally require the installation of electrically commanded actuators (or equivalent) somewhere within the system controlling the particular control effector of interest. In both cases, the pilot would interface with the APO software through the control display unit. Sensors and instrumentation installed on current state-of-the-art aircraft appear adequate for performing APO.

REFERENCES

[1] “Long Live the Leviathan,” *Flight International*, Sept. 15–21, 1993, pp. 30–31.

[2] “P&W Plans PW4000 Improvement Tests,” *Flight International*, June 30–July 6, 1993, p. 11.

[3] Szodruch, J., “Viscous Drag Reduction On Transport Aircraft,” AIAA 91-0685, 1991.

[4] *Advanced Fighter Technology Integration F-111 Mission Adaptive Wing*, NASA CP-3055, 1990 (ITAR restricted document).

[5] Phillips, Paul W. and Stephen B. Smith, *AFTI/F-111 Mission Adaptive Wing (MAW) Automatic Flight Control System Modes Lift and Drag Characteristics*, AFFTC-TR-89-03, May 1989. (Distribution limited to U.S. Government agencies only (Test and Evaluation), Apr. 1989. Other requests for this document shall be referred to the AFTI/F-111 (MAW) Program Office (WRDC/FIMF), Wright-Paterson AFB, OH, 45433-6503.)

[6] Szodruch, J. and R. Hilbig, “Variable Wing Camber For Transport Aircraft,” *Progress In Aerospace Sciences*, vol. 25, no. 3, 1988,pp. 297–328.

[7] Renken, J. H., “Mission-Adaptive Wing Camber Control Systems for Transport Aircraft,” AIAA 85-5006, Oct. 1985.

[8] Renken, Jürgen, *Variable Wing Camber Control Systems for the Future Airbus Program*, Messerschmitt-Bölkow-Blohm GmbH UT-104-88, Feb. 1988 (in German; English summary).

[9] Sorensen, John A., S. A. Morello, and H. Erzberger, “Application of Trajectory Optimization Principles to Minimize Aircraft Operating Costs,” IEEE TA3-9:00, 1979.

[10] Lee, Homer Q. and Heinz Erzberger, *Algorithm for Fixed-Range Optimal Trajectories*, NASA TP-1565, July 1980.

[11] Erzberger, Heinz, *Automation of On-Board Flightpath Management*, NASA TM-84212, Dec. 1981.

[12] Visser, H. G., *An Approach to On-Board Optimization of Cruise at Constant Altitude*, Delft Technische University, The Netherlands, report no. LR-581, 1989.

[13] Gilyard, Glenn B. and Martín D. España, *On the Use of Controls for Subsonic Transport Performance Improvement: Overview and Future Directions*, NASA TM-4605, Aug. 1994.

[14] España, Martín and Glenn Gilyard, *Direct Adaptive Performance Optimization of Subsonic Transports: A Periodic Perturbation Technique*, NASA TM-4676, Mar. 1995.

[15] Gilyard, Glenn, *Development of a Real-Time Transport Performance Optimization Methodology*, NASA TM-4730, Jan. 1996.

[16] Rhodes, J. A., K. Ravindra, and D. M. Freidman, "CFD Drag Predictions for a Wide Body Transport Fuselage With Flight Test Verification," AIAA 93-3418, 1993.

[17] Weisenseel, Charles W. and Chester Gong, *C-17A Cruise Configuration Performance Evaluation*, AFFTC-TR-93-23, Dec. 1993. (Distribution limited to U.S. Government agencies and their contractors (Critical Technology), Sept. 1993. Other requests for this document shall be referred to ASC/YC, 2600 Paramount Place, Fairborn, Ohio 45324-6766.)

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A flight research program exploring the practical application of real-time performance optimization based on aircraft measurements and calculation of incremental drag from forced-response maneuvers is presented. The outboard ailerons of the L-1011 test bed aircraft were modified to provide for symmetric deflections to permit a recambering of the wing in that localized area, which in turn modifies the entire wing load distribution. The National Aeronautics and Space Administration developed an onboard research engineering test station from which the flight experiments are conducted and all analyses, both qualitative and quantitative, are performed in a real-time or near real-time manner. Initial flight test results are presented that indicate real-time drag minimization is attainable. An approach to an operational implementation of adaptive performance optimization on current and future commercial and military transports is discussed with the goal of keeping the required modifications simple and the pilot interface minimal and user friendly.

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