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Optimizing Aircraft Performance with Adaptive, Integrated Flight/Propulsion Control

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ABSTRACT

An adaptive, integrated flight/propulsion control algorithm called Performance Seeking Control (PSC) has been developed to optimize total aircraft performance during steady state engine operation. The multi-mode algorithm will minimize fuel consumption at cruise conditions; maximize excess thrust (thrust minus drag) during aircraft accelerations, climbs, and dashes; and extend engine life by reducing Fan Turbine Inlet Temperature (FTIT) when the extended life mode is engaged. On-board models of the inlet, engine, and nozzle are optimized to compute a set of control trims, which are then applied as increments to the nominal engine and inlet control schedules. The on-board engine model is continually updated to match the operating characteristics of the actual engine cycle through the use of a Kalman filter, which accounts for anomalous engine operation. The PSC algorithm will be flight demonstrated on an F-15 test aircraft under the direction of the NASA Ames/Dryden Flight Research Facility. This paper discusses the PSC design strategy, describes the control algorithm, and presents results from high fidelity, nonlinear aircraft/engine simulations. Simulation results indicate that thrust increases as high as 15% and specific fuel consumption reductions up to 3% are realizable by the PSC system.

NOMENCLATURE

AJ	Nozzle Throat Area
CEM	Compact Engine Model
CIVV	Compressor Inlet Variable Vanes
DEEC	Digital Electronic Engine Control
DEFCS	Digital Electronic Flight Control System
DFCC	Digital Flight Control Computer
EAIC	Electronic Air Inlet Controller
EPR	Engine Pressure Ratio (PT6 / PT2)
FNP	Net Propulsive Force
FTIT	Fan Turbine Inlet Temperature
HIDEC	Highly Integrated Digital Electronic Control
LP	Linear Programming
MCAIR	McDonnell Aircraft Company
NASA	National Aeronautics and Space Administration
N1C2	Corrected Fan Speed
PASCOT	Programmable Asynchronous Serial CommunicationTranslator
PLA	Power Lever Angle
PSC	Performance Seeking Control
PB	Burner Pressure
PPH	Pounds Mass per Hour
PT#	Total Pressure at Engine Station #
P&W	Pratt and Whitney
RCVV	Rear Compressor Variable Vanes
SDF	Six Degree-of-Freedom
SFC	Specific Fuel Consumption
SSVM	Steady State Variable Model
TT#	Total Temperature at Engine Station #
$\mathbf{u}$	Control Vector
WF	Combustor Fuel Flow
WFAB	Augmentor Fuel Flow
W2C	Corrected Fan Airflow
$\mathbf{x}$	State Vector
$\mathbf{y}$	Output Vector
α	Angle of Attack
β	Angle of Sideslip

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I. INTRODUCTION

Traditionally, aircraft flight and inlet control systems are designed to operate independently of the engine control system. This design philosophy often produces a system where performance is compromised to ensure operability. For example, engine operating point and variable vane positions are scheduled to produce high engine performance, while maintaining adequate fan stall margin to accommodate the most severe aircraft maneuvers. Therefore, when an aircraft is at moderate angles of attack, there is excess engine stability margin, which can usually be traded for increased thrust or extended engine life.

Another problem with conventional aircraft and engine control is the difficulty in designing trim schedules to account for the wide range of operating conditions experienced by modern tactical aircraft. Trim settings are typically generated by optimizing the best available system model for a number of steady state points spanning the design operating envelope and then storing the results in tabular form in aircraft and engine control computers. Control system parameters which might be stored as trim values include canard and wing flap deflections for flight control, ramp and bypass door positions for inlet control, and internal pressures and rotor speeds for engine control. Sensed variables, such as Mach number, temperatures, and pressures, are used to schedule these stored trim values in flight. These schedules must often be modified after initial flight tests, when better data becomes available. Even then, aircraft-to-aircraft aerodynamic variations, variable aircraft store loadings, engine-to-engine component variations, engine deterioration, changing levels of engine bleed and horsepower extraction requirements, and non-standard atmospheric conditions are seldom explicitly taken into account. Such system variations will limit the performance of schedules which do not adapt to off-nominal operating characteristics.

The emergence of digital flight, inlet, and engine controllers, as well as multiplex data buses for communicating between them, has provided the means for mechanizing integrated control solutions to the above problems. Further, advances in control technology, estimation techniques, and system modeling have provided better analytical tools with which to design multivariable control laws. Because of this opportunity, a number of studies have been conducted to design integrated flight/propulsion control algorithms which improve overall aircraft performance.

Under the Air Force's Design Methods for Integrated Control Systems (DMICS) program, two multidisciplinary teams developed methodologies for designing integrated control laws for advanced tactical fighters (Joshi et al., 1983), (Clifton et al., 1983). The targeted aircraft had a high degree of airframe/engine coupling, brought about by such features as thrust vectoring and propulsive lift. The emphasis of the DMICS program was improving aircraft dynamic response with inner-loop integration, and both design teams demonstrated multivariable control laws through high-fidelity simulations. Another Air Force program, Performance Seeking Control (PSC), produced an adaptive trim control algorithm that minimizes fuel consumption during cruise, even when the aircraft and engine are operating in an off-nominal fashion (Tich et. al., 1987). The work done under these Air Force programs, combined with the pioneering work under the NASA HIDEC program, led to the initiation of the NASA Performance Seeking Control program, which is the subject of this paper.

