Role of Dynamic Simulation in Fighter Engine Design and Development

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A modern fighter engine has stringent requirements for performance, operability, and durability. To meet these conflicting requirements and to ensure a balanced design, dynamic simulation is exercised during flow-path design, control-mode design, and development testing. This assures problem prevention and reduces development costs. This analytical process is described with the aid of "real world" examples. Representative engine models, which accurately account for off-design and dynamic effects, are used early in the design phase for judicious configuration selection and control-mode design. Favorable component matching is ensured before hardware fabrication, and thus costly mistakes are prevented. The special flow-path design considerations in fast-response twin-spool afterburning turbofan engines are discussed. In addition to flow-path design, simulation tradeoff studies are used to optimize the control system to satisfy systems requirements. Novel control modes can be analytically evaluated across the operating spectrum and made practicable with appropriate activation criteria that are readily implemented in digital-control logic. Simulation applications during development/flight testing include calculation of hard-to-measure engine parameters using test data driven dynamic engine models, thus facilitating design verification. The described process has been successfully used and is illustrated here with its application to the F100-PW-229 (PW229).

Nomenclature

A_{wetted}	= effective wetted area
AB	= augmentor, afterburner
AJ	= exhaust nozzle throat area
dN/dt	= rotor speed time derivative
$FG_i/(P_T \cdot AJ)$	= ideal gross thrust function
fc	= film coefficient
H	= total gas flow enthalpy
h	= gas enthalpy
J	= rotor moment of intertia
K	= constant
$\dot{m}$	= mass flow rate
$\dot{m}\sqrt{T}/(P_T \cdot AJ)$	= mass flow function
N	= rotor speed
$N1$	= fan speed
$N1C2$	= corrected fan speed
P_S	= static pressure
P_T	= total pressure
$PT3$	= compressor exit total pressure
$PT6M$	= mixed engine discharge pressure
$\dot{q}$	= heat transfer rate
$SPMXE$	= augmentor core side stability parameter, $V/(P_S{*}T^{1.7})$
T	= temperature
T_{gas}	= gas temperature
T_{metal}	= effective metal temperature
t	= time
V	= flow velocity
WC	= corrected comprssor flow
η_c	= compressor efficiency

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Introduction

THE maneuvering requirements of a fighter airplane dictate the use of a high thrust-to-weight ratio power plant capable of flawless operation throughout the flight envelope with unrestricted throttle movement. In addition to thrust and fuel consumption, the key operational requirements include stable engine operation permitting quick thrust response within permissible parameter limits and low strain range of components for acceptable durability.[1] To meet these conflicting requirements, a balanced engine design is necessary. This process requires customer participation.

Periodic technical reviews were conducted to keep the customer cognizant of the design and development process. This ensured customer participation in establishing systems requirements. Toward meeting these requirements, systems analyses and tradeoff studies were performed using the analytical tool of dynamic simulation from the time of conceptual design through flight testing. Earliest use of this tool ensured judicious configuration selection and control-mode design, thereby effectively preventing operational problems and reducing development cost. Some applications of this method to the F100-PW-229 (PW229) are presented. PW229 is an increased-thrust derivative of the F100 engine incorporating increased flow components.[2] Fitting these components within the same installation envelope required creative flow-path design aided by analytical tools, including dynamic simulation.

This paper first addresses the need for constructing high-fidelity engine models for performing the design studies.[3,4] It is required to accurately generalize the nonlinear representations of engine components and to separately bookkeep the various loss mechanisms to ensure that off-design component matching is realistic. Additionally, engine dynamic characteristics due to rotor moment of inertias, metal heat soak, turbomachinery clearances, and leakages have to be properly modeled. The lessons learned on engine characteristics during engine test programs are factored in the engine simulations. This continual updating of the engine model enhances its prediction capability.

The purpose of this paper is to show some applications of engine dynamic simulation in the areas of flow-path design, control-system design, and development testing. System design and optimization can be particularly challenging for an

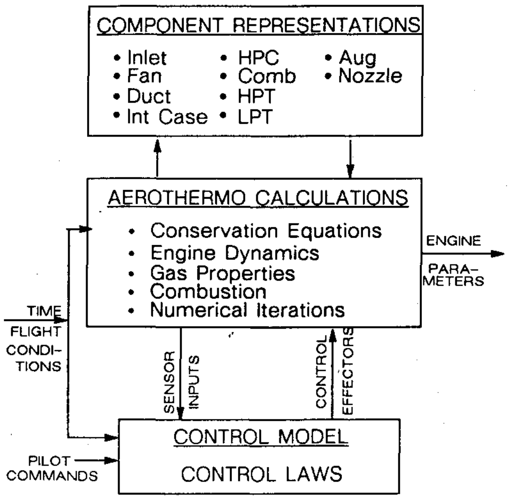

Fig. 1 Dynamic evaluation of flow-path configurations.

