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"PSC Algorithm Description"

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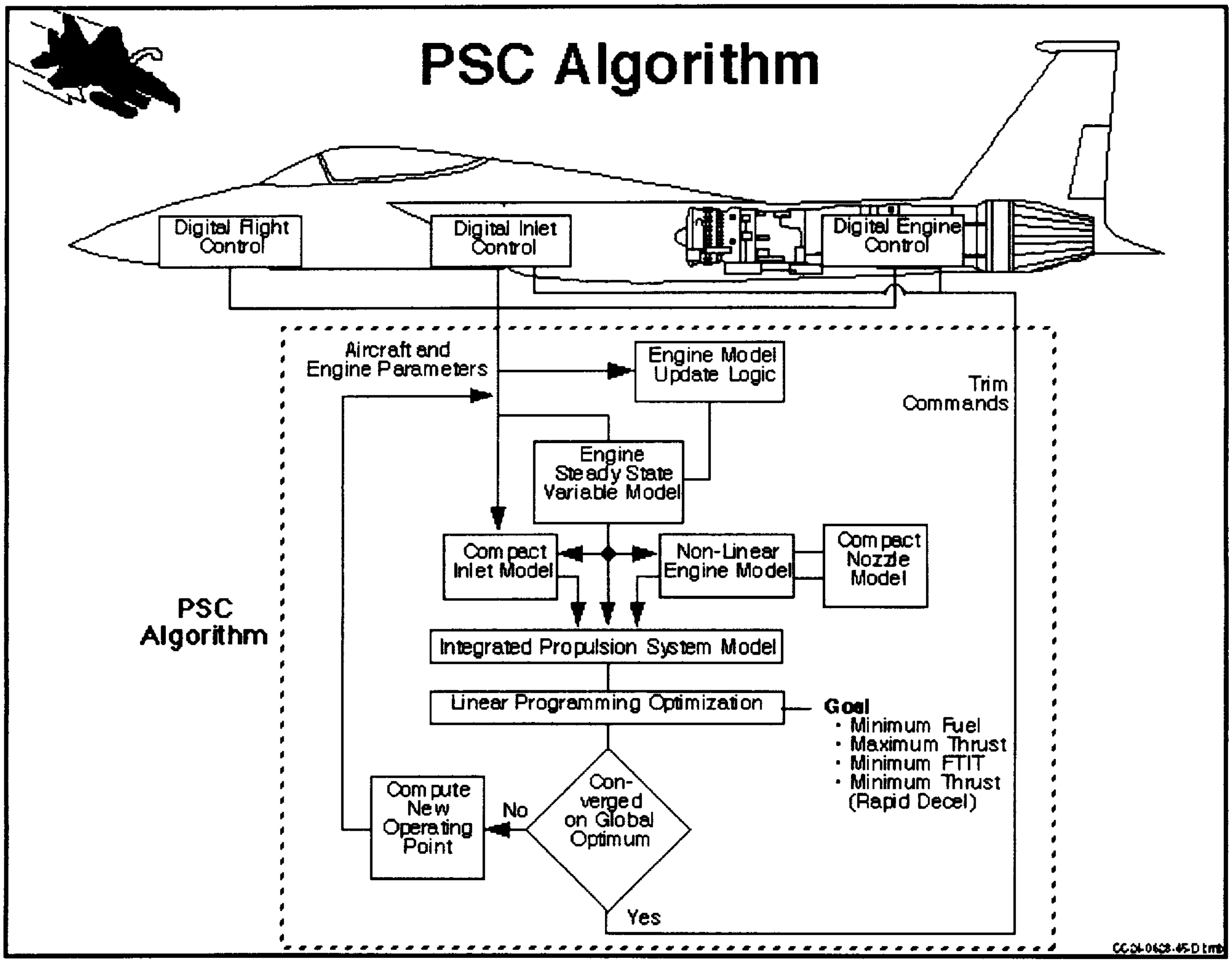

PSC ALGORITHM DESCRIPTION

In this section, an overview of the PSC algorithm and details of the important components of the algorithm are given. The onboard propulsion system models, the linear programming optimization and engine control interface are described.

The PSC algorithm receives inputs from various computers on the aircraft including the digital flight computer, digital engine control, and electronic inlet control.

The PSC algorithm contains compact models of the propulsion system including the inlet, engine, and nozzle. The models compute propulsion system parameters, such as inlet drag and fan stall margin, which are not directly measurable in flight. The compact models also compute sensitivities of the propulsion system parameters to changes in control variables. The engine model consists of a linear steady state variable model (SSVM) and a non–linear model. The SSVM is updated with efficiency factors calculated in the engine model update logic, or Kalman Filter. The efficiency factors are used to adjust the SSVM to match the actual engine.

The propulsion system models are mathematically integrated to form an overall propulsion system model. The propulsion system model is then optimized using a linear programming optimization scheme. The goal of the optimization is determined from the selected PSC mode of operation. The resulting trims are used to compute a new operating point about which the optimization process is repeated. This process is continued until an overall (global) optimum is reached before applying the trims to the controllers.

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Onboard Propulsion System Models

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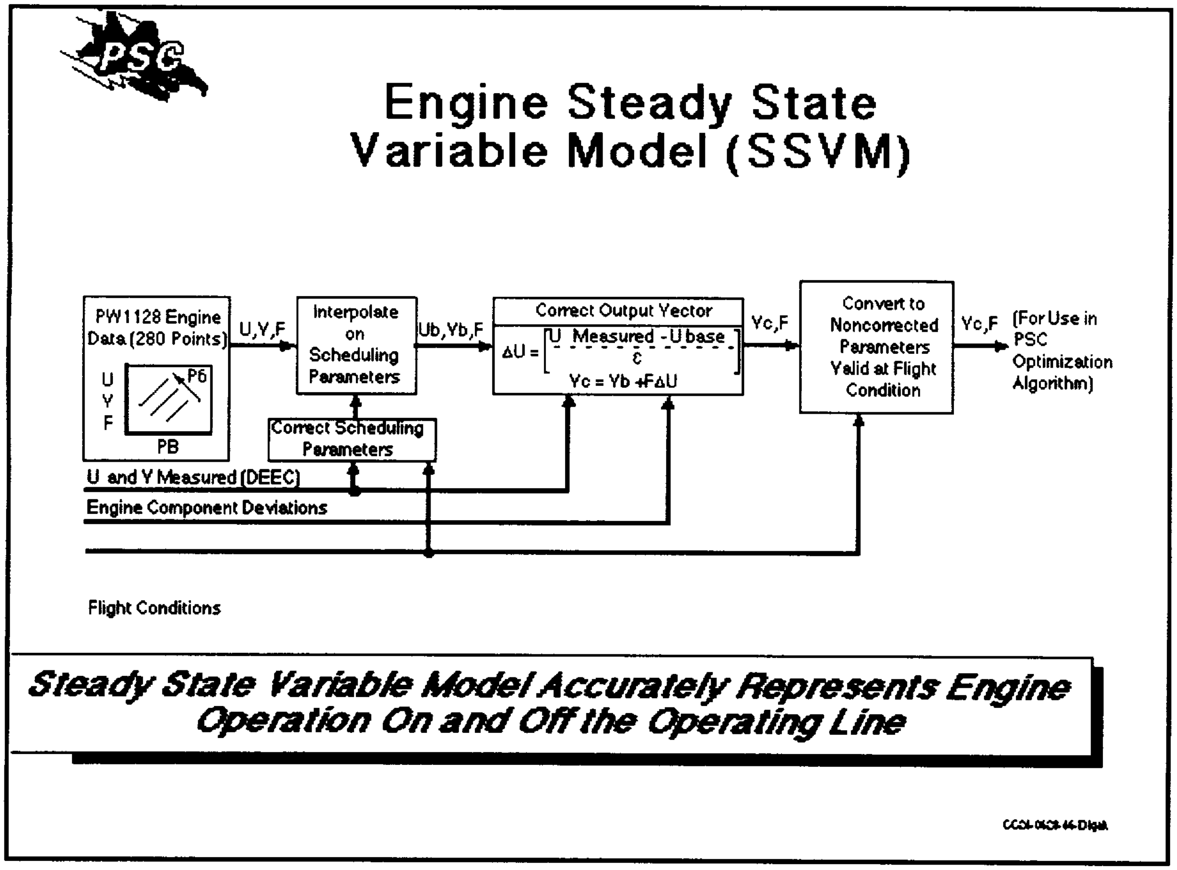