Under the NASA Highly Integrated Digital Electronic Control (HIDEC) program, four integrated flight/propulsion control modes were developed and flight demonstrated on an F-15. One, Trajectory Guidance, generates flight trajectories for minimizing mission fuel usage or time to reach a specified end point. The other three modes improve aircraft operation through sophisticated scheduling techniques, which integrate information from the engine and airframe. HIDEC test results proved that substantial gains in excess thrust (thrust minus drag), for increased performance, or reductions in Fan Turbine Inlet Temperature (FTIT), for extended engine life, can be realized through integrated trim schedules (Yonke et al., 1987). It is anticipated that additional benefits can be realized by replacing the HIDEC schedules, which are based on a nominal engine, with a model-based trim control algorithm, that adapts to engine variations.

The goal of the Performance Seeking Control program, sponsored by the NASA Ames/Dryden Flight Research Facility, is to develop such an adaptive, integrated flight/propulsion control algorithm and to flight demonstrate the concept on a NASA F-15 aircraft in 1990. McDonnell Aircraft Company (MCAIR) is the prime contractor for the PSC program, with Pratt & Whitney (P&W) as principal subcontractor.

The multi-mode PSC algorithm, which is currently in the final stage of development, minimizes fuel consumption during aircraft cruise; maximizes excess thrust (thrust minus drag) during accelerations, climbs, and dashes; and extends engine life by reducing FTIT when the extended life mode is engaged. On-board models of the inlet, engine, and nozzle are optimized to compute a set of control trims, which are then applied as increments to the nominal engine and inlet control schedules. The adaptive feature of PSC is provided through a Kalman filter, which estimates engine component deviations to account for off-nominal engine performance. The component deviation estimates are used to match the on-board engine model to the operating characteristics of the actual engine cycle. This process provides the on-line trim optimization with an accurate representation of that particular propulsion system over the entire life of the engine.

II. CONTROL INTEGRATION STRATEGY

Before describing the PSC algorithm, it is useful to put it in proper perspective by discussing its relationship to other problems which can be addressed within the context of integrated flight/propulsion control. A good place to begin is with an examination of a conventionally designed, minimally integrated aircraft/engine control structure. Figure 1 depicts an example of such a system, the original (pre-HIDEC) NASA F-15 aircraft, equipped with PW1128 engines.

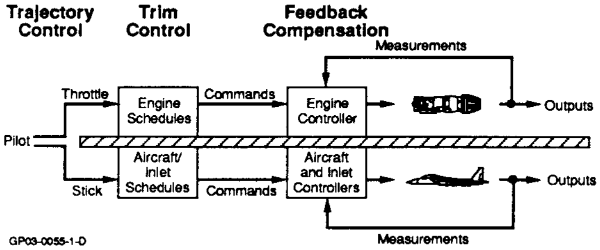

Figure 1. Original F-15/PW1128 Control Structure

The figure shows the aircraft/engine control structure divided into three areas: 1) trajectory control, 2) trim control, and 3) feedback compensation. This division of control structure by tasks is described by Clifton et al. (1983), and is borrowed here for its usefulness in characterizing integrated control problems.

As shown in Figure 1, the only integration of aircraft/engine controls in the original F-15/PW1128 was carried out by the pilot as he tried to optimize throttle and stick commands for a given mission. Trim control and feedback compensation were carried out by separate flight, inlet, and engine controllers without the benefit of shared information. Of course, the designers of the inlet control laws were aware of the nominal airflow demands of the PW1128, and designed the F-15 variable inlet geometry schedules accordingly. Likewise, designers of the DEEC control for the PW1128 had knowledge of the pressure distortion levels likely to be encountered behind the F-15 inlet and produced engine control laws with sufficient stability margin to accommodate these levels and still yield high performance. Because these subsystems were not designed to communicate in flight, however, performance compromises were unavoidable.

Clifton et al. (1983) point out that improved aircraft performance can be achieved by integrating flight/propulsion controls in either or all of the forementioned areas: trajectory control, trim control, or inner-loop feedback/feedforward compensation. Because both the goals and control design techniques are different for each of the three , a brief discussion of these areas is useful.

Trajectory control is the generation of flight profiles that achieve a desired design goal. The benefits are improved mission performance and reduced pilot workload. Typical design goals are: minimizing mission fuel usage, minimizing the time to reach a specified end point, and minimizing the fuel expenditure to reach a specified end point at a specific time. By nature, trajectory optimization is open loop and relies on ground-based or on-board model predictions. If the Mach numbers, altitudes, and power settings commanded by the pilot or trajectory-generating algorithm do not produce the desired results, there is no way (short of re-flying the mission) to correct the problem. For this reason, accurate system models are essential for the success of trajectory control.

The second area suitable for control integration, trim control, is the determination of the best set point about which to regulate the system. Once the pilot or trajectory control algorithm has determined a flight condition and power setting, the steady-state trim control sets the engine operating point and nominal aircraft/inlet control surface deflections. Typical design goals are: minimizing fuel flow for a given cruise condition, minimizing engine turbine temperature at constant thrust, or maximizing excess thrust (thrust minus drag) during an aircraft acceleration.

The final area where controls can be integrated is within the inner-loop feedback/feedforward compensation. Inner-loop compensation is the modification of system dynamics to improve response characteristics. Both the goals and design techniques used in this area of work are those most commonly associated with controls engineering. Typical goals include: minimizing response time while maintaining adequate damping, minimizing tracking error with minimum control effort, and providing disturbance rejection and insensitivity to plant variations. The Air Force DMICS program emphasized inner-loop integration, and Clifton et al. (1983) and Joshi et al. (1983) describe design approaches for carrying out this task.

Of the three areas where aircraft and engine controls can be integrated, trim optimization offers the greatest payoff potential. The reason is that the propulsion system operates the great majority of time at trimmed conditions. For a typical air superiority mission, nearly 85% of flight time and 45% of fuel is spent during cruise segments (Clifton et al., 1982). Adding the time spent during climbs, accelerations, and dashes (where the power setting is usually constant), it is found that over 95% of the air superiority mission is carried out with the propulsion system operating near steady-state. To demonstrate the benefits of integrated aircraft/engine trim optimization, NASA initiated the HIDEC program.