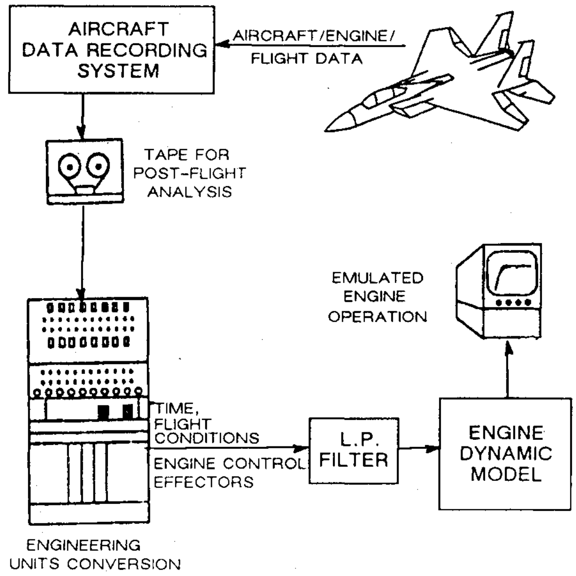

Fig. 2 Test data driven engine model.

afterburning turbofan fighter engine with fast rotor response and augmentor transient requirements. Under transient conditions, the engine components can operate at far off-design conditions. To prevent any aerodynamic matching problems and adverse component interactions, engine configurations are thoroughly evaluated using dynamic simulation (Fig. 1) before hardware fabrication commitment. This ensures timely identification of the required flow-path modifications and compensatory control actions.

The verification and refinement of the propulsion system occurs during development tesing and flight testing. The requirement to analyze engine operation during these phases is facilitated by employing an accurate dynamic engine model. The measures of merit to assess system performance are often not obtainable in a consistent and reliable manner from local internal measurements. In fact, some parameters, such as inflight transient thrust and combustor exit gas temperature, cannot be measured. This paper will show an effective method of calculating measures of merit using measured engine control system outputs as input to a representative engine model (Fig. 2). This emulation is valuable in evaluating operating characteristics and in investigating unforeseen anomalies, thus expediting the development program.

Ensuring a Representative Engine Model

The approach used in model construction will be outlined in this section. It is not the purpose to describe the algorithm details but to highlight the key features. The nonlinear aerothermodynamic representations of engine components are integrated using cycle analysis methods as in steady-state simulation, but with the addition of unsteady terms in the conservation equations.

The key relationships that are required to be satisfied are summarized below:

1) Power-balance equation for each rotor with the rotor inertia term, turbine power = compressor power + parasitics + acceleration power:

$$(\dot{m}.\,\Delta h)_{\text{turbine}} = (\dot{m}.\,\Delta h)_{\text{compressor}} + f(N) + K.J.N.\left(\frac{\mathrm{d}N}{\mathrm{d}t}\right)$$

2) Continuity equation for each component with transient mass storage term:

$$\dot{m}._{\text{out}} = \dot{m}._{\text{in}} - \dot{m}._{\text{bleed}} + \dot{m}._{\text{fuel}} + \text{Volume.}\left(\frac{\mathrm{d}P}{\mathrm{d}t}\right)/(\Upsilon.R.T.)$$

3) Accounting for transient metal heat transfer of each component in total gas enthalpy at the exit of each component:

$$H_{\text{total}} = \dot{m}.h_{\text{adiabatic}} + \dot{q}$$

where $\dot{q} = fc\,A_{\text{wetted}}\,(T_{\text{gas}} - T_{\text{metal}})$.

4) Assure static pressure balance at the mixing surface boundary of the duct and core flow.

The multidimensional Newton-Raphson iteration technique[5] is used to simultaneously satisfy all the relationships to achieve cycle balance at each instantaneous point. The component dynamics, including rotor moment of inertias and heat-transfer characteristics used in the equations, are obtained from the respective design technology groups. Attention is paid to proper heat sink distribution in the engine model and to film coefficient scaling for varying flow properties. The model results of engine transient characteristics have shown excellent agreement with engine test data. This substantiation process has been described in Ref. 4.

The steady-state component performances are continually changing during the course of an engine development program as a result of aerodynamic and hardware refinements. Therefore it is necessary to make the adjustments to the steady-state representations during the development program to ensure accurate model output at initial and final conditions. This is a prerequisite for high-fidelity transient simulation.

Another important requirement is to accurately model off-nominal variable geometry effects because during a transient the variable geometry tracking migrates significantly away from the nominal schedule. Figure 3 shows test data for compressor efficiency and flow capacity acquired by fixing the variable stators at various positions. The dashed line shows the compressor performance for the nominal variable stator schedule. The deltas indicated by the arrows show the required compressor performance correction for off-nominal variable geometry. The data acquired from a current engine test are incorporated in the most current engine model to adjust the nominal compressor performance.

The turbomachinery performance and compressor stall line are also adjusted for the deviation of transient clearances from steady-state clearances. This deviation occurs because rotor thermal growth is much slower than the case thermal growth. This differential thermal expansion and the corresponding effect on compressor efficiency is depicted in Fig. 4. The engine model incorporates an algorithm to calculate transient clearances as a function of rotor speed and internal pressures and temperatures. Component performances/stall line are then correspondingly adjusted using empirically established clearance sensitivities.

Meeting Systems Requirements

The system analysis process is depicted in Fig. 5, which shows some of the key operational requirements of a fighter engine. The challenge is to satisfy all the requirements. For example, high thrust and low thrust specific fuel consumption (TSFC) at subsonic/transonic conditions can be achieved with an engine configuration that produces a fan discharge pressure profile that supercharges the compressor. At the same time, it is very important that the selected configuration results in stable engine operation during throttle transients. By using dynamic simulation of this configuration, any component flow incompatibility during transients can be identified and appropriate flow-path modifications can be evaluated. Another example is control system trade-off studies performed to achieve engine acceleration requirements while assuring that turbine-inlet temperature path is not detrimental to turbine durability.[6] Other durability criteria include reduced excursions/overshoots in rotor speeds for enhanced low cycle fatigue (LCF) life, avoiding operating conditions conducive to high cycle fatigue (HCF), and ensuring transient clearances to prevent heavy rubs. Relative to clearances, a careful analysis is required because large clearances impact engine performance and stall margin. The key