Engine Steady State Variable Model (SSVM)

Steady State Variable Model Accurately Represents Engine Operation On and Off the Operating Line

ONBOARD PROPULSION SYSTEM MODELS

The onboard propulsion system models are the engine, nozzle and inlet models. The engine model consists of the Steady State Variable Model (SSVM), engine model update logic and non–linear engine model. The propulsion models are integrated together to form the Integrated Propulsion System Model.

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.

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 acheived by modeling the engine in terms of corrected parameters. Each point model consists of a basepoint control vector (Ub), a basepoint output vector (Yb), and a sensitivity coefficient matrix (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 (Ub, Yb, and 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 F matrix are then shifted from their corrected values to the current flight condition for the optimization procedure.

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Engine Model Update Logic

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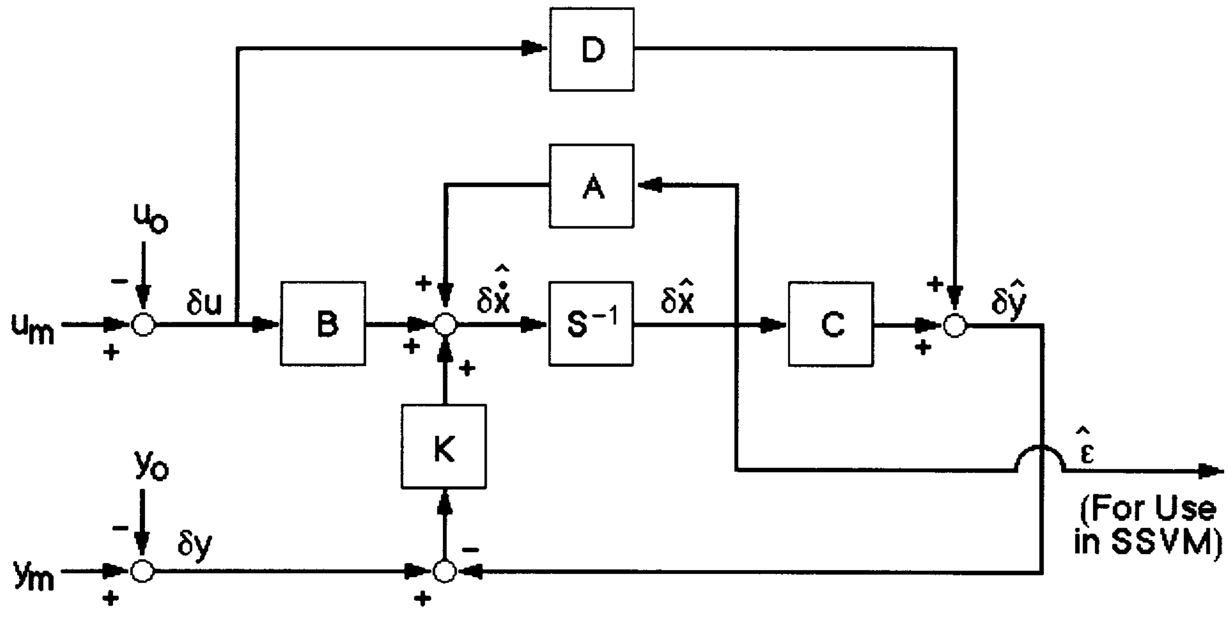
Engine Model Update Logic

Kalman Filter



$x = [\ N1, N2, TM, \varepsilon\ ]^T$

$y = [\ N1, N2, PB, FTIT, PT6\ ]^T$

$u = [\ WF, AJ, CIVV, RCVV, HPX, WBLCD\ ]^T$

ε = Engine Efficiency 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 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 outputs satisfies the + 2% design goal at nearly all conditions, when compared to a nonlinear aero/thermodynamic engine model (truth model).

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Non–Linear Engine Model

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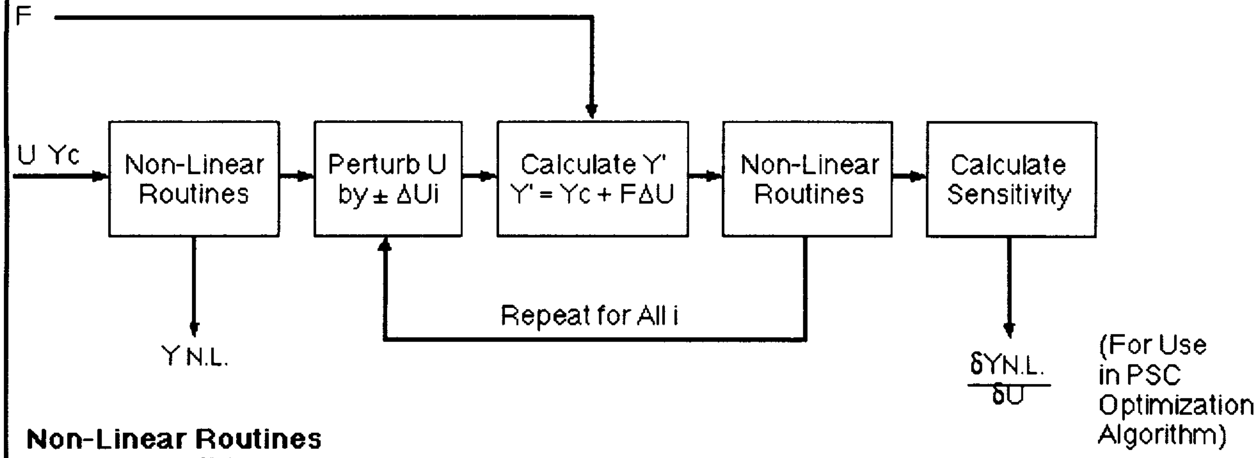
Non-Linear Engine Model



Non-Linear Routines

- Augmenter Effects
- Net Thrust
- Fan Stall Margin
- High Pressure Compressor Stall Margin
- Nozzle Exit Area
- Nozzle Drag

NON–LINEAR ENGINE MODEL

The nonlinear engine model contains those engine effects which cannot be accurately approximated with linear relationships, such as, 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, Um, and the SSVM output vector, Yc. The sensitivities are determined by mathematically perturbing the elements of the control vector and calculating the resulting changes in the nonlinear parameters.

