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Glenn B. Gilyard and John S. Orme
Dryden Flight Research Facility
Edwards, California

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PERFORMANCE-SEEKING CONTROL: PROGRAM OVERVIEW AND FUTURE DIRECTIONS

Glenn B. Gilyard[*] and John S. Orme[*]
NASA Dryden Flight Research Facility
P.O. Box 273
Edwards, California 93523-0273

Abstract

A flight test evaluation of the performance-seeking control (PSC) algorithm on the NASA F-15 highly integrated digital electronic control research aircraft was conducted for single-engine operation at subsonic and supersonic speeds. The model-based PSC system was developed with three optimization modes: minimum fuel flow at constant thrust, minimum turbine temperature at constant thrust, and maximum thrust at maximum dry and full afterburner throttle settings. Subsonic and supersonic flight testing were conducted at the NASA Dryden Flight Research Facility covering the three PSC optimization modes and over the full throttle range. Flight results show substantial benefits. In the maximum thrust mode, thrust increased up to 15 percent at subsonic and 10 percent at supersonic flight conditions. The minimum fan turbine inlet temperature mode reduced temperatures by more than 100 °F at high altitudes. The minimum fuel flow mode results decreased fuel consumption up to 2 percent in the subsonic regime and almost 10 percent supersonically. These results demonstrate that PSC technology can benefit the next generation of fighter or transport aircraft. NASA Dryden is developing an adaptive aircraft performance technology system that is measurement based and uses feedback to ensure optimality. This program will address the technical weaknesses identified in the PSC program and will increase performance gains.

Nomenclature

AAHT	area adder high-pressure turbine component deviation parameter, in^2
AdAPT	adaptive aircraft performance technology
AJ	nozzle throat area, in^2
CEM	compact engine model
CIM	compact inlet model
CIVV	compressor inlet variable guide vane angle, deg
COWL	cowl deflection, deg
CPSM	compact propulsion system model
DEEC	digital electronic engine control
DEHPT	high-pressure turbine component deviation parameter, percent
DELPT	low-pressure turbine component deviation parameter, percent
DINL	inlet drag, lbf
DWFAN	change in fan airflow component deviation parameter, lb/sec
DWHPC	change in high-pressure compressor airflow component deviation parameter, lb/sec
EPR	engine pressure ratio, *PT6*/*PT2*
F	steady-state variable model sensitivity matrix
FNP	net propulsive force, lbf
FTIT	fan turbine inlet temperature, °F
g	acceleration caused by gravity, ft/sec^2
HIDEC	highly integrated digital electronic control
M	Mach number
N1	fan rotor speed, rpm
N1C2	fan rotor speed, corrected to station 2 temperature, rpm
N2	compressor rotor speed, rpm
PCTC	percent critical inlet mass flow
PSC	performance-seeking control
PSM	propulsion system matrix

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[*] Aerospace Engineer. Member AIAA.

PT	total pressure at specified engine station number (see suffix list that follows), lb/in^2
RAMP	ramp deflection, deg
RCVV	rear compressor variable vanes, deg
SDR	inlet shock displacement ratio
SMF	fan stall margin, percent
SMHPC	high-pressure compressor stall margin, percent
S/MTD	Short Takeoff and Landing/Maneuvering Technology Demonstrator
SSVM	steady-state variable model
SVM	state variable model
T	(superscript) transpose
TMT	composite turbine metal temperature, °F
TSFC	thrust-specific fuel consumption, *WF*/*FNP*, hr^{-1}
TT	total temperature at specified engine station numbers (see suffix list that follows), °F
$\mathbf{u}$	vector of control variables in the SVM
$\mathbf{u_e}$	vector of control variables in the SSVM
$\mathbf{u_i}$	vector of control variables in the CIM
$\mathbf{u_p}$	vector of control variables in the linear-programming problem
WACC	DEEC-calculated airflow, lb/sec
WCFAN	corrected fan airflow, lb/sec
WCHPC	corrected high-pressure compressor airflow, lb/sec
WF	gas generator fuel flow, lb/hr
WFAB	afterburner fuel flow, lb/hr
$\mathbf{x}$	vector of state variables in the SVM
$\mathbf{y}$	vector of output variables in the SVM
$\mathbf{y_e}$	vector of output variables in the SSVM
$\mathbf{y_i}$	vector of output variables in the CIM
$\mathbf{y_p}$	vector of output variables in the linear-programming problem
δ	control deflection angle, deg
δ_c	cowl deflection, deg
δ_s	stabilator deflection, deg

Suffixes (PW1128 engine station numbers, Fig. 2)

2	fan inlet
2.5	compressor inlet
3	compressor discharge
4	high-pressure turbine inlet
4.5	low-pressure turbine inlet
6	afterburner inlet
7	nozzle inlet

Introduction

The application of optimal control technology to the integrated airframe–propulsion system has the potential to significantly improve total aircraft performance. Developing and implementing this technology will benefit both civilian and military applications by improving fuel efficiency, increasing thrust, or prolonging engine life.

As part of a continuing effort to enhance aircraft performance and to mature this optimal performance technology base, the NASA Dryden Flight Research Facility, McDonnell Douglas Aerospace–East (St. Louis, Missouri), and Pratt & Whitney (West Palm Beach, Florida) developed and flight-tested an adaptive model-based performance-seeking control (PSC) system for optimizing the quasi-steady-state performance of the F-15 airframe–propulsion system.[1, 2] The PSC system was developed with the following optimization modes: (a) minimum fuel flow at constant thrust, (b) minimum turbine temperature at constant thrust, and (c) maximum thrust at maximum dry and full afterburner throttle settings. Subsonic and supersonic flight testing of the PSC algorithm has been concluded at NASA Dryden covering the three PSC optimization modes and over the full throttle range. References 3–5 reported the PSC performance results for various phases of the flight test program. References 6–9 presented additional program results covering comparisons of PSC operation with predictions, operation of the real-time in-flight estimation process, in-flight identification, and ground test results.

Although developing and demonstrating PSC represents a major milestone in optimal aircraft performance technology, as with any emerging technology, some areas require additional research. The PSC model-based adaptive estimation methodology approach produces estimated optimal trim commands rather than measurement-based, true optimal trim commands. Therefore, to expand on the optimal performance technology base, NASA Dryden, McDonnell Douglas, and Pratt & Whitney are developing an adaptive aircraft performance technology (AdAPT) system that will use a measurement-based performance optimization algorithm. Plans envision use of the modified F-15 Short Takeoff and Landing/Maneuvering Technology Demonstrator

(S/MTD) aircraft to demonstrate this technology. Initial planning is directed at quasi-steady optimization modes such as minimum fuel consumption at constant thrust or maximum thrust for a fixed fuel flow. The AdAPT optimization approach uses measurement feedback of performance metrics to ensure optimality, while the PSC approach was heavily based on models and estimated optimality conditions.

This paper describes the PSC algorithm, reviews the flight test program including how the data were collected, presents quantitative flight results of the benefits of the various modes for the entire aircraft flight envelope, and summarizes lessons learned. Included also is a discussion of the AdAPT control system design approach and the results of a preliminary evaluation of the critical AdAPT technology. The evaluation shows that a measurement-based performance optimization system is both feasible and promising.

Airplane and Engine Description

The PSC system was implemented on the NASA F-15 highly integrated digital electronic control (HIDEC) research airplane (Fig. 1), which is capable of speeds greater than Mach 2. Two F100 derivative (PW1128) afterburning turbofan engines power the NASA F-15. The aircraft has been modified with a digital electronic flight control system. More information on the F-15 can be found in Ref. 10.