Under the NASA HIDEC program, the contracting team of MCAIR and P&W developed and flight demonstrated three integrated flight/propulsion trim control modes for the F-15/PW1128. The modes are: 1) Adaptive Engine Control System (ADECS), 2) Extended Engine Life (EEL), and 3) Inlet Integration. In the ADECS mode, excess fan stall margin is traded for additional engine thrust. Yonke et al. (1987) report that FNP increases from 2 to 12 percent are achieved through this technique at subsonic flight conditions. In the EEL mode, instead of increasing thrust, turbine operating temperatures are decreased while maintaining constant thrust, thereby reducing wear on the engine. Recent flight evaluations of this mode have demonstrated FTIT reductions as high as 100 °F. The inlet integration mode (Chisholm et al., 1989) realizes increased aircraft performance by controlling inlet ramp positions based on a DEEC calculation of engine airflow. Increases in excess thrust (thrust minus drag) as high as 12% over the nominal F-15/PW1128 have been achieved in flight.

The NASA F-15/PW1128 control structure modifications made under the HIDEC program are depicted in Figure 2. The three trim control modes described above use the same basic approach, predefined schedules which integrate information between subsystems. The schedules are implemented as increments to the nominal control trim settings so that the aircraft can be flown with or without HIDEC engaged. The trim settings are calculated off-line using the best aircraft/engine simulations and databases available to the control law designer. Although these schedules are optimum for a nominal aircraft/engine, they do not adapt to off-nominal operating characteristics such as engine deterioration and nonstandard atmospheric conditions.

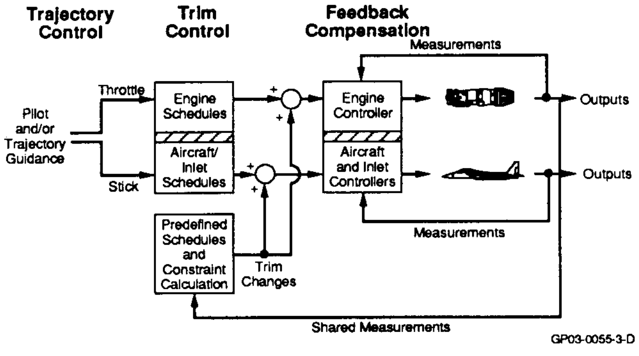

Figure 2. HIDEC Control Structure

Two approaches are available for designing trim control laws which do adapt to off-nominal conditions: 1) direct plant perturbation search and 2) adaptive model-based optimization. In the first of these, the control effectors are perturbed, and their impact on the objective function (fuel flow for instance) is measured. The controls are then moved in the direction of improved performance, and the process is repeated. Unfortunately, performance is usually lost during the perturbation process; actuator life is shortened; system stability may be decreased; the objective function gradient is difficult to accurately measure, and the perturbation process may disturb the pilot. Because the second technique, indirect model-based optimization, does not have these disadvantages, it is preferred over direct plant perturbation.

NASA initiated the PSC program in 1988 to demonstrate the benefits of adaptive, model-based, aircraft/engine trim optimization. In addition to accounting for off-nominal conditions, model-based optimization is also more versatile than trim schedules. Multiple modes such as minimum fuel consumption, maximum excess thrust, or extended engine life, can be implemented by simply changing the objective function in the on-board optimization routine. With trim scheduling, each mode requires that a new set of schedules be generated and stored on-board.

Under PSC, the HIDEC trim schedules, depicted in Figure 2, are replaced with adaptive models, constraint calculation, and on-line optimization. Because the PSC on-board models must run within the limitations of flight-worthy computers, they are much simpler than the off-line simulations used to generate the HIDEC trim schedules. The PSC approach has the advantage, however, of being able to tune these models in flight, to match the actual system operating condition.

The challenge of the PSC design problem is to create on-board models that provide a better representation of system performance over the life of a particular engine than the best ground-based nominal models. With this accomplished, performance improvements beyond those available through the HIDEC approach will be realized.

III. ALGORITHM DESCRIPTION

Under the direction of NASA, the MCAIR/P&W team has developed a PSC system for optimizing aircraft steady state performance under four different modes: 1) minimum SFC at constant thrust, 2) maximum excess thrust, 3) minimum FTIT at constant thrust (extended life), and 4) maximum excess thrust at constant FTIT. This section contains an overview of the PSC system design and provides descriptions of the system models, the integration of these models, and the optimization procedure.

OVERVIEW

A diagram of the PSC system architecture is shown in Figure 3. The primary components in the system architecture are the Digital Electronic Engine Controls (DEECs), Electronic Air Inlet Controllers (EAICs), Digital Flight Control Computer (DFCC), and Rolm Hawk computer. In addition, the Inertial Navigation System, Air Data Computer, and flight control sensors supply information used by the PSC algorithm. These components are linked together by data buses which allow information exchange between the various subsystems. Communication with the DEECs is via serial data link. The PASCOT interface unit translates DEEC inputs and outputs between the serial link and the H009 bus. The H009 and 1553 data buses exchange information through the Central Computer.

The majority of the PSC logic resides in the Hawk computer. The compact propulsion system models, engine model update logic, optimization routine, and supervisory logic modules comprising the PSC control law are all contained in the Hawk. The PSC logic uses information from the other flight/propulsion control subsystems to calculate optimum trim commands, which are then applied to the EAIC and DEEC. The PSC trim commands sent to the DEEC adjust the engine operating point, the variable stator vane positions, and the afterburner operation. The trim commands sent to the EAIC adjust the cowl and third ramp positions on the variable geometry F-15 inlet.