Compact Nozzle Model

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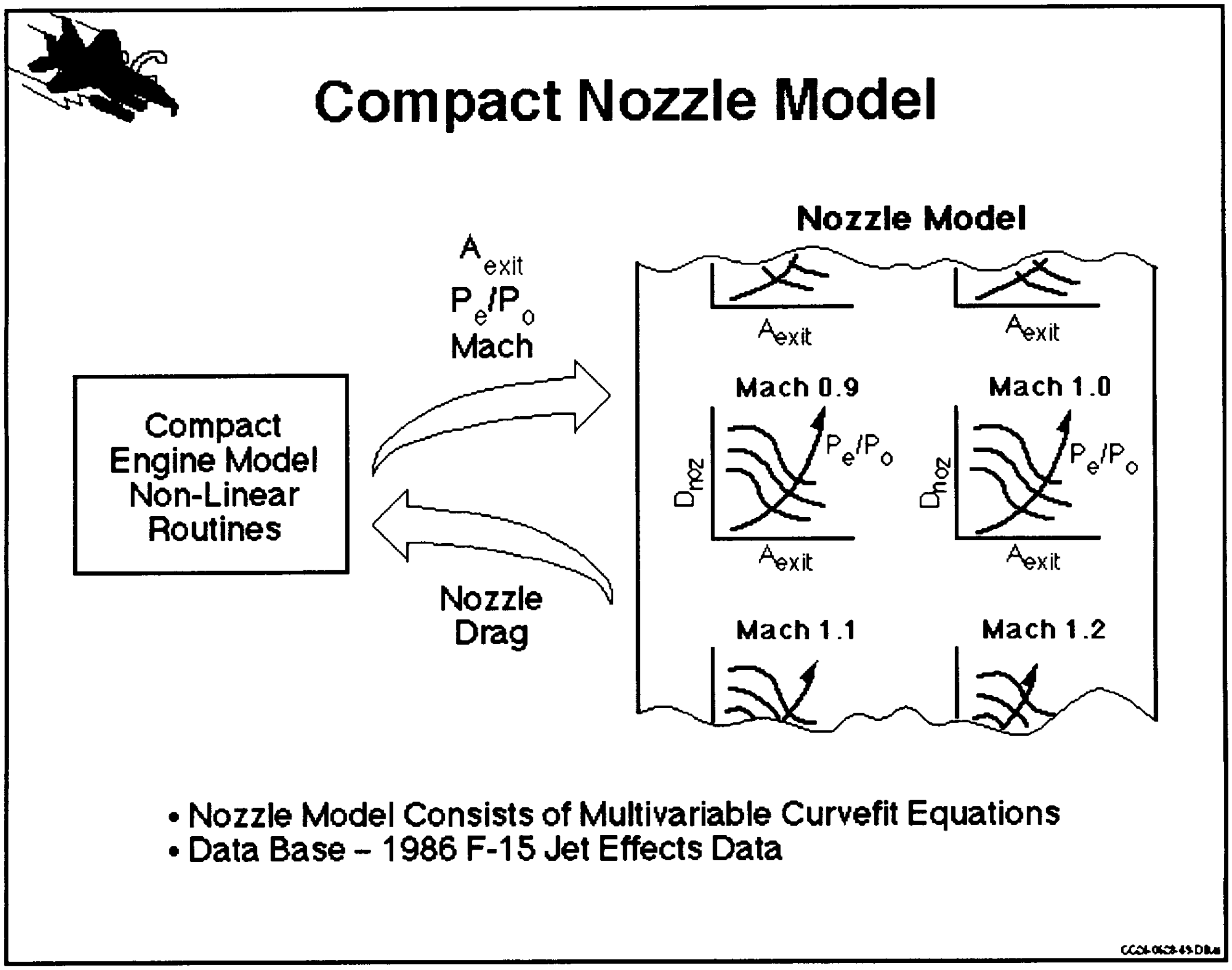

Compact Nozzle Model

- Nozzle Model Consists of Multivariable Curvefit Equations
- Data Base – 1986 F-15 Jet Effects Data

COMPACT NOZZLE MODEL

The PSC nozzle model computes the incremental F–15 aft end drag due to the engine exhaust plume and the 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 for independently controlling 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.

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Compact Inlet Model

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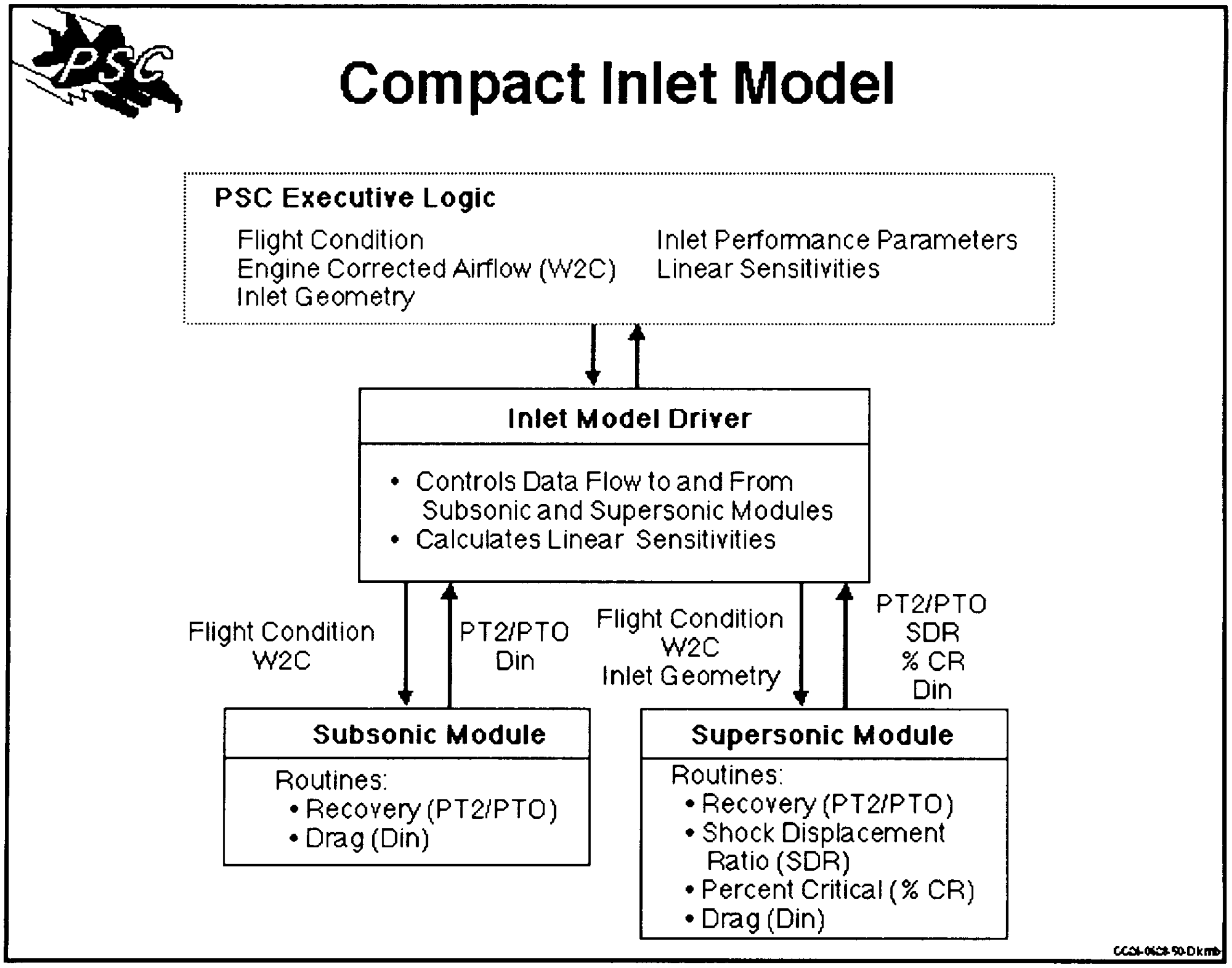