The PW1128 engine is a low-bypass ratio, twin-spool, afterburning turbofan technology demonstrator, derived from the F100–PW-100 engine. The engine is controlled by a full-authority digital electronic engine control system (DEEC) that is similar to the current production F100–PW-220 engine controller. The DEEC provides both open-loop scheduling of compressor inlet vanes (*CIVV*) and rear compressor variable vanes (*RCVV*) based on rotor speeds and closed-loop feedback control of corrected fan speed (*N1C2*) via the fuel flow (*WF*) and engine pressure ratio (EPR) via the nozzle area (*AJ*). The DEEC software has been modified to accommodate PSC trim commands; but the normal DEEC control loops (i.e., *N1C2* and EPR) have not been modified. The DEEC trim commands for subsonic, nonafterburning conditions are perturbations on *CIVV*, *RCVV*, *N1C2*, and *AJ*; for supersonic conditions with the throttle in afterburner, the trim commands are *CIVV*, *RCVV*, EPR, DEEC-calculated airflow (WACC), afterburner fuel flow *(WFAB)*, cowl deflection *(COWL)*, ramp deflection *(RAMP)*, and stabilator deflection, which are commanded indirectly through altitude hold control. Figure 2 shows a diagram of the PW1128 engine, and Ref. 11 provides a more detailed description of the PW1128 engine.

The F-15 aircraft has two-dimensional variable geometry external compression inlets as shown in Fig. 3. Compression is accomplished through three oblique shocks and a normal shock during supersonic operation. Actuators provide independent control of the first ramp (*COWL*) and the third ramp (*RAMP*). A digital control system based on the sensed variables—Mach (*M*), angle of attack, and fan inlet total pressure (*PT*)—controls the variable inlet geometry.

Figure 2 shows the locations of the DEEC instrumentation and the DEEC-calculated parameters. Fan airflow (*WCFAN*) and fan inlet total pressure (*PT2*) are independently modeled by both the DEEC and PSC control laws. The PSC algorithm uses only conventional DEEC-instrumented parameters as inputs, and the algorithm estimates other necessary parameters required by the optimization process. Internal parameters are recorded for the Kalman-filter estimator; the compact propulsion system modeling; estimates of unmeasurable parameters such as temperatures, pressures, stall margins, thrust, and drag components; and the actual trim commands.

Performance-Seeking Control Law Algorithm

The algorithm flow diagram (Fig. 4) consists of estimation, modeling, and optimization. The estimation process is a Kalman-filter estimation of five component deviation parameters. These parameters account for the off-nominal behavior of the engine during flight. They reflect the changes in efficiency of the low- and high-pressure turbine (*DELPT* and *DEHPT*), the changes in fan and high-pressure compressor airflow (*DWFAN* and *DWHPC*), and a change in the high-pressure turbine area (*AAHT*). The second step formulates and uses the compact propulsion system model (CPSM) to estimate unmeasured engine outputs required for an optimal solution. The CPSM uses the component deviation parameters estimated in the first step to update the engine–model to reflect actual engine operation that can vary from engine to engine; this provides the adaptive feature of PSC. Flight measurements are used to look up model data and as direct inputs to the Kalman filter and CPSM.

The propulsion system matrix (PSM), derived from the CPSM, is used by the linear-programming algorithm to determine the local optimum within the accuracy of the models and the defined constraints. The optimal engine operating point is determined by iterating on the CPSM modeling and linear-programming optimization.

Kalman Filter

The first step in the estimation process is designed to identify the off-nominal characteristics of the engine when operating at or near steady-state conditions. This is done by estimating the five previously mentioned component deviation parameters with a Kalman filter. These parameters are used in the formulation of the CPSM to match more closely the actual engine operating condition. A piecewise state variable model (SVM) is used in the design and implementation of the Kalman estimator. The SVM consists of a state-space perturbation model and associated tables of steady-state trim values for all required engine variables. The state (**x**), control (**u**), and measurement (**y**) vectors are defined as follows:

$$\mathbf{x} = [N1\ N2\ TMT\ DEHPT\ DELPT\ DWFAN\ DWHPC\ AAHT]^T \tag{1}$$

$$\mathbf{u} = [WF\ AJ\ CIVV\ RCVV]^T \tag{2}$$

$$\mathbf{y} = [PT6\ PT4\ TT4.5\ N1\ N2]^T \tag{3}$$

The fan rotor speed (*N1*), compressor rotor speed (*N2*), and turbine metal temperature (*TMT*) are the original states of the engine model; these three states are augmented in the Kalman-filter estimator by the five component deviation parameters so that the component deviation parameters can be estimated. Values for the following measurements and control variables are taken directly from flight data: *N1*, *N2*, *PT4*, *TT4.5*, *PT6*, *WF*, *AJ*, *CIVV*, and *RCVV.* Other engine and flight parameters are used indirectly by the Kalman-filter algorithm for correcting the engine data and calculating other engine variables. Additional information on developing and implementing the Kalman filter can be found in Refs. 7 and 12.

Compact Propulsion System Model

The second step in the estimation process is formulation of the CPSM. The CPSM combines two smaller compact models—the compact engine model (CEM) and the compact inlet model (CIM)—that together model the propulsion system and form the basis for the optimization process. The CPSM also includes integration of cowl and stabilator pitching moment and drag characteristics at supersonic Mach numbers.

Compact engine model

The CEM consists of a linear steady-state variable model (SSVM) and follow-on nonlinear calculations. The SSVM is of the form

$$\mathbf{y_e} = [F]\mathbf{u_e} \tag{4}$$

F is the sensitivity matrix and $\mathbf{u_e}$ and $\mathbf{y_e}$ represent the SSVM control input and response vectors, respectively. They are defined to be

$$\mathbf{u_e} = [WF\ WFAB\ PT6\ CIVV\ RCVV\ DEHPT\ DELPT\ DWHPC\ DWFAN\ AAHT]^T \tag{5}$$

$$\mathbf{y_e} = [N1\ N2\ AJ\ PT2.5\ PT4\ TT2.5\ TT3\ TT4\ TT4.5\ TT6\ WCFAN\ WCHPC]^T \tag{6}$$

The SSVM uses engine measurements for the following variables: *WF*, *WFAB*, *PT6*, *CIVV*, and *RCVV.* The Kalman-filter estimates of the component deterioration parameters are input to the SSVM calculation as part of the control vector. The SSVM estimates the $\mathbf{y_e}$ variables used in subsequent nonlinear CEM calculations.

Following completion of the linear SSVM calculation, the nonlinear CEM estimates are calculated. These variables include *PT7*, *TT7*, *SMF*, *SMHP*C, net propulsive force *(FNP)*, gross thrust, effective nozzle throat area, nozzle drag, and ram drag. The nonlinear calculations use a combination of analytical equations and empirically derived data tables. The tables are based upon both measured engine variables and SSVM estimates. If an SSVM variable is measured, the flight measurement (instead of the estimated value) is used in the nonlinear calculations. The nonlinear calculated variables—*SMF*, *SMHPC*, *FNP*, and effective nozzle throat area—are linearized with respect to *WF*, *WFAB*, *PT2*, *PT6*, *CIVV*, and *RCVV* in real time. The partials generated are used in the follow-on optimization process. More information on the CEM calculations is available in Refs. 5 and 7.

Compact inlet model

At subsonic flight conditions, the nominal inlet schedules were found to be close to optimal, and as such, inlet geometry is not included in the PSC algorithm at subsonic conditions. At supersonic flight conditions the inlet is included in the modeling and subsequent optimization process. The inlet equations are nonlinear and have the following input and output variables:

$$\mathbf{u_i} = [WCFAN\ COWL\ RAMP]^T \tag{7}$$

$$\mathbf{y_i} = [PT2\ DINL\ SDR\ PCTC]^T \tag{8}$$

where *DINL* is inlet drag, *SDR* is inlet shock displacement ratio, and *PCTC* is percent critical inlet mass flow. More information on the CIM is available in Ref. 13.

Airframe model

The PSC system optimization, which includes the airframe, is only done at supersonic flight conditions, where benefits were predicted to be more pronounced. The stabilator is the primary pitch control surface; however, cowl rotation obviously produces significant lift, moment, and drag effects. As such, tradeoffs can be made between stabilator and cowl positions to optimize net aircraft performance. The airframe modeling consists of tabulated pitching moment and drag effects for the combined stabilator and cowl positions. No direct PSC stabilator trim capability exists; instead, the autopilot (or pilot) is relied on to change the stabilator position so that altitude is held constant.

Optimization Process

The PSC algorithm seeks to optimize the combined performance of the inlet, engine, and airframe. The PSC algorithm uses linear-programming techniques to find the optimal trims for the defined airframe–engine–inlet model and their related constraints. The linear-programming optimization is based on a linear steady-state model referred to as the propulsion system matrix (PSM). The linear-programming problem finds the optimum set of control deflections and output variables, subject to a specific set of constraints.