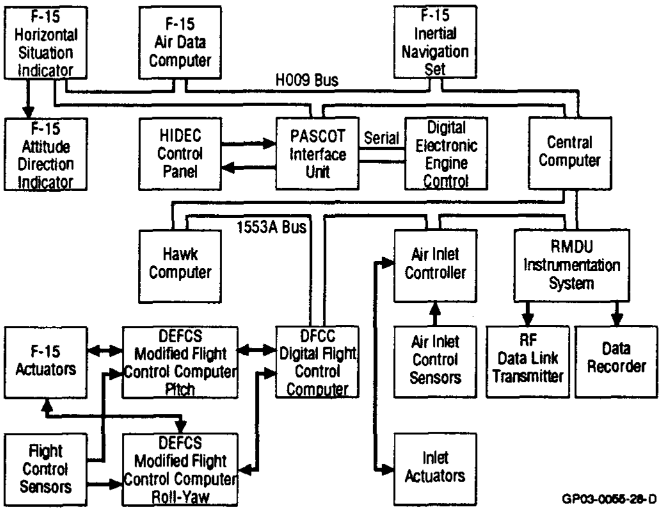

Figure 3. Performance Seeking Control Architecture

An important part of the PSC logic that is not contained in the Hawk is the alpha/beta predictor. This logic, which resides in the DFCC, sends predicted angle-of-attack, $\hat{\alpha}$, and sideslip angle, $\hat{\beta}$, to the Hawk computer, where it is used in the maneuver accommodation logic to maintain engine stability during aircraft maneuvers. The DFCC predicts α and β 0.5 seconds in the future, based on air data measurements and inertial angular body rates. As the F-15 maneuvers, the pressure distortion at the engine fan face increases, resulting in decreased stall margin. Although the PSC optimization logic constrains stall margin in the trimmed state, aircraft transient maneuvers can be executed significantly faster than the PSC trim optimization time. To prevent engine stall from occurring during rapid aircraft maneuvers, the PSC maneuver accommodation logic monitors $\hat{\alpha}$, $\hat{\beta}$, and the engine operating point. If a fan stall situation is predicted, this logic rapidly reduces Engine Pressure Ratio (EPR) to regain adequate stall margin. This same approach was successfully demonstrated in the HIDEC program.

A flow diagram of the PSC logic within the Hawk computer is shown in Figure 4. The split between the foreground and background tasks is indicated. The foreground tasks are carried out every 50 msec, while the background tasks are computed as time permits. Initial timing estimates predict that the Hawk background will compute optimum propulsion system trims every six seconds. Simulation results show that this trim rate is adequate to optimize aircraft performance during cruise segments, accelerations, and climbs.

The supervisory logic, which runs in the Hawk foreground, performs three main tasks: maneuver accommodation, velocity hold, and engine transient detection. The maneuver accommodation logic, which is described above, protects against engine stalls during aircraft maneuvers generating significant inlet distortion. The velocity hold logic is a flight test option which can be selected during the minimum SFC or minimum FTIT (extended life) modes of operation. During these modes, the PSC trims are calculated to hold thrust constant. If, however, model inaccuracies result in minor thrust changes, the velocity hold logic will issue autothrottle commands to compensate. The purpose of the transient detection logic is to momentarily suspend the operation of the PSC algorithm if a significant engine transient is detected. The PSC trims are computed to optimize performance when the engine is near steady state; they are not valid during engine power transients.

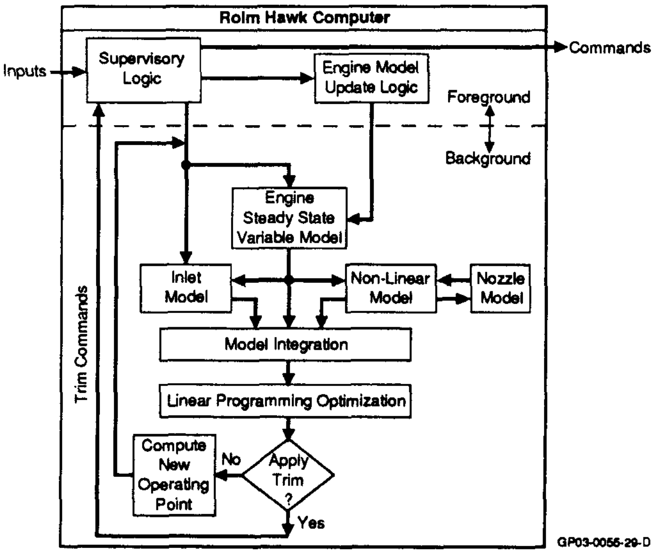

Figure 4. PSC Control Logic

The Hawk background contains compact models of the engine, nozzle, and inlet, as well as the optimization logic. The models compute propulsion system parameters, such as inlet drag and fan stall margin, which are not measurable in flight. The compact engine model receives information from the engine model update logic, which runs in the Hawk foreground, to match it to the operating characteristics of the actual engine. In addition to calculating propulsion system outputs, the compact models also compute sensitivities of these parameters to changes in control variables.

The model outputs and sensitivities are mathematically combined to form an overall propulsion system model. This propulsion system model is then optimized using a Linear Programming (LP) optimization scheme. The goal of the optimization is determined from the selected PSC mode of operation. The resulting trims can either be applied directly to the DEEC and EAIC or used to compute a new operating point, about which the optimization process is repeated. The latter method is used to calculate an overall (global) optimum before applying the trims to the controllers.

COMPACT ENGINE MODEL

The compact engine model (CEM) calculates engine output parameters and the sensitivity of these output parameters to changes in control variables. The CEM outputs include temperatures, pressures, rotor speeds, airflows, thrust, and stall margins. The control variables are primary and augmentor fuel flows (WF, WFAB), augmentor entrance total pressure (PT6), and variable fan and compressor stator vane positions (CIVV, RCVV).