Compact Inlet Model

PSC Executive Logic

Flight Condition
Engine Corrected Airflow (W2C)
Inlet Geometry

Inlet Performance Parameters
Linear Sensitivities

Inlet Model Driver

- Controls Data Flow to and From Subsonic and Supersonic Modules
- Calculates Linear Sensitivities

Flight Condition
W2C

PT2/PTO
Din

Flight Condition
W2C
Inlet Geometry

PT2/PTO
SDR
% CR
Din

Subsonic Module

Routines:
- Recovery (PT2/PTO)
- Drag (Din)

Supersonic Module

Routines:
- Recovery (PT2/PTO)
- Shock Displacement Ratio (SDR)
- Percent Critical (% CR)
- Drag (Din)

COMPACT INLET MODEL

The compact inlet model calculates inlet performance and sensitivities for the variable three–ramp F–15 inlet . In subsonic operation, inlet performance is calculated in terms of total pressure recovery and inlet drag. In supersonic operation, inlet performance is also calucated 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 variables are cowl angle, third ramp angle, and engine corrected airflow. The PSC system will not adjust the bypass door position since it is postioned closed for best performance, as is already done. The inlet controller only opens the bypass door at the onset of inlet flow instabilities.

Subsonically, PSC will not alter the inlet ramp positions. 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 McDonnell'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.

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Integrated Propulsion Model

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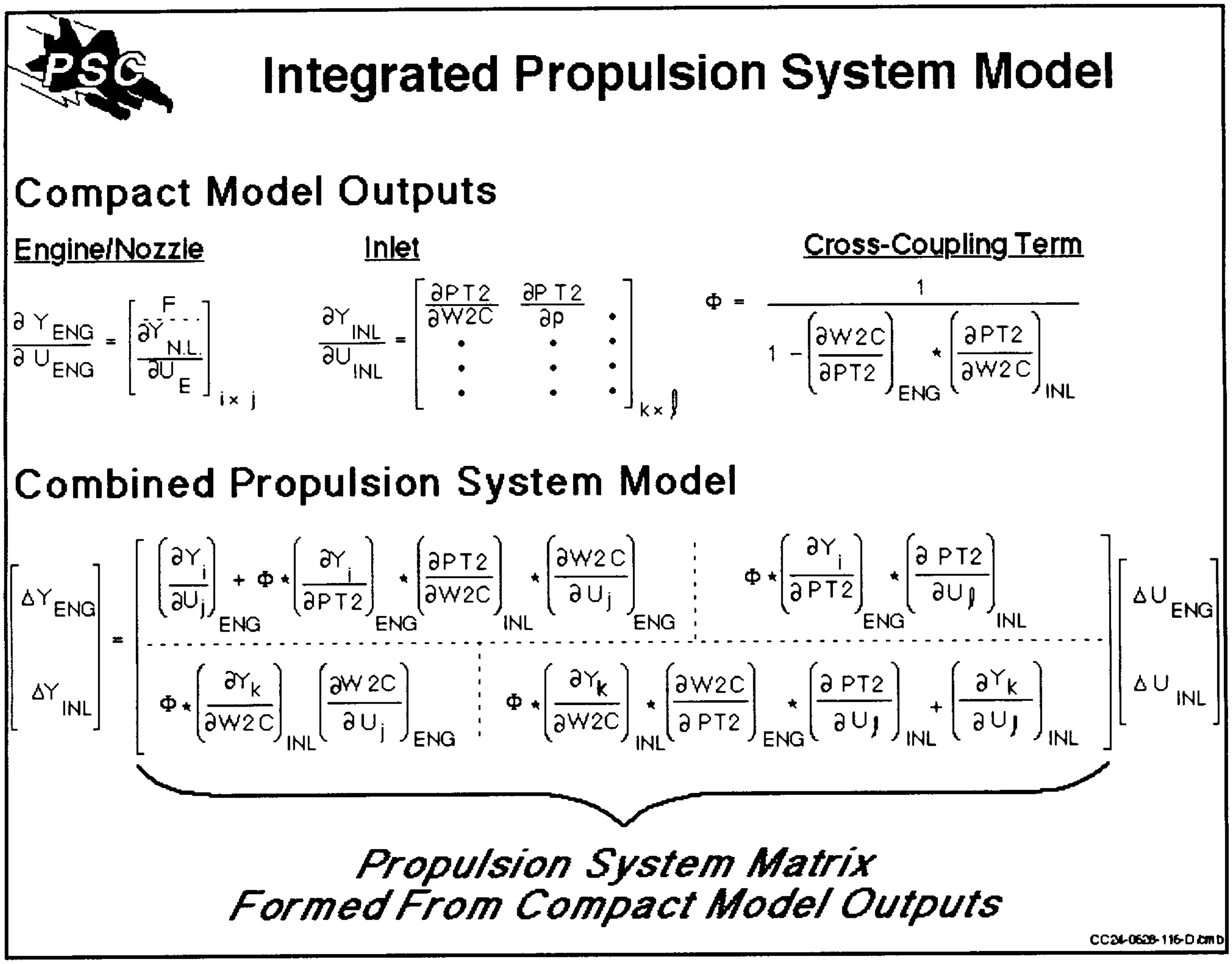

Integrated Propulsion System Model

Compact Model Outputs

Engine/Nozzle

$$\frac{\partial Y_{ENG}}{\partial U_{ENG}} = \begin{bmatrix} \dfrac{\partial Y^{F}_{N.L.}}{\partial U_{E}} \end{bmatrix}_{i \times j}$$

Inlet

$$\frac{\partial Y_{INL}}{\partial U_{INL}} = \begin{bmatrix} \dfrac{\partial PT2}{\partial W2C} & \dfrac{\partial PT2}{\partial p} & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet \end{bmatrix}_{k \times \ell}$$

Cross-Coupling Term

$$\Phi = \frac{1}{1 - \left(\dfrac{\partial W2C}{\partial PT2}\right)_{ENG} * \left(\dfrac{\partial PT2}{\partial W2C}\right)_{INL}}$$

Combined Propulsion System Model

$$\begin{bmatrix} \Delta Y_{ENG} \\ \Delta Y_{INL} \end{bmatrix} = \left[\begin{array}{c:c} \left(\dfrac{\partial Y_i}{\partial U_j}\right)_{ENG} + \Phi * \left(\dfrac{\partial Y_i}{\partial PT2}\right)_{ENG} * \left(\dfrac{\partial PT2}{\partial W2C}\right)_{INL} * \left(\dfrac{\partial W2C}{\partial U_j}\right)_{ENG} & \Phi * \left(\dfrac{\partial Y_i}{\partial PT2}\right)_{ENG} * \left(\dfrac{\partial PT2}{\partial U_\ell}\right)_{INL} \\ \hdashline \Phi * \left(\dfrac{\partial Y_k}{\partial W2C}\right)_{INL} \left(\dfrac{\partial W2C}{\partial U_j}\right)_{ENG} & \Phi * \left(\dfrac{\partial Y_k}{\partial W2C}\right)_{INL} * \left(\dfrac{\partial W2C}{\partial PT2}\right)_{ENG} * \left(\dfrac{\partial PT2}{\partial U_\ell}\right)_{INL} + \left(\dfrac{\partial Y_k}{\partial U_\ell}\right)_{INL} \end{array}\right] \begin{bmatrix} \Delta U_{ENG} \\ \Delta U_{INL} \end{bmatrix}$$

Propulsion System Matrix
Formed From Compact Model Outputs

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INTEGRATED PROPULSION MODEL

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). Total pressure losses occur in the inlet duct due to diffuser geometry changes 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 to 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.