The PSC system has three primary modes of operation: minimum fuel flow at constant *FNP*, minimum *FTIT* at constant *FNP*, and maximum thrust at maximum dry and full afterburner throttle settings. The first two modes are designed primarily for cruise flight conditions while the last mode is primarily intended for use during accelerating flight conditions. The minimum fuel flow at constant *FNP* mode is designed to effectively reduce thrust-specific fuel consumption (*TSFC*); the minimum *FTIT* at constant *FNP* mode is designed to prolong engine life; and the maximum thrust mode is designed to increase thrust.

The propulsion system matrix (PSM) forms the basis of the linear-programming problem. Linear models from the CEM and CIM are integrated to form the PSM. The PSM control and output vectors, $\mathbf{u_p}$ and $\mathbf{y_p}$, and are defined to be:

$$\mathbf{u_p} = [WF\ WFAB\ PT2\ PT6\ CIVV\ RCVV\ COWL\ RAMP]^T \tag{9}$$

$$\mathbf{y_p} = [N1C2\ N2\ PT4\ WCFAN\ TT3\ FTIT\ SMF\ SMHPC\ AJ\ FNP\ SDR\ PCTC]^T \tag{10}$$

Each control and output variable has associated constraints used in the formulation of the linear-programming problem. The constraints are functions of engine hardware, empirical data, nonlinearity considerations, and the desired goal of the optimization.[13]

The PSC system benefits in general accrue from more accurate, real-time knowledge of various safety margins–that is, where the system currently is and where it can safely go. The PSC system takes advantage of this difference to maximize benefits.

Flight Test Program

The subsonic PSC flight test program was conducted at NASA Dryden during 1990–91 and covered 10 months. The supersonic program was flown in 1992 and covered two months. The flight test activity was a joint NASA, McDonnell Douglas, and Pratt &Whitney effort. The subsonic flight test series was in turn broken into three phases: initial algorithm validation, baseline algorithm evaluation, and evaluation of a very degraded engine. The supersonic test phase was similar to the subsonic phase except that no degraded engine evaluation was made. All flight testing to date has consisted of single-engine PSC operation. Simultaneous PSC operation of both engines was not possible because of limited computational capability, but PSC could be selected on either engine. Single-engine testing was satisfactory since most PSC benefits are on a per-engine basis. The single-engine operation was more advantageous for initial PSC flight evaluation be-cause the flight safety issues for a single-engine research effort are fewer than those for two engines. (The nontest engine was in a standard F-15 configuration and safe single-engine capability was always available.) The flexibility afforded by reduced safety concerns for single-engine test flight operation was a major benefit in the PSC algorithm troubleshooting, modification, and evaluation process. References 4 and 7 provided a more detailed breakdown of the subsonic flight test phase.

Flight Test Maneuvers

The PSC evaluation process collected flight data primarily from trimmed cruise flight (wings-level and constant speed and altitude) and from constant altitude accelerations.

Cruise flight

Stabilized cruise flight conditions were used to collect data for all three PSC modes. The maneuver consisted of stabilizing the aircraft at the desired Mach and altitude flight conditions with PSC disengaged. Altitude was normally controlled with the autopilot, although the pilot was capable of similar manual flightpath performance with heads-up display commands. In general, constant velocity flight conditions were maintained through pilot commanded throttle inputs to the nontest engine, but some tests were conducted by having the pilot not touch the throttles once the condition was stabilized. The first technique is similar to a wind-tunnel test in which conditions are maintained constant, and the second technique allows an independent assessment of performance effects by observing changes in acceleration (or deceleration).

Acceleration

Accelerating flight conditions were used to collect data for the maximum thrust and minimum *FTIT* modes. The maneuver nominally consisted of accelerating the aircraft from Mach 0.50 to 0.95 and from Mach 1.25 to 2.00 at constant altitude flight conditions. Neither engine was throttled by the pilot during accelerations. For subsonic testing with the nontest engine in idle, the acceleration progressed more slowly and as such the algorithm was nearer to a steady-state condition. Maximum dry power was used on the nontest engine at conditions where the acceleration progressed too slowly or the aircraft could not accelerate to Mach 0.95. All supersonic accelerations were conducted with both engines in maximum afterburner. Although acceleration times are drastically affected by the nontest engine throttle position, the primary results presented are for the thrust or temperature changes of the test engine; these are not affected by the nontest engine. Altitude was controlled either manually by the pilot or the autopilot.

System Flight Test Capabilities

The PSC system was designed with a high level of capability and flexibility to conduct parametric studies of the PSC algorithm. Most changes required to conduct desired parametric studies were invoked in real time through pilot entries on a cockpit keyboard. Some of the capabilities are as follows: (a) PSC system engaged or disengaged, (b) right- or left-engine select, (c) real-time or preflight estimation, (d) unbiased or biased measurement input, (e) PSC optimization with or without vanes (*CIVV*, *RCVV*), and (f) PSC optimization with or without inlet-stabilator.

Besides the real-time changes that the pilot could make, many other control law changes were possible between flights without a new control law release. Other more complex flight code changes could be made very efficiently. The overall system flexibility was a major attribute in the PSC flight test program.

Flight Test Results

The three PSC modes have undergone full-envelope flight testing. Flight testing was performed over a Mach range of 0.50–2.00 and over an altitude range of 15,000–50,000 ft. At subsonic flight conditions the optimization only included the propulsion system. At supersonic conditions, the full PSC algorithm also included airframe optimization as mentioned previously; however, supersonic tests were also conducted with only the propulsion system to quantify the integrated benefits. The results of the individual modes are presented separately. Only one example time history is presented; other time history cases can be found in Refs. 3 and 4.

Minimum Fuel Flow Mode

The minimum fuel flow mode is designed to reduce fuel flow while maintaining constant *FNP* (effectively reducing *TSFC*) during cruise flight conditions. Flight data were collected for a range of throttle conditions.

Figure 5 presents the results for a typical minimum fuel flow mode maneuver at a flight condition of Mach 0.88 and 45,000 ft altitude. Time histories are presented for performance parameters (*M*, *FTIT*, *FNP*, and *TSFC*) and control variables (*WF*, *CIVV*, *RCVV*, and *AJ*). The PSC algorithm was disengaged from 0 to approximately 120 sec. The steady-state value of *TSFC* with PSC disengaged was approximately 0.99. The PSC system was engaged from 120 sec through the end of the run. The steady-state *TSFC* with PSC engaged was approximately 0.97 yielding an approximate 2-percent improvement on fuel consumption. The fuel reduction (at constant thrust) was achieved by opening *RCVV* 2° to its limit (4°) and closing *AJ* 40 in^2 to its minimum nozzle area (388 in^2). The *CIVV* is on its limit throughout the run. The PSC algorithm held *FNP* to within ±2 percent of the initial value after PSC was engaged. This flight condition is near the optimal minimum *TSFC* condition for the baseline aircraft as determined by the manufacturer.

A summary of fuel-saving benefits resulting from PSC is presented in Fig. 6 for subsonic and supersonic conditions. The *TSFC* savings are in general small at subsonic conditions. The calculation of *TSFC* is especially sensitive to the parameters that define it (*TSFC* = *WF*/*FNP*) and the short run of data collected. At supersonic conditions, the *TSFC* reduction is large, which is due in large part to the optimization tradeoffs between the engine core and afterburner. At subsonic conditions, core fuel flow is reduced while at supersonic conditions, core thrust is increased so that afterburner fuel flow can be reduced. The afterburner is approximately one-third as efficient at converting fuel usage to thrust as the core is, and as such, large benefits are possible. A small additional *TSFC* reduction also results from net airframe drag reduction. In general, these *TSFC* reductions would be significant in reducing takeoff gross weight or increasing range when considering long-range cruise segments as might be encountered for a second-generation supersonic transport.