The compact engine model consists of two parts: 1) a piecewise-linear steady state variable model (SSVM) which represents engine gas generator operation and 2) a nonlinear model which represents those engine effects for which linear relationships are generated on-board. The SSVM represents engine operation on and off the nominal operating line throughout the entire F-15 flight envelope. Characterizing engine operation off the nominal operating line is essential, since the PSC commands will generally move the engine operating point off the baseline schedules. An overview diagram of the SSVM is provided in Figure 5.

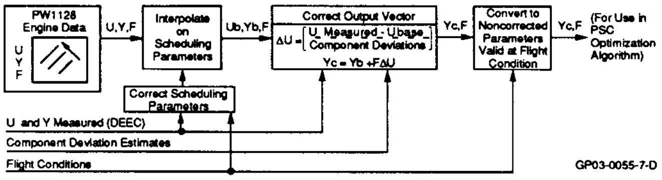

Figure 5. PSC Steady State Variable Model (SSVM)

The foundation of the SSVM is a set of linear point models located on and off the operating line for a reference flight condition. Full envelope capability is achieved by modeling the engine in terms of corrected parameters[1]. Each point model consists of a basepoint control vector ($\mathbf{u}_b$), a basepoint output vector ($\mathbf{y}_b$), and a sensitivity coefficient matrix ($\mathbf{F}$), which relates changes in control positions to changes in outputs. The point models are scheduled with sensed engine parameters. By interpolating between the models with the scheduling parameters, a single point model ($\mathbf{u}_b$, $\mathbf{y}_b$, and $\mathbf{F}$) to be used for optimization is formed. The output vector is adjusted for control deviations (the difference between the actual control positions and the model basepoint values) and engine component deviations, as identified by the Kalman filter in the update logic. The output vector and $\mathbf{F}$ matrix are then uncorrected, shifting them to the current flight condition for the optimization procedure.

The nonlinear model contains those engine effects which cannot be accurately approximated with linear relationships (i.e. augmentor operation). This model calculates both the nonlinear parameters and the linear sensitivities of these parameters to changes in controls. The nonlinear parameters are calculated using the measured control settings, $\mathbf{u}_m$, and the SSVM output vector, $\mathbf{y}_c$. The sensitivities are determined by mathematically perturbing the elements of the control vector and calculating the resulting changes in the nonlinear parameters.

ENGINE MODEL UPDATE LOGIC

The goal of the engine model update logic is to match the compact engine model to the operating characteristics of the actual engine. To accomplish this task, a Kalman filter has been designed to account for anomalous engine performance. The filter, similar to that described by Luppold et al. (1989), estimates five component deviations which fully characterize off-nominal engine performance. The five parameters are low spool efficiency adder, high spool efficiency adder, fan airflow adder, compressor airflow adder, and high turbine area adder. Due to the limited number of sensed engine parameters, isolation of efficiency changes to a specific component is not possible. However, off-nominal performance can be isolated to a particular spool. Changes to the fan and low turbine efficiencies are combined into a low spool adder, while those of the compressor and high turbine are lumped into the high spool adder. This technique has been found to work well within the PSC system and can also be adapted for use in engine monitoring and fault detection.

The component deviation estimates are augmented to the SSVM control vector to improve the accuracy of the compact engine model (CEM) output calculations. Extensive evaluations of the Kalman filter/CEM tandem have been conducted with nonlinear simulations. Hundreds of flight conditions spanning the F-15 subsonic flight envelope have been analyzed, with several levels of engine deterioration simulated. Results show that, with the engine model update logic, the CEM accuracy in computing steady state outputs satisfies the ± 2% design goal at nearly all conditions, when compared to a nonlinear aero/thermodynamic engine model (truth model).

COMPACT NOZZLE MODEL

The PSC nozzle model computes the incremental F-15 aft end drag due to the engine exhaust plume and the

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[1] It is standard engineering practice to correct engine rotor speeds, temperatures, pressures, and mass flows as a function of engine face pressure and temperature. The resulting corrected parameters provide a basis for the comparison of engine operation at different atmospheric and flight conditions.

external nozzle aerodynamics. The compact nozzle model was designed by curve-fitting wind tunnel jet effects data. The model consists of multivariable equations, each corresponding to a specific freestream Mach number. Each equation expresses nozzle drag as a function of external nozzle exit area and the ratio of exit static pressure to ambient pressure.

The F-15 does not have an actuator to independently control the nozzle exit area. Instead, the exit area is mechanically linked to the nozzle throat area and floats within the bounds provided by the linkage, based on internal and external pressures. Therefore, at a given flight condition, nozzle drag is a function of only the engine control variables, which determine both the exit area and exit static pressure. To optimize overall aircraft performance, it is important to know how nozzle drag changes as the engine controls are varied. The compact nozzle model supplies the PSC optimization with these sensitivities through an on-line linearization procedure similar to that carried out in the nonlinear portion of the compact engine model.

COMPACT INLET MODEL

The compact inlet model calculates inlet performance and sensitivities for the variable three-ramp F-15 inlet, illustrated in Figure 6. The model will be designed for the full F-15 envelope, although only the subsonic portion has been developed to date. In subsonic operation, inlet performance is calculated in terms of total pressure recovery and inlet drag. In supersonic operation, inlet performance will also be calculated in terms of shock displacement ratio and percent critical mass flow. In addition to performance levels, the inlet model also calculates the sensitivity of the performance parameters to changes in the inlet input variables. For PSC, the inlet input variables are cowl angle, third ramp angle, and engine corrected airflow. The PSC system will not adjust the bypass door position since it is positioned closed for best performance, as is already done. The inlet controller only opens the bypass door at the onset of inlet flow instabilities.