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Linear Programming Optimization

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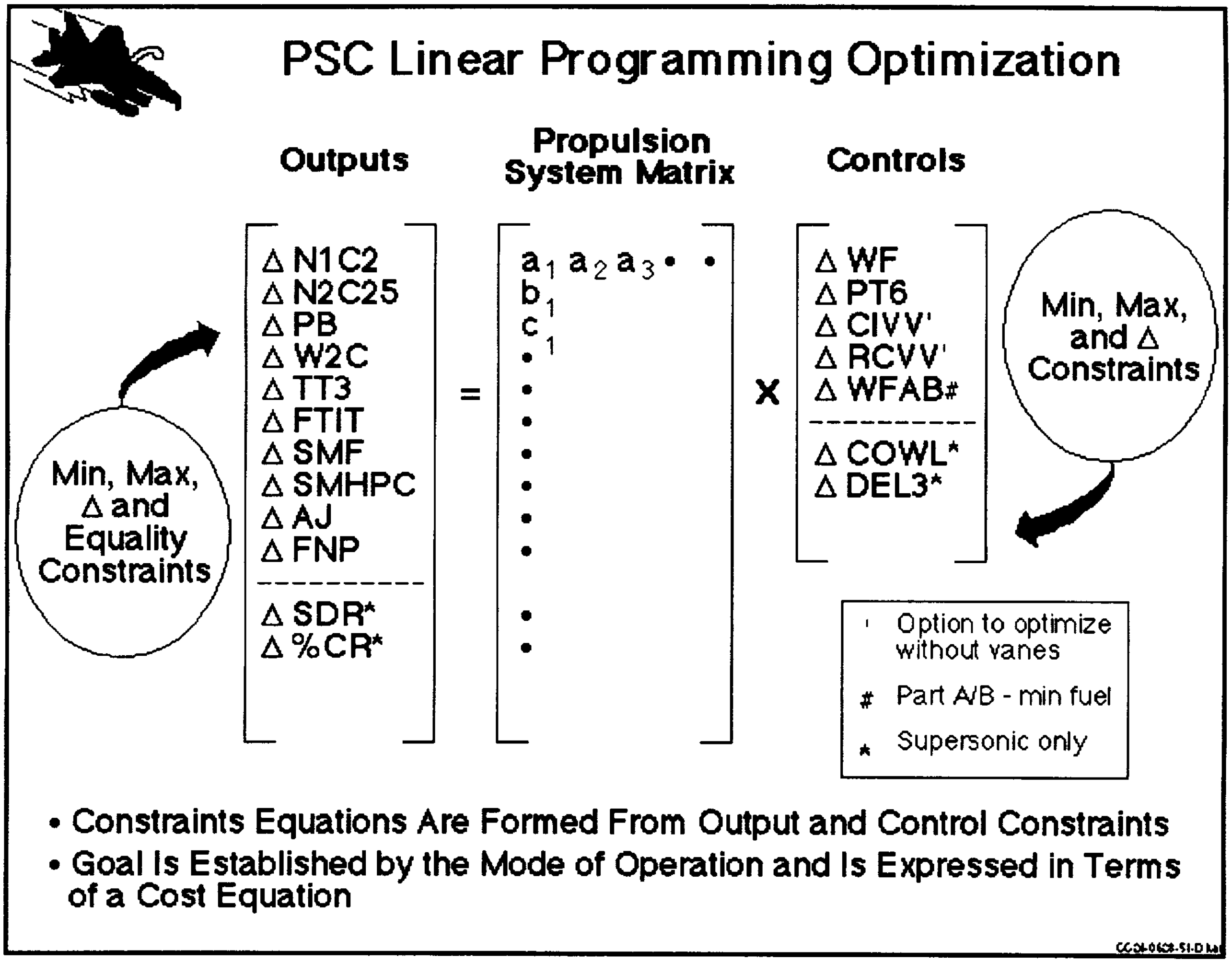

PSC Linear Programming Optimization

$$
\begin{array}{cccccc}
\textbf{Outputs} & & \textbf{Propulsion System Matrix} & & \textbf{Controls} \\
\begin{bmatrix}
\Delta \mathrm{N1C2} \\
\Delta \mathrm{N2C25} \\
\Delta \mathrm{PB} \\
\Delta \mathrm{W2C} \\
\Delta \mathrm{TT3} \\
\Delta \mathrm{FTIT} \\
\Delta \mathrm{SMF} \\
\Delta \mathrm{SMHPC} \\
\Delta \mathrm{AJ} \\
\Delta \mathrm{FNP} \\
\hdashline
\Delta \mathrm{SDR}^{*} \\
\Delta \%\mathrm{CR}^{*}
\end{bmatrix}
& = &
\begin{bmatrix}
a_1 & a_2 & a_3 & \bullet & \bullet \\
b_1 \\
c_1 \\
\bullet_1 \\
\bullet \\
\bullet \\
\bullet \\
\bullet \\
\bullet \\
\bullet \\
\\
\bullet \\
\bullet
\end{bmatrix}
& \times &
\begin{bmatrix}
\Delta \mathrm{WF} \\
\Delta \mathrm{PT6} \\
\Delta \mathrm{CIVV}' \\
\Delta \mathrm{RCVV}' \\
\Delta \mathrm{WFAB}\# \\
\hdashline
\Delta \mathrm{COWL}^{*} \\
\Delta \mathrm{DEL3}^{*}
\end{bmatrix}
\end{array}
$$

Min, Max, Δ and Equality Constraints

Min, Max, and Δ Constraints

' Option to optimize without vanes

\# Part A/B - min fuel

* Supersonic only

- **Constraints Equations Are Formed From Output and Control Constraints**
- **Goal Is Established by the Mode of Operation and Is Expressed in Terms of a Cost Equation**

LINEAR PROGRAMMING OPTIMIZATION

A linear programming optimization is performed to determine optimal propulsion system control settings.

Determining the global optimum at each operating point requires solving a constrained nonlinear programming problem. The PSC appraoch 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 linearity assumptions. Constraints for each 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.