Minimum Fan Turbine Inlet Temperature Mode

The minimum *FTIT* mode is designed to increase engine life by decreasing *FTIT* while maintaining a constant *FNP* level during both cruise and accelerating flight conditions. Figure 7 presents a summary of *FTIT* reduction benefits resulting from PSC for subsonic and supersonic conditions. In general, the *FTIT* reductions at subsonic conditions are large (≈100 °F) at the higher altitudes and are significantly less at lower altitudes. At supersonic flight conditions the airframe drag reduction reduces thrust requirements thus reducing engine turbine temperatures. To put these temperature reductions in perspective—based only on temperature effects—every 70-°F reduction will double turbine life.[5] These benefits are very important, especially at high-power settings where the engine operates near its temperature limit.

Maximum Thrust Mode

The maximum thrust mode is designed to maximize *FNP* at maximum dry power and maximum afterburner throttle positions primarily during accelerating flight conditions. Figure 8 presents a summary of thrust increase benefits due to PSC for subsonic and supersonic conditions. As noted, benefits in the 10-percent range are available over the Mach range. The supersonic results are lower because only the efficiency of the engine core can be optimized (afterburner efficiency is approximately fixed), and at supersonic conditions with the afterburner on, the benefits from the core represent a smaller percentage of the total thrust. Thrust increases generally cause increases in *FTIT* (although *FTIT* cannot exceed its predetermined limit and can in turn limit thrust increases).

Dynamically, all three modes are stable with no oscillations present in the engine response parameters or control effectors. The PSC technology is generic and can be applied to any aircraft system; however, the benefits to be accrued are configuration dependent and are obviously limited by the “system potential” remaining.

Follow-on Optimization Concepts

The F-15 PSC program developed a technical approach and methodology that can enhance the performance of high-performance and transport aircraft. The F-15 PSC algorithm as currently implemented, however, requires accurate models that predict actual flight hardware performance operation. In addition, the adaptive estimation technique dependends on accurate measurements of the inputs and outputs of the system being optimized.[7] Because of the model-based open-loop approach used by the F-15 PSC, errors in modeling and measurements produce suboptimal results in the current algorithm. No intrinsic means in the F-15 PSC approach can compensate for problems in these areas.

The evolution of the F-15 PSC algorithm required continuous improvement of models, which was possible because of the 15+ years of experience with the F100 class of engines and accurate nonlinear simulation model of the engine. These accurate models enabled the F-15 PSC algorithm to perform well and to approach the true optimal solution. Another difficult problem arises from the biases that many measurements used in the algorithm have. The use of models is affected since the model-based approach requires accurate measurements. Frequently in control problems, perturbation feedback control techniques are used, and in these cases, biases on measurements do not affect results. The F-15 PSC approach, however, is neither perturbation based nor closed loop but relies on absolutes and open-loop commands. As such, biases can play an adverse role. The real-time identification of biases would be ideal but is not possible because of the limited sensor set available.[14] The solution used to get to flight was *a priori* identification of key biases from ground-based tests and their integration into the flight algorithm. This is far from ideal since each engine has a unique set of biases.

An approach to suitably accommodate the above problems applies adaptive optimal techniques that would not be affected by either problem. The adaptive optimal approach is based on the real-time determination of gradients of performance measures to control variables. These gradients are based on flight measurements and not based on predictions; and since gradients are used, the approach will not be sensitive to measurement biases.

The adaptive optimal approach is ideally suited for environments in which a high degree of uncertainty surrounds the model and measurement accuracy. This is particularly true for a program that is of limited duration or in its initial flight testing phase; the application of adaptive control concepts could be of great advantage for such cases where there is lack of knowledge about system characteristics. The F-15 PSC approach requires, as a minimum, an aircraft that has had sufficient flight testing to ensure model and measurement system accuracy.

Adaptive control, as applied to flight control, has not found wide acceptance with the aerospace community after initial application on the X-15, F-111, and F-8 aircraft. The lack of interest in adaptive control is mainly because the results from conventional design techniques are satisfactory, and insufficient reason exists to obtain similar results using a more complex technique. Most of the required information about the aircraft over its entire envelope is already available, and little uncertainty is involved in the modeling process. The application of adaptive control is particularly advantageous when a change in the environment results in insufficient knowledge about the system behavior in its range of operation.

Unlike the performance problem, application of adaptive optimal control to the flight control problem normally centers on optimizing very subjective criteria typically involving handling qualities. As such, the application of adaptive control to the flight control problem does not take full advantage of the attributes of the methodology. The application of adaptive optimal control to the performance problem, however, has clear benefits that are not achievable with any other control design process. The performance problem (thrust–drag) has well-defined objectives, and adaptive optimal control is well-suited to the problem. In addition, the application of adaptive optimal control is insensitive to both modeling inaccuracies and measurement biases because the critical optimization parameters are measurable. In many flight control applications, the use of adaptive techniques leads to safety concerns relative to gain and phase margin reductions. Although safety is also a concern for performance optimization, safety issues are much less a problem because of the low bandwidth of the problem. Reference 15 discusses the potential for current generation propulsion system performance benefits using adaptive control.

Aircraft Configuration Requirements

Since the F-15 PSC concentrated on optimization of the propulsion system and treated the airframe (stabilator) integration aspects only superficially, initial AdAPT concepts are primarily exploring optimization of airframe controllers. The first requirement to demonstrate airframe optimization, however, is that there are more controllers than controlled variables. Considering only the longitudinal equations, the elevator (stabilator or elevons) controls the pitching moment and fuel flow controls forward velocity; this is a minimum set for most configurations and leaves no excess capability for optimization. The F-15 has a movable cowl that is scheduled as a function of flight condition to provide some degree of *a priori* optimization. As such, this configuration has one excess surface that enables the optimization of the set of longitudinal controllers. The F-15 S/MTD, which is being viewed as a potential candidate aircraft for this research, has movable canards and vectoring nozzles and would further increase the options for optimization of the aircraft.

AdAPT Algorithm

The proposed F-15 S/MTD-based, AdAPT control system architecture (Fig. 9) consists of system excitation, estimation of performance sensitivity to controller excitation, and optimal control command. Ideally, the required performance sensitivity parameter identification could be performed using the baseline system operation. With tight pitch-rate, pitch-attitude, and altitude-hold control laws, however, external-environment-based disturbances and associated responses would be very small. As such, forced excitation is designed into the algorithm to ensure identifiability. Parameter identification of the performance–control coefficient could be done by several techniques covering a broad range of sophistication. System optimization is a direct fallout of the parameter identification, but because of performance system nonlinearities, the optimal solution cannot be calculated directly but must be converged to instead. Figure 10 shows an example of how the optimization search process would work for the cowl and stabilator drag minimization problem. Optimization using the proposed approach with one extra controller is straightforward; the complexity of the problem increases rapidly with additional extra surfaces.

Feasibility Flight Evaluation

Because of the challenging nature of the measured performance optimization approach, a “quick look” flight assessment of the identifiability of performance–control coefficients was performed on the NASA F-15 HIDEC aircraft. As stated previously, the F-15 aircraft has one excess controller (the cowl angle), which enabled simple parametric optimization evaluation. The evaluation maneuver consisted of straight and level flight at a constant forward velocity. In this configuration the aircraft has a trimmed stabilator deflection and a scheduled cowl deflection. The cowl is then biased down causing both inlet performance (and thrust) changes and pitching moment effects. The pilot or autopilot counter balances the cowl pitching moment effects by finding a new stabilator trim position which in turn causes some aircraft drag change. The sum of the thrust and drag changes causes a net performance change that produces either an accelerating or decelerating flight condition that is directly measurable. The test is repeated by biasing the cowl up to complete the performance sensitivity evaluation.

Figure 11 presents the results of performing this test at Mach 1.25 and 24,000 ft altitude in time history format. The time histories clearly show the control surface changes and the resulting change in Mach number (i.e., acceleration). The analysis results of Fig. 11 are presented in Fig. 12. The summary data yield the performance–control sensitivity coefficient that would be used in an optimization algorithm. Even with this simple test, a drag reduction of at least 800 lb was identified for the case of Fig. 11 with the cowl biased down. Reference 16 presents a detailed analysis of this performance sensitivity evaluation.

Concluding Remarks

A flight test evaluation of the F-15 performance-seeking control (PSC) algorithm has been conducted for single-engine operation at subsonic and supersonic speeds. The F-15 PSC system was designed with a high level of capability and flexibility to conduct parametric studies of the algorithm. The overall system flexibility was a major attribute in the F-15 PSC flight test program.

Flight results show substantial benefits from the F-15 PSC algorithm. In the maximum thrust mode, increases in thrust of up to 15 percent at subsonic and 10 percent at supersonic flight conditions were identified. The minimum fan turbine inlet temperature mode caused temperature reductions exceeding 100 °F at high altitudes. The minimum fuel flow mode decreased fuel consumption up to 2 percent in the subsonic regime and almost 10 percent supersonically. This single-engine flight evaluation has provided a validation of the PSC technology objectives. Based on flight test results, PSC technology can clearly benefit the next generation of fighter and transport aircraft.

The proposed adaptive aircraft performance technology approach further builds on the F-15 PSC results described and addresses many practical application issues identified with the algorithm approach selected for the F-15 PSC. A feasibility flight evaluation of this measurement-based optimization concept has been successfully conducted and showed significant benefits over the model-based F-15 PSC algorithm.

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Fig. 1. The F-15 HIDEC aircraft.

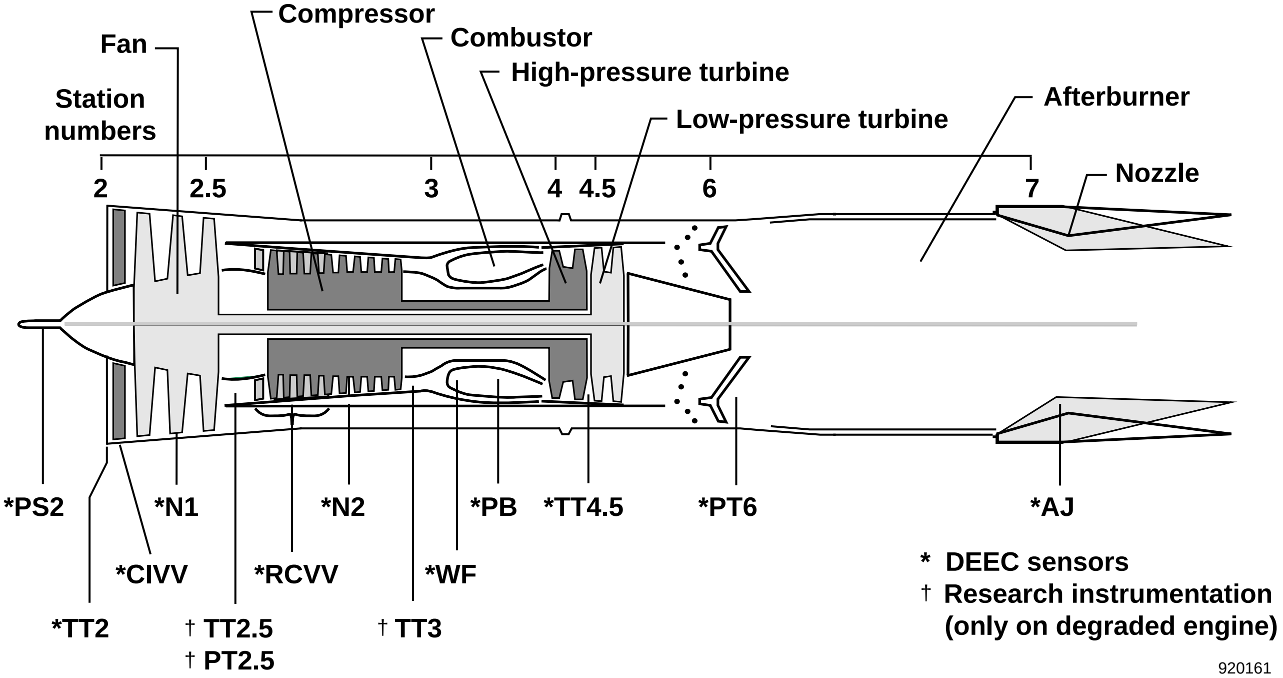

Fig. 2. The PW1128 engine, sensor, and parameter locations.

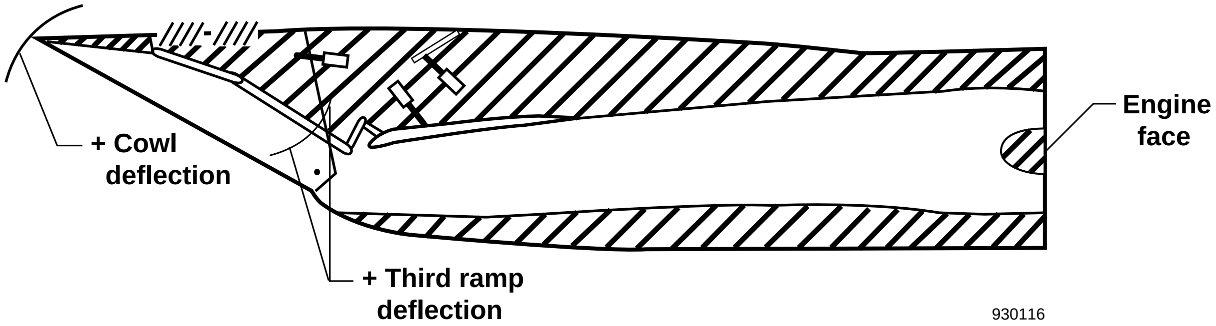

Fig. 3. The F-15 variable inlet geometry and layout.

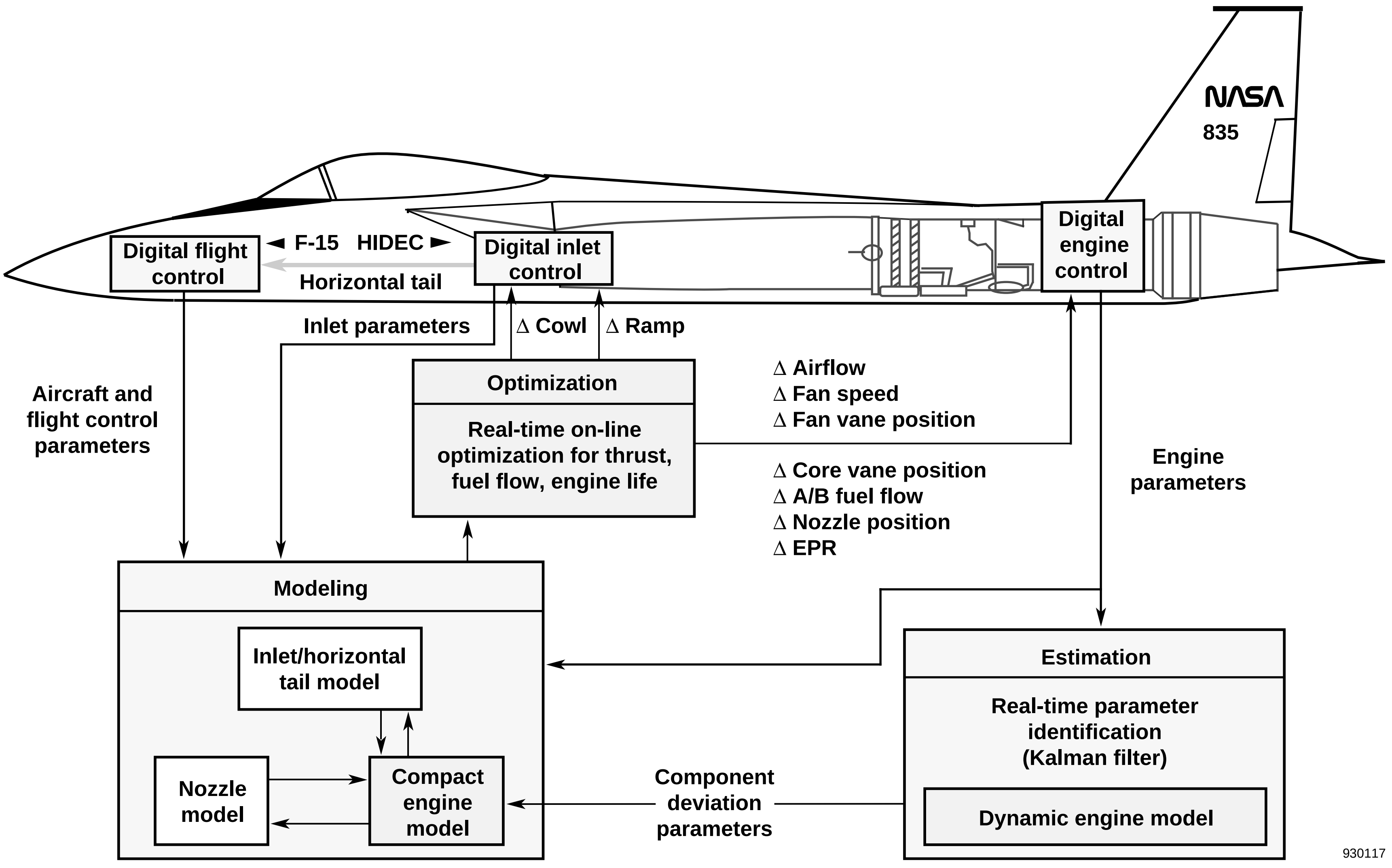

Fig. 4. Performance seeking control.

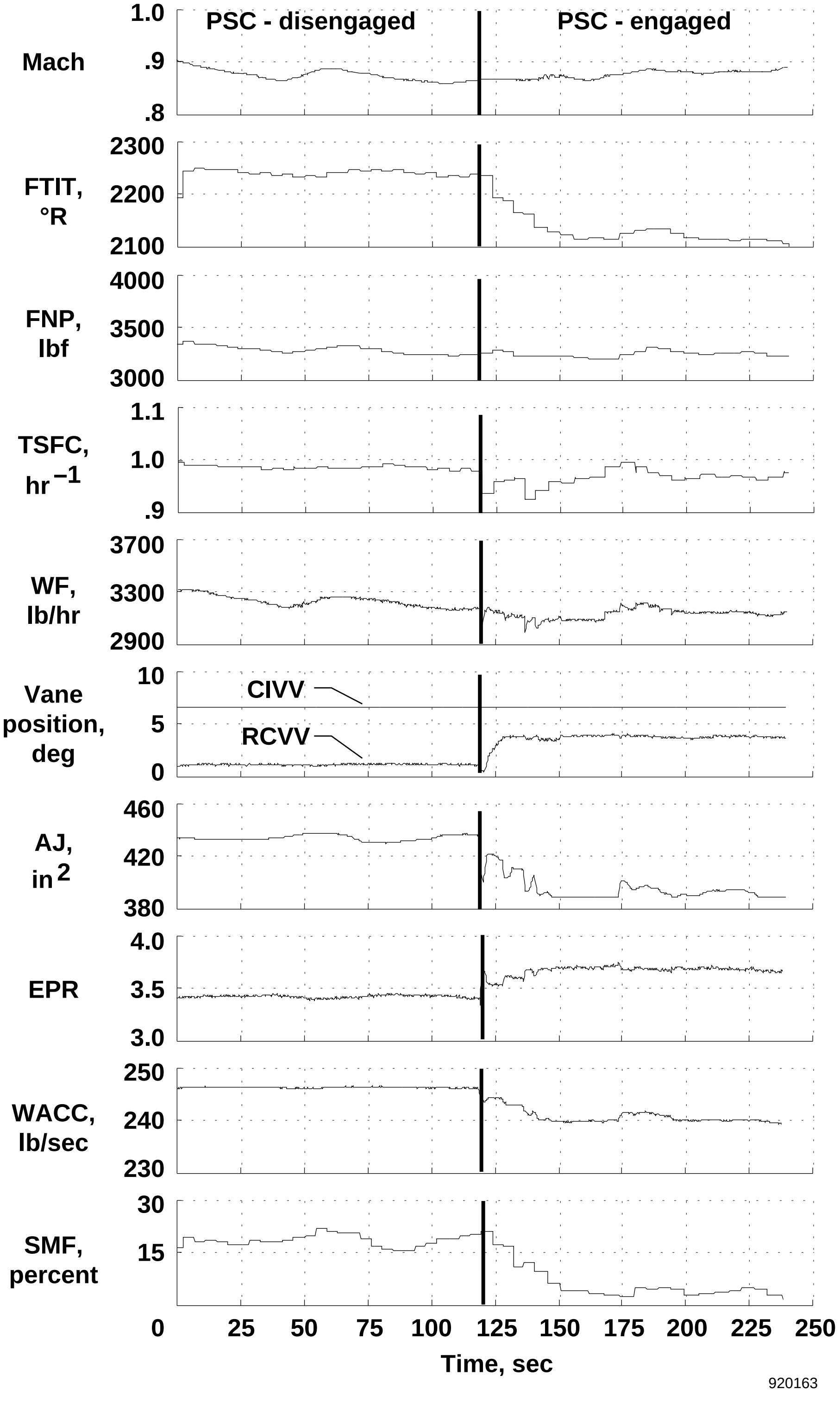

Fig. 5. Typical engine parameter time histories for minimum fuel flow mode evaluation (45,000 ft, degraded engine, military power).

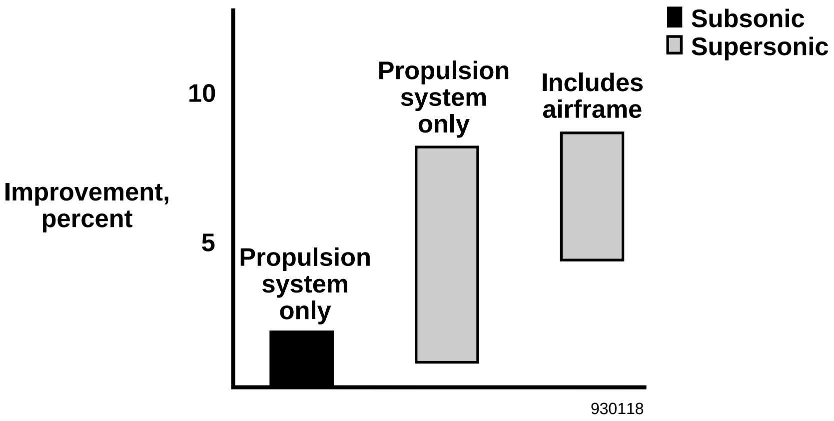

Fig. 6. Summary of subsonic and supersonic PSC flight test results for the minimum fuel mode (for flight conditions of Mach 0.5–2.0 and altitude 5,000–50,000.

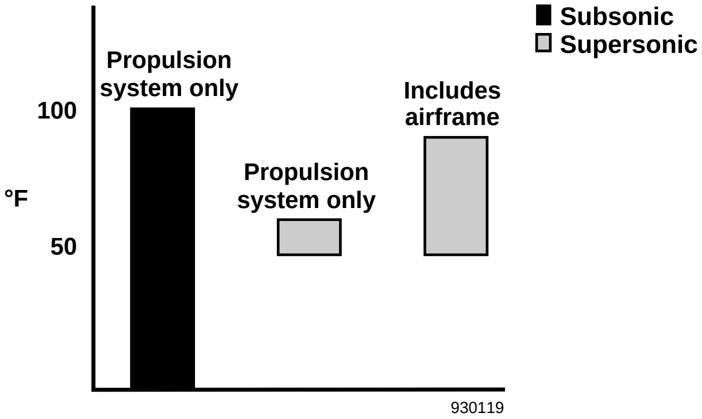

Fig. 7. Summary of subsonic and supersonic PSC flight test results for the minimum FTIT mode (for flight conditions of Mach 0.5–2.0 and altitude 15,000–50,000 ft.

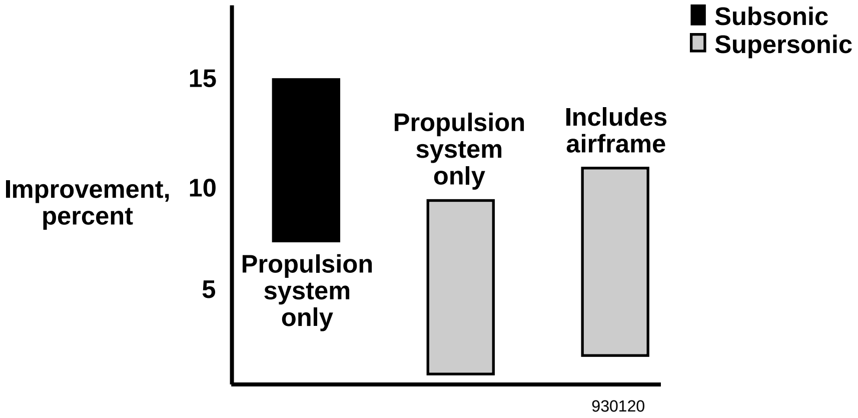

Fig. 8. Summary of subsonic and supersonic PSC flight test results for the maximum thrust mode (for flight conditions of Mach 0.5–2.0 and altitude 5,000–50,000 ft.

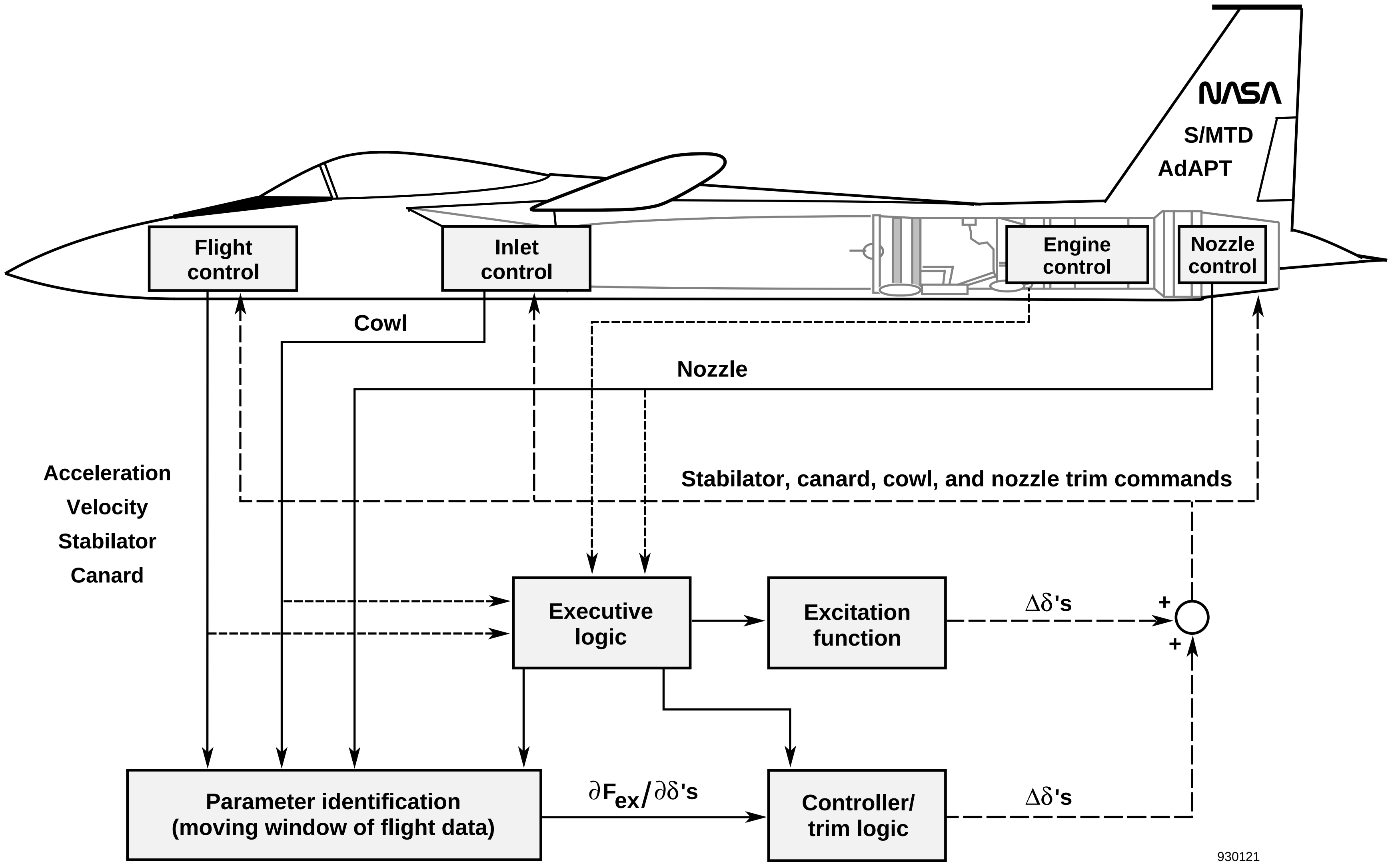

Fig. 9. Adaptive aircraft performance technology (AdAPT) concept.

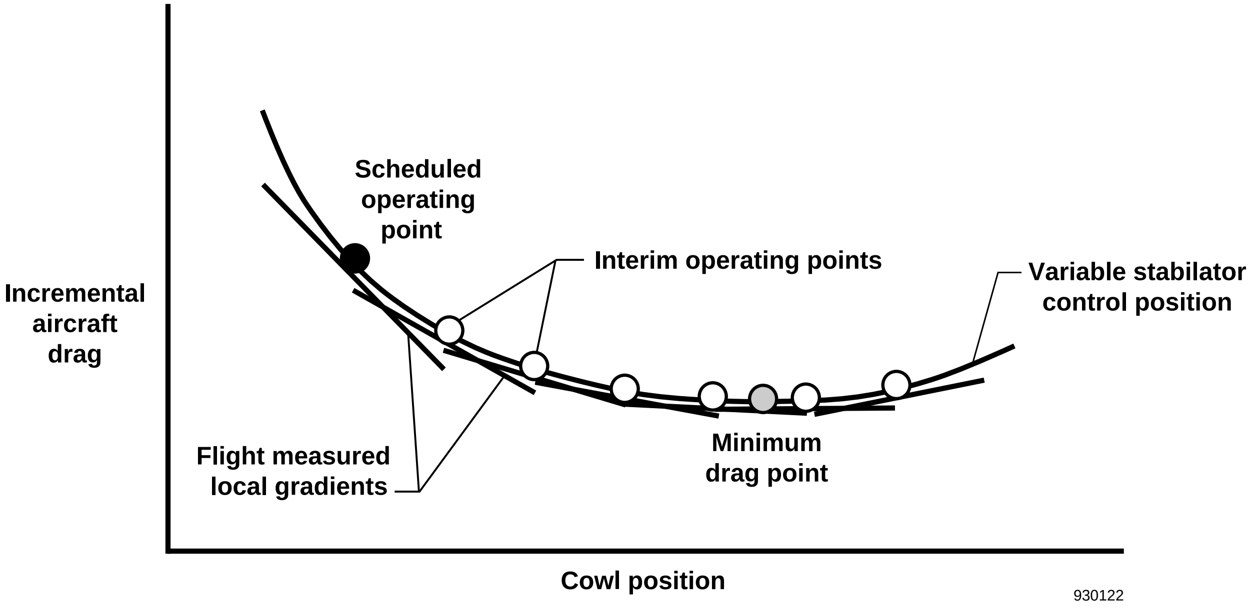

Fig. 10. Adaptive drag minimization search example.

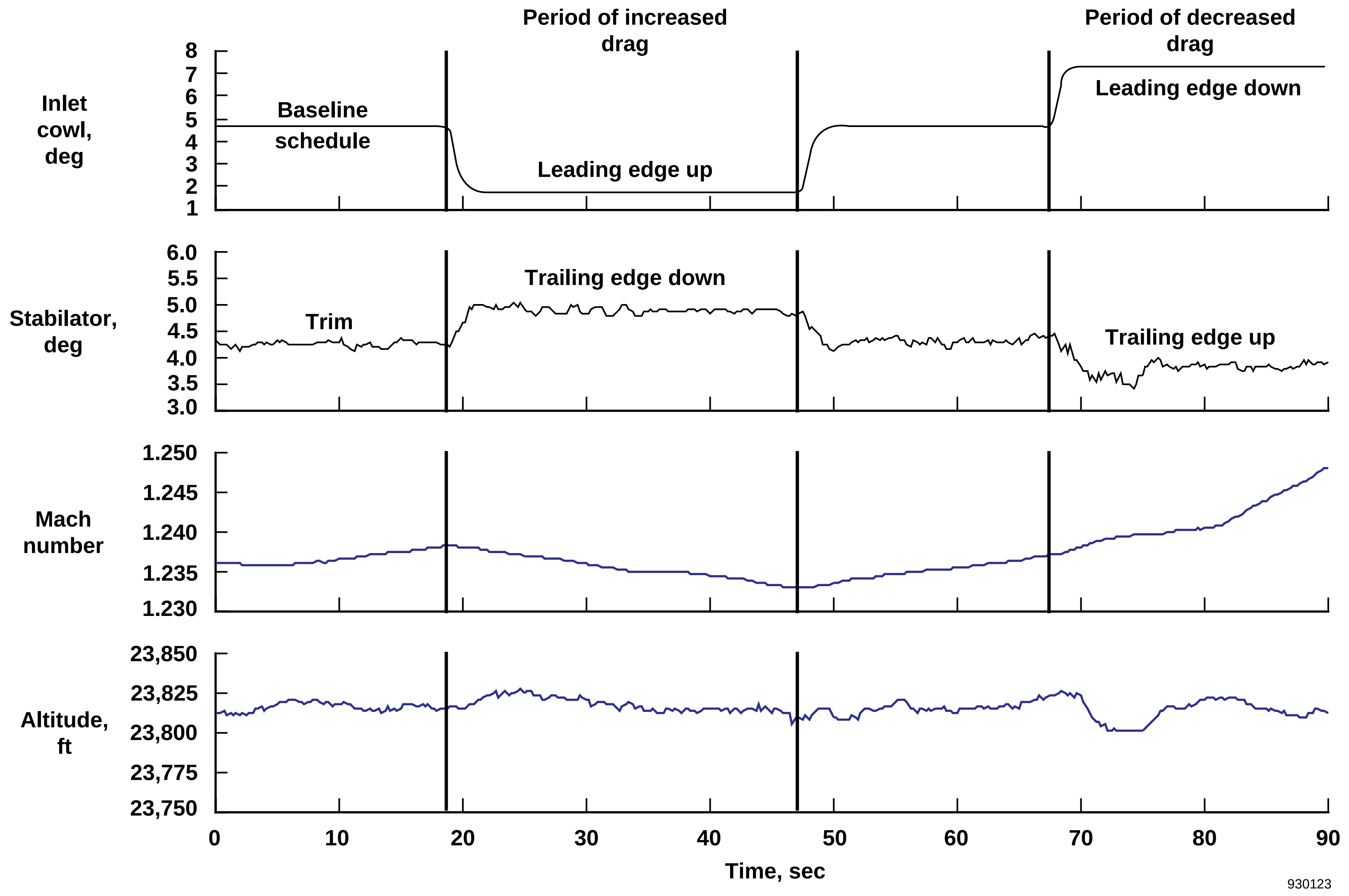

Fig. 11. Cowl-perturbation time histories from measurement-based performance optimization feasibility study; 1.25 Mach, 25,000 ft.

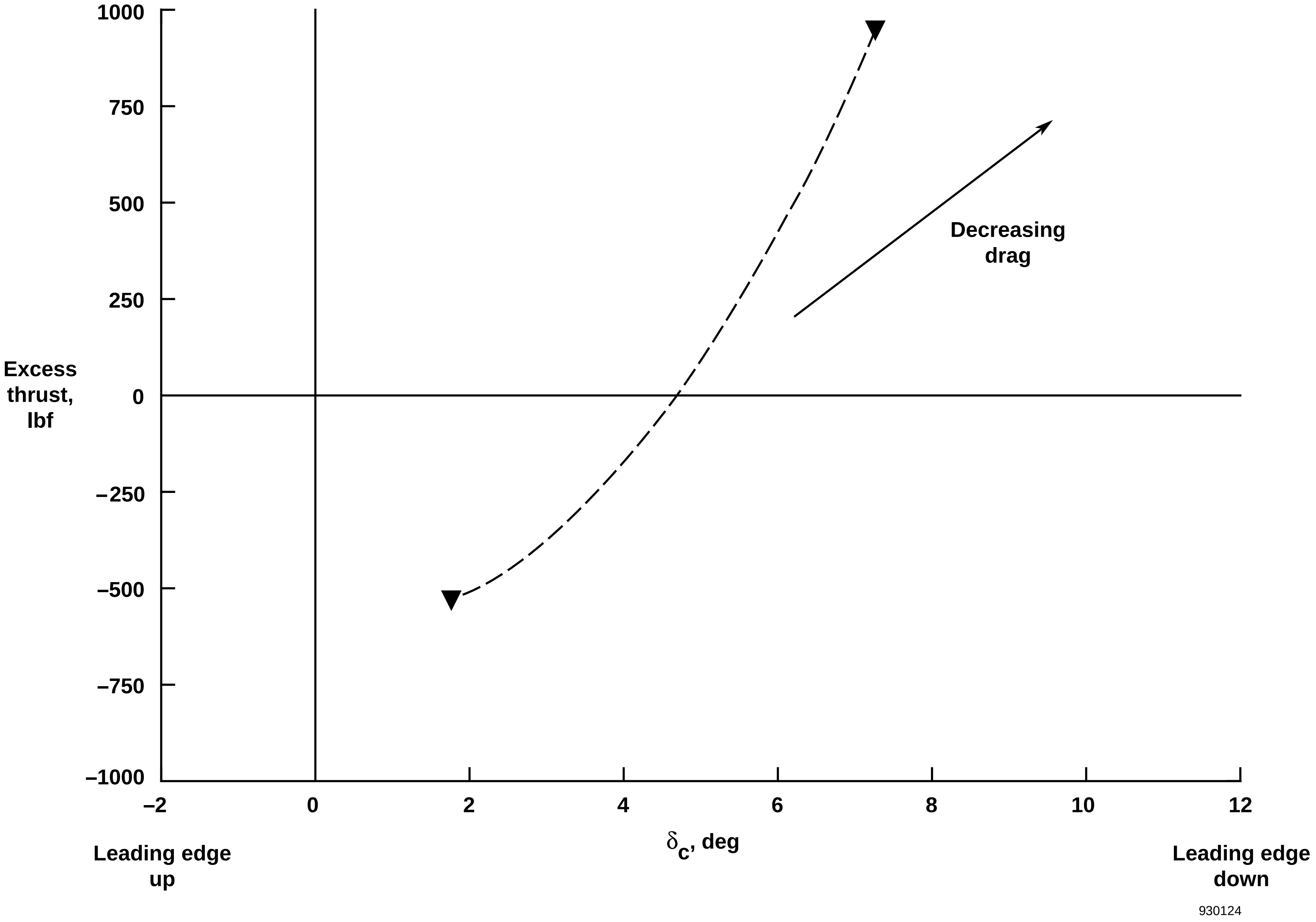

Fig. 12. Summary of cowl perturbation from measurement-based performance optimization feasibility study.

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A flight test evaluation of the performance-seeking control (PSC) algorithm on the NASA F-15 highly integrated digital electronic control research aircraft was conducted for single-engine operation at subsonic and supersonic speeds. The model-based PSC system was developed with three optimization modes: minimum fuel flow at constant thrust, minimum turbine temperature at constant thrust, and maximum thrust at maximum dry and full afterburner throttle settings. Subsonic and supersonic flight testing were conducted at the NASA Dryden Flight Research Facility covering the three PSC optimization modes and over the full throttle range. Flight results show substantial benefits. In the maximum thrust mode, thrust increased up to 15 percent at subsonic and 10 percent at supersonic flight conditions. The minimum fan turbine inlet temperature mode reduced temperatures by more than 100 °F at high altitudes. The minimum fuel flow mode results decreased fuel consumption up to 2 percent in the subsonic regime and almost 10 percent supersonically. These results demonstrate that PSC technology can benefit the next generation of fighter or transport aircraft. NASA Dryden is developing an adaptive aircraft performance technology system that is measurement based and uses feedback to ensure optimality. This program will address the technical weaknesses identified in the PSC program and will increase performance gains.

14. SUBJECT TERMS
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