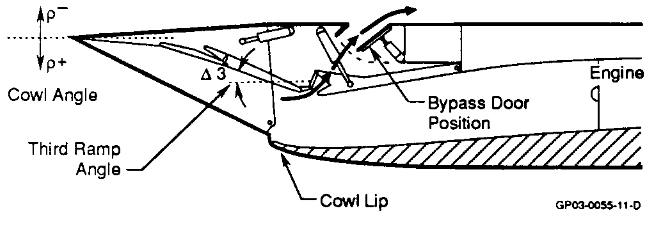

Figure 6. F-15 Air Induction System

Subsonically, PSC will not alter the inlet ramp positions either. Analysis has shown that the best subsonic inlet performance is obtained with the inlet scheduled wide open, as is currently done. However, the influence of engine corrected airflow on inlet performance must be computed to account for the coupling between the inlet and engine. Therefore, the subsonic portion of the compact inlet model consists of curve-fit equations to calculate total pressure recovery and inlet drag as a function of engine corrected airflow. The curve-fits were generated from MCAIR's best analytical/empirical representation of the F-15 inlet. The inlet sensitivities are calculated by mathematically perturbing the input variables, using a technique similar to that described for the nonlinear engine model.

MODEL INTEGRATION

The compact models produce outputs and the sensitivity of those outputs to control changes. The sensitivities from the compact models are then combined to form an overall propulsion system model. The primary goal in this step is to account for the coupling between engine corrected airflow (W2C) and total pressure at the engine face (PT2). When an inlet is used to supply the engine airflow, total pressure losses occur in the inlet duct due to diffuser geometry and surface friction. The amount of total pressure loss increases with increasing W2C. In the compact engine model, PT2 is modeled as an independent input, which does not vary with engine outputs, such as W2C. To account for this coupling, the engine and inlet sensitivities are mathematically combined to form an overall propulsion system matrix. This matrix relates changes in engine and inlet controls to changes in the propulsion system outputs. Included are relationships, such as the sensitivity of inlet drag to changes in CIVV position, that can only be determined from an integrated model.

LINEAR PROGRAMMING OPTIMIZATION

Determination of the global optimum for each mode of operation requires solving a constrained nonlinear programming problem. The PSC approach to solving this problem is to perform a series of linear programming (LP) optimizations. For each optimization, a linear representation of the propulsion system about the specific operating point is provided by the propulsion system matrix. Maximum allowable control input changes are computed to prevent violation of model linearization assumptions. Constraints for each system model output are also computed to prevent violation of physical operating limits.

An LP problem is set up and solved, using the Simplex method, to obtain the local optimum under these constraints. The resulting control changes are then used to compute a new system operating point, about which the models are again linearized. The above procedure is again performed, and a new local optimum is obtained. By repeated linearization of the on-board models at each intermediate solution, a sequence of control variable changes is generated, which converges to the global optimum solution.

This process is illustrated in Figure 7 for a maximum thrust mode optimization. To simplify the illustration, the PSC optimization is reduced to a two-dimensional problem (two control variables). The global optimum for this case is located at the intersection of the minimum nozzle throat area constraint and the maximum FTIT constraint. A series of local optimums is computed to reach the global optimum.

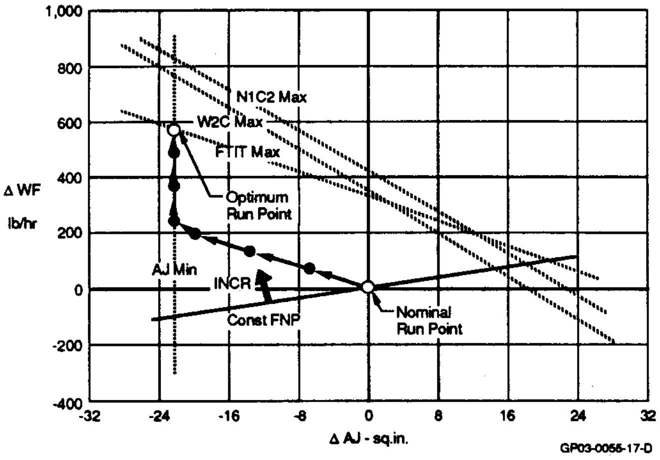

Figure 7. Determination of the Global Optimum

IV. PERFORMANCE EVALUATIONS

Three simulations have been developed to evaluate the PSC system: 1) a steady state simulation, 2) a dynamic propulsion system simulation, and 3) a six-degree-of-freedom (SDF) simulation. In all these simulations, the PW1128 engine is represented by an aerodynamic/thermodynamic model, which is P&W's most complete analytical representation of engine performance. To complete the propulsion system model, the F-15 installation program is added. This program contains MCAIR's highest fidelity analytical/empirical representation of the F-15 inlet, nozzle, and engine parasitics (e.g. compressor bleed and horsepower extraction). Through these simulations, the operation of the PSC system is verified, and the PSC performance benefits are quantified.

The simulation results shown here are for the minimum SFC and maximum thrust modes, which are the two modes which have been analyzed most extensively to date. Results are shown for the subsonic portion of the F-15 flight envelope, which is where the first PSC flight test evaluations will be flown. The original, pre-HIDEC F-15/PW1128 is the baseline for all the performance improvements presented.

The steady state simulation is used to evaluate the steady state interaction between the PSC logic and the propulsion system. The aero/thermodynamic engine model is operated in a steady state mode. When the PSC trims are applied to the engine simulation, they have immediate effect, eliminating engine dynamics. In addition, the simulation is operated at a fixed flight condition since no airframe interaction is modeled.