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Optimization Process Example for Maximum Thrust Mode

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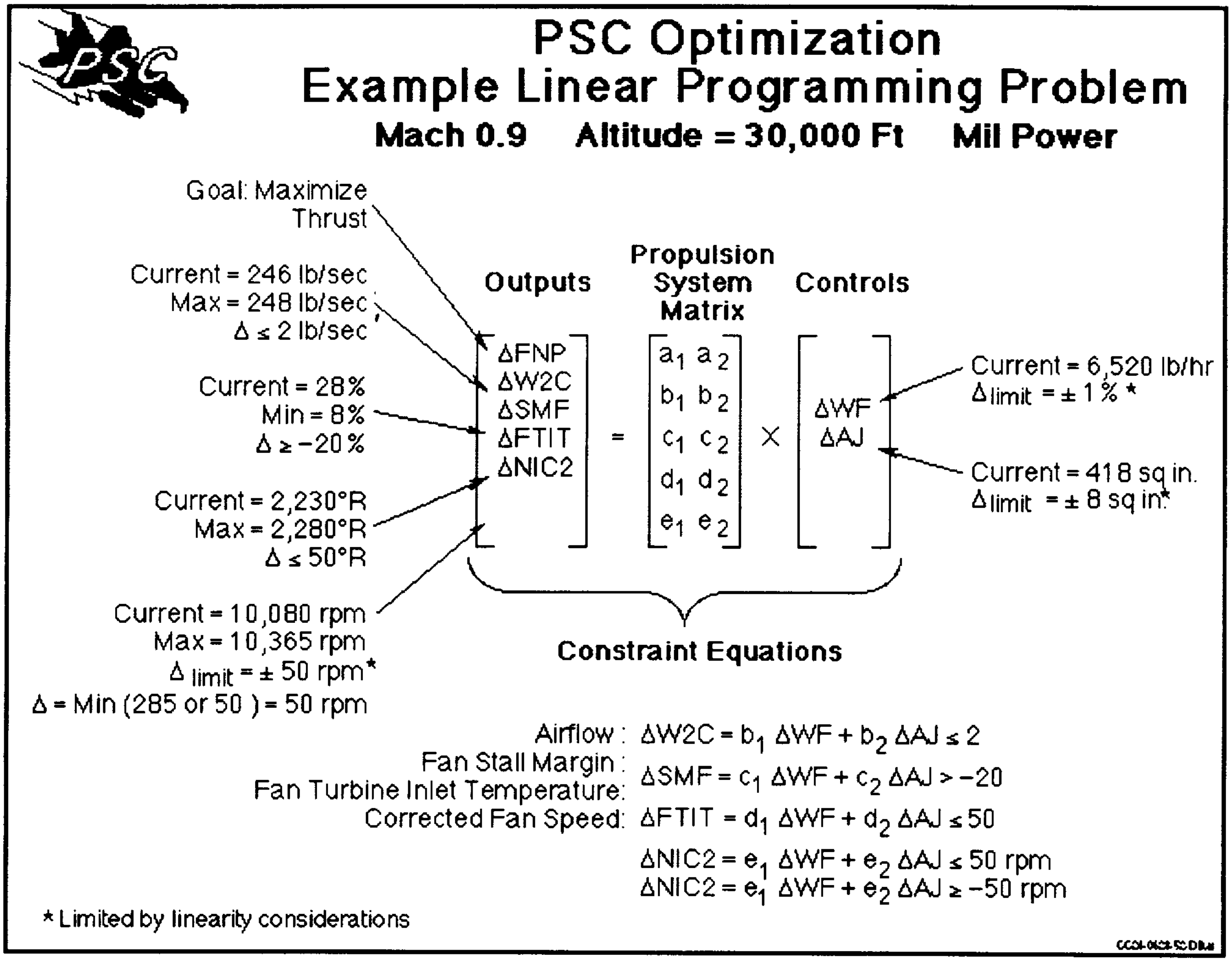

PSC Optimization

Example Linear Programming Problem

Mach 0.9 Altitude = 30,000 Ft Mil Power

Goal: Maximize Thrust

Current = 246 lb/sec
Max = 248 lb/sec
Δ ≤ 2 lb/sec

Current = 28%
Min = 8%
Δ ≥ −20%

Current = 2,230°R
Max = 2,280°R
Δ ≤ 50°R

Current = 10,080 rpm
Max = 10,365 rpm
Δ limit = ± 50 rpm*
Δ = Min (285 or 50) = 50 rpm

Outputs **Propulsion System Matrix** **Controls**

$$\underbrace{\begin{bmatrix}\Delta FNP\\ \Delta W2C\\ \Delta SMF\\ \Delta FTIT\\ \Delta NIC2\end{bmatrix} = \begin{bmatrix}a_1 & a_2\\ b_1 & b_2\\ c_1 & c_2\\ d_1 & d_2\\ e_1 & e_2\end{bmatrix} \times \begin{bmatrix}\Delta WF\\ \Delta AJ\end{bmatrix}}_{\text{Constraint Equations}}$$

Current = 6,520 lb/hr
Δlimit = ± 1 % *

Current = 418 sq in.
Δlimit = ± 8 sq in*

Constraint Equations

Airflow : $\Delta W2C = b_1\, \Delta WF + b_2\, \Delta AJ \le 2$
Fan Stall Margin : $\Delta SMF = c_1\, \Delta WF + c_2\, \Delta AJ > -20$
Fan Turbine Inlet Temperature: $\Delta FTIT = d_1\, \Delta WF + d_2\, \Delta AJ \le 50$
Corrected Fan Speed: $\Delta NIC2 = e_1\, \Delta WF + e_2\, \Delta AJ \le 50$ rpm
$\Delta NIC2 = e_1\, \Delta WF + e_2\, \Delta AJ \ge -50$ rpm

* Limited by linearity considerations

OPTIMIZATION PROCESS EXAMPLE FOR MAXIMUM THRUST MODE

An example of the PSC optimization process is shown for the maximum thrust mode. To simplify the explanation, the PSC optimization is presented for a two dimensional problem (two control variables). In the LP optimization, constraint equations are constructed. Ouput variable limits are based on physical operating limits in the engine and control variable limits are based on model linearity considerations.

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Optimization Region

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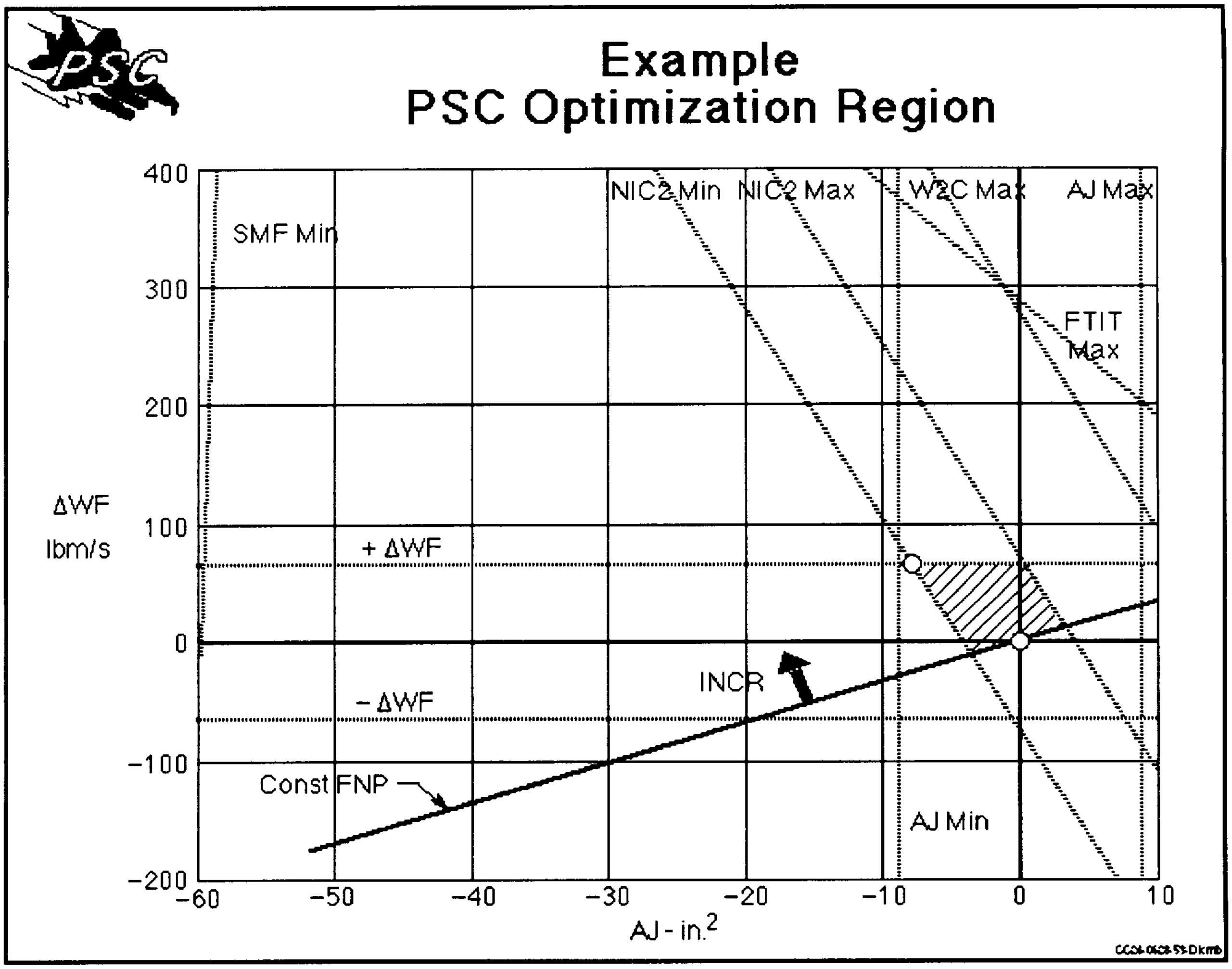

OPTIMIZATION REGION

The PSC optimization region is illustrated for the example problem. The local optimum for this two dimensional problem is at the intersection of two constraints: the maximum fuel flow (WF) and the minimum fan speed (N1C2).

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Optimization Looping Procedure

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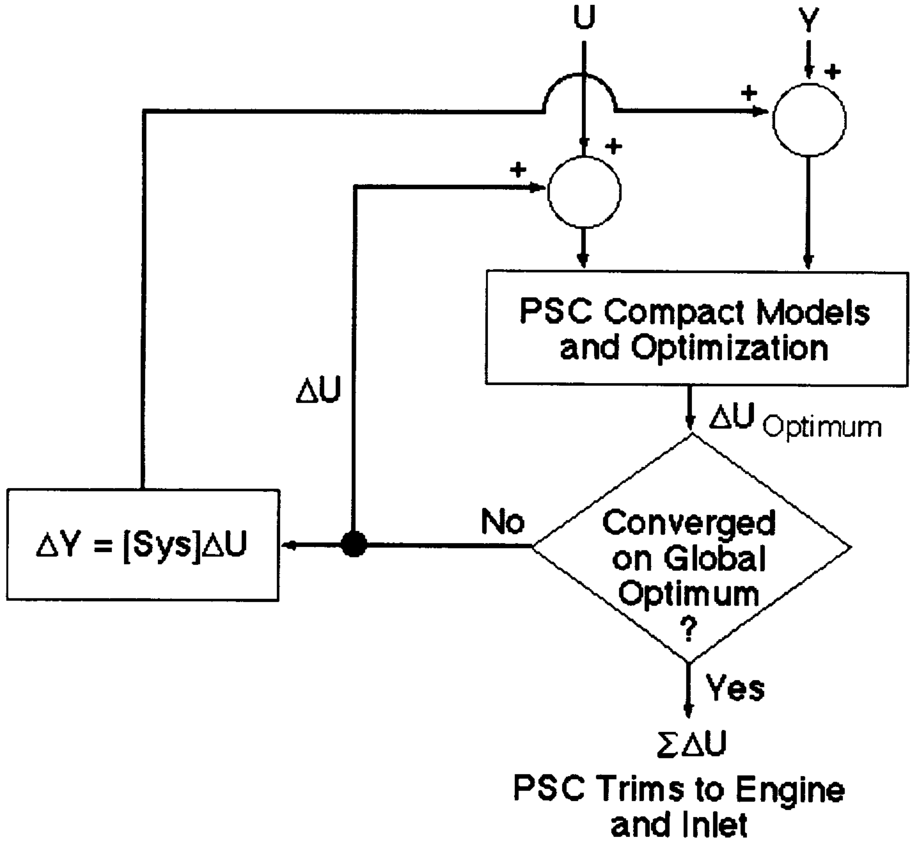
Multiple Looping



OPTIMIZATION LOOPING PROCEDURE

The control changes resulting from the LP optimization are used to compute a new system operating point, about which the models are again linearized. The above procedure is repeated until a sequence of control variable changes is generated, which converges to the global optimum solution. The number of loops is fixed. For subsonic operation 6 local optimizations are performed and for supersonic operation 3 local optimizations are performed.

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Maximum Thrust Mode Global Optimization Example

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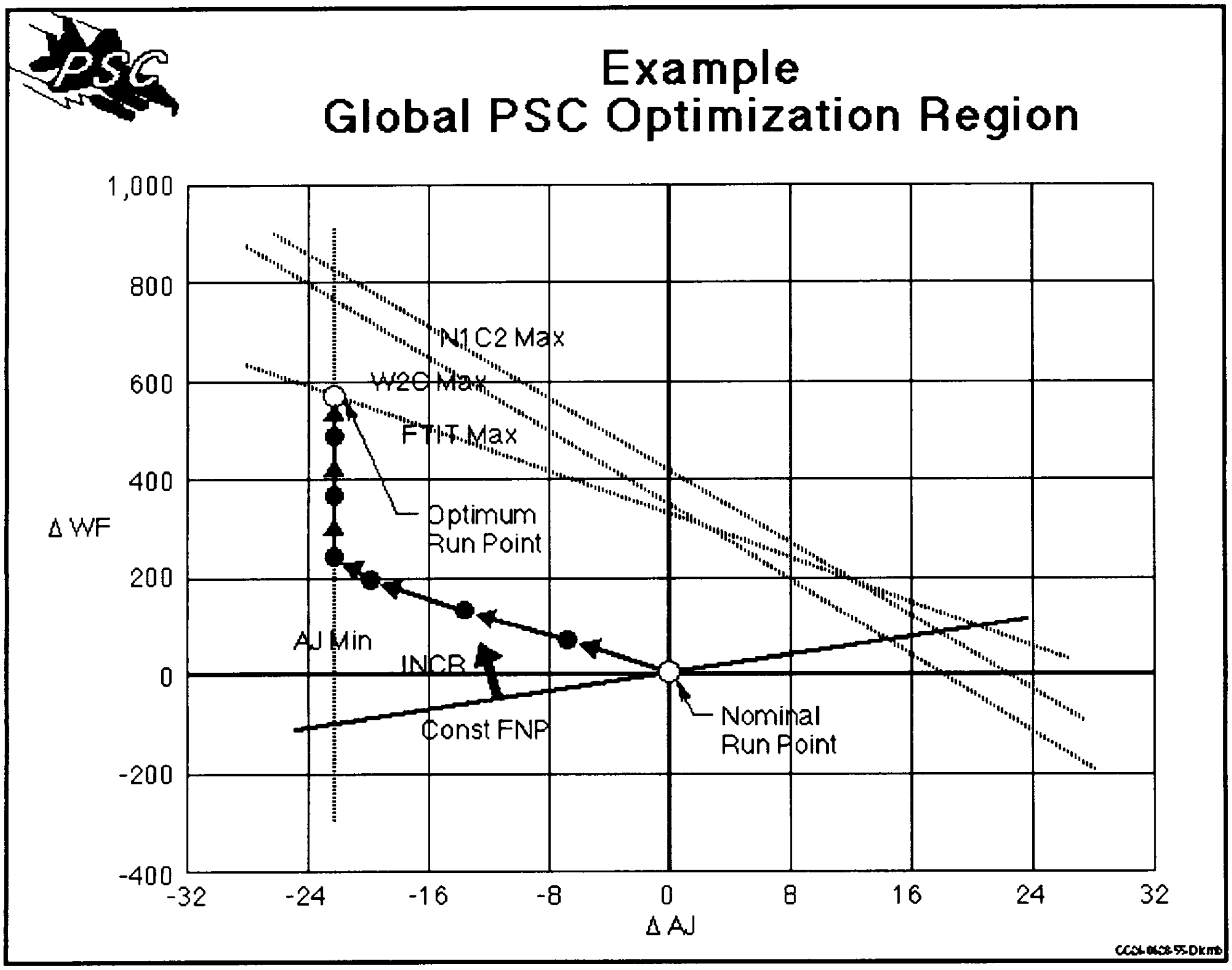

MAXIMUM THRUST MODE GLOBAL OPTIMIZATION

This example illustrates a Maximum Thrust Mode global optimization. As in the local optimization example, the PSC optimization is reduced to a two dimensinal problem (two control variables) to simplify the illustration. The global optimum for this case is at the intersection of two constraints: the minimum nozzle throat area (AJ) and the maximum FTIT.

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Engine Control Interface

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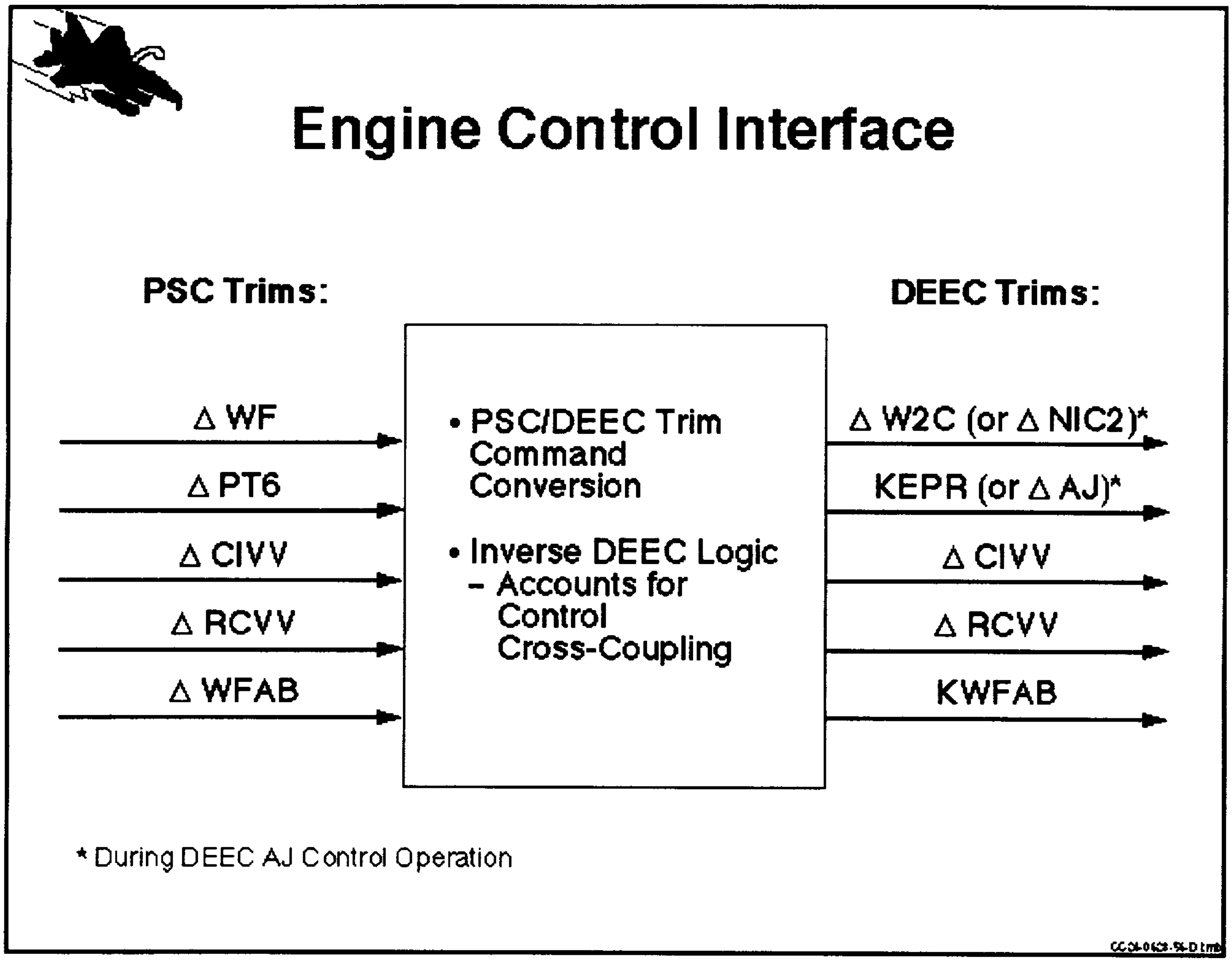

Engine Control Interface

PSC Trims:

- Δ WF
- Δ PT6
- Δ CIVV
- Δ RCVV
- Δ WFAB

- PSC/DEEC Trim Command Conversion
- Inverse DEEC Logic
  - Accounts for Control Cross-Coupling

DEEC Trims:

- Δ W2C (or Δ NIC2)*
- KEPR (or Δ AJ)*
- Δ CIVV
- Δ RCVV
- KWFAB

* During DEEC AJ Control Operation

ENGINE CONTROL INTERFACE

The purpose of the engine control interface, or inverse DEEC, is to convert the trims calculated in the PSC optimization to trims that can be applied to the DEEC. For example, the PSC optimization determines a fuel flow (WF) trim which must be converted to either an airflow (W2C) or a fan speed (N1C2) trim so that it can be applied to the DEEC. The engine control interface also accounts for control cross–coupling.

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