The steady state simulation has been used to evaluate PSC operation in all four modes, throughout the subsonic flight envelope. The performance benefits in the maximum thrust mode are quantified in Figure 8. The percent increase in net propulsive force (FNP) achieved by PSC at Military power (maximum nonafterburning power setting) is plotted for the subsonic flight envelope. The FNP increase is seen to range from 5% up to 15%. The largest performance improvements are achieved in the upper left portion of the flight envelope. In this operating region, improved thrust is achieved primarily through increased engine pressure ratio (EPR). EPR is raised by increasing fan speed while decreasing nozzle throat area. The EPR increase is limited by fan stall margin requirements and the maximum allowable fan speed and turbine temperature.

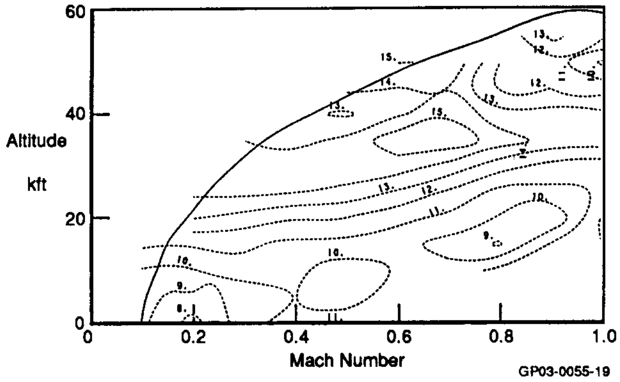

Figure 8. PSC Maximum Thrust Mode Performance
Percent Increase in FNP, Military Power

The performance benefits in the minimum SFC mode are quantified in Figure 9. The percent change in specific fuel consumption achieved by PSC at a cruise power setting is plotted across the subsonic flight envelope. PSC decreases SFC by up to 3%. To minimize SFC in the lower left hand portion of the flight envelope, PSC decreases W2C by cambering the CIVVs and lowering N1C2. Thrust is maintained by increasing EPR. In the upper right hand portion of the flight envelope, PSC increases W2C by moving CIVVs axially and increasing N1C2. Thrust is held constant by decreasing EPR. Throughout the flight envelope PSC moves the RCVVs axially. The more efficient propulsion system operation results in the SFC reductions.

To verify that the PSC system captures all the performance improvements available, PSC results have been compared to truth model optimization results. In the truth model optimization, the nonlinear propulsion system simulation is directly optimized using linear programming in a repeated linearization scheme[2]. This

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[2] An earlier analysis (Landy, 1987) showed that equivalent results are obtained using a nonlinear programming technique.

procedure eliminates any modeling errors associated with the PSC compact models. Results from this analysis show that the PSC system captures the great majority of the available benefit for all modes of operation.

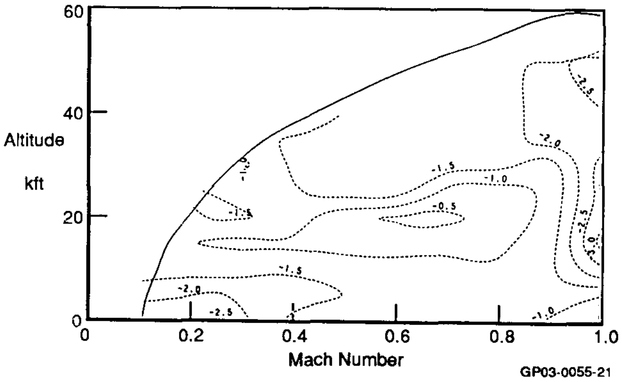

Figure 9. PSC Minimum SFC Mode Performance
Percent Change in SFC, Cruise Power

The dynamic propulsion simulation is used to evaluate the time-dependent PSC operating characteristics. The aero/thermodynamic engine model is run in a dynamic mode to simulate the actual engine response. The PSC logic is split into foreground and background tasks to accommodate the timing issues associated with dynamic operation. The foreground contains the Kalman filter and a small portion of the supervisory logic associated with trim application. The background contains the compact propulsion system models and optimization logic. This simulation is also operated at a fixed flight condition.

The dynamic response of the PSC system in the maximum thrust mode is shown in Figure 10 for a subsonic maneuvering condition at Military power. The propulsion system responds rapidly to the PSC trims, achieving 90% of the thrust improvement in under 10 seconds. The PSC trim commands to the DEEC are seen to settle to their steady state values within 15 seconds. The dynamic response in the minimum SFC mode is shown in Figure 11 for a typical cruise condition. The engine SFC is seen to reach a minimum within 20 seconds. The PSC trim commands have a settling time of up to 75 seconds. Between 20 and 75 seconds, PSC trims are attempting to equalize the FNP. This response is more than adequate for a cruise condition where the aircraft will spend long periods of time.

The SDF simulation, our highest fidelity simulation, is used to evaluate PSC's interaction with the airframe and propulsion system. A non-linear six-degree-of-freedom F-15 aircraft model is used in the simulation, and the PSC trims are applied to both engines. The actual PSC flight test code is used in this simulation. This code contains major portions of the supervisory logic not included in the dynamic propulsion simulation.

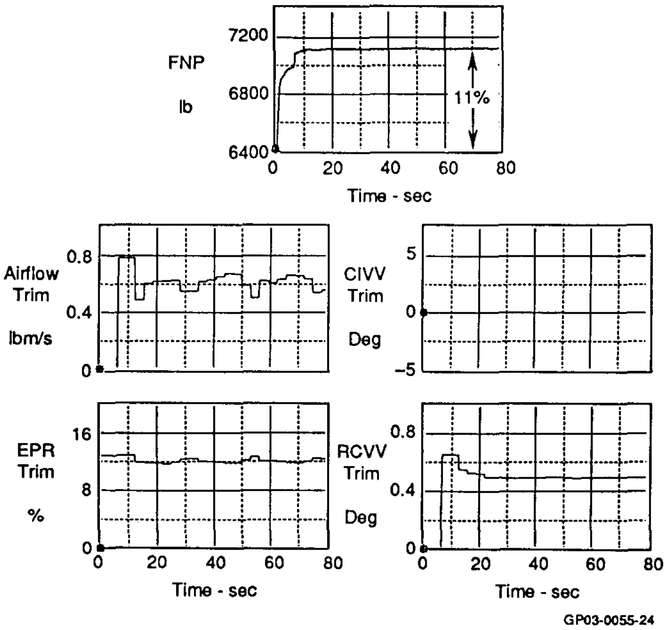

Figure 10. PSC Dynamic Response – Max Thrust Mode
Maneuvering Flight Condition, Mil Power

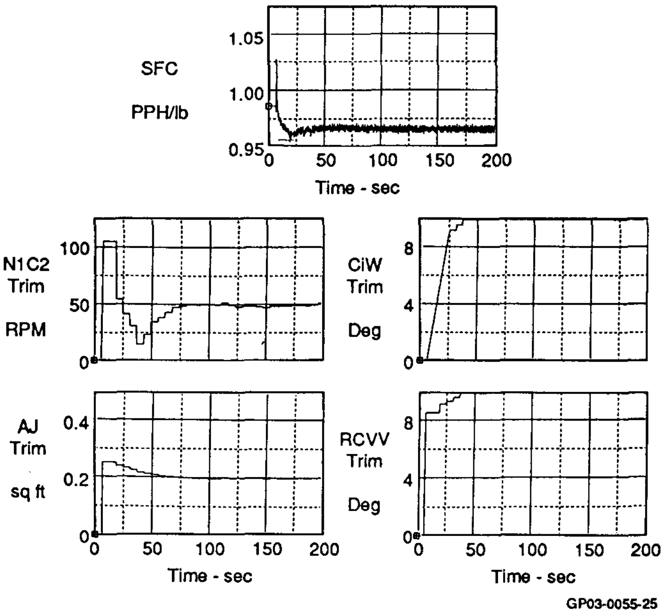

Figure 11. PSC Dynamic Response – Min SFC Mode
Typical Cruise Condition

The SDF simulation has been used to evaluate PSC performance for aircraft cruise segments, accelerations, and climbs. The aircraft response to the PSC maximum thrust mode is shown in Figure 12 for a 45,000 ft, Military power acceleration from Mach 0.75. In this figure, the Mach number and FNP are plotted for both a nominal F-15 and one equipped with PSC. The PSC system reduces the time to reach Mach 0.95 by 24%.

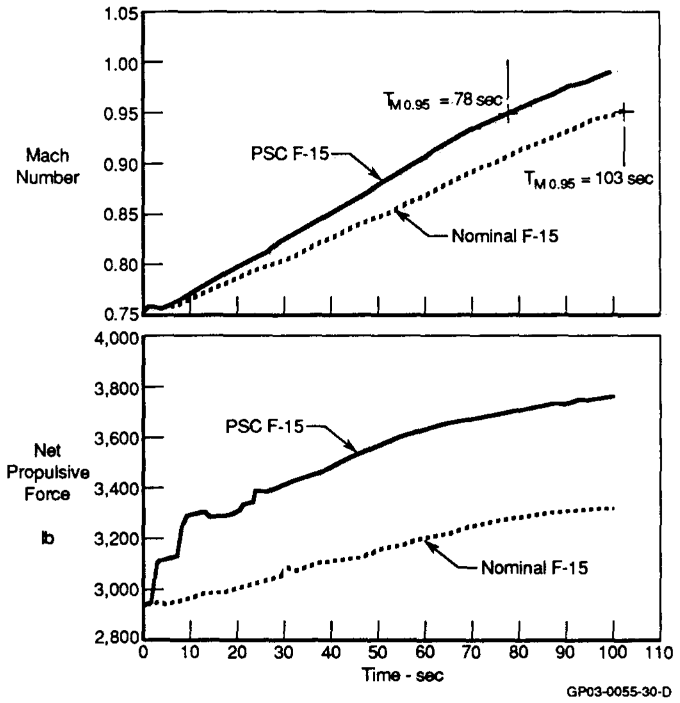

Figure 12. SDF Results
Max Thrust Mode 45,000 Ft Mil Power

V. SUMMARY AND CONCLUSIONS

An adaptive, model-based, Performance Seeking Control algorithm has been developed to optimize steady state aircraft/engine performance. On-board models of the inlet, engine, and nozzle are optimized to compute a set of control trims, which are then applied as increments to the nominal engine and inlet control schedules. Extensive simulation evaluations have identified that significant increases in thrust (up to 15%), and reductions in specific fuel consumption (up to 3%) are realizable by the PSC system. The PSC system will be flight demonstrated on the NASA Ames/Dryden Research Facility F-15 in 1990.

The most difficult challenge in the development of the PSC system has been the creation of on-board models accurate enough for the on-line optimization. If the models do not provide a good representation of the actual propulsion system operation, the potential benefits of adaptive control will not be realized. The models in the current system are the result of several years of development effort. This effort has required close coordination among NASA, MCAIR, and P&W.

Although the PSC system is currently targeted toward a specific aircraft and engine type, the modeling and optimization procedures which have been developed are applicable to a wide variety of aircraft. In fact, the anticipated PSC payoffs are greater for aircraft with thrust vectoring, where flight/propulsion control integration becomes essential, or for transatmospheric vehicles such as the National Aerospace Plane (NASP), where the extremely large operating envelope and limited data base make conventional control trim scheduling extremely difficult. Another potential application is using the PSC system to minimize engine exhaust temperature for heat signature reduction in tactical aircraft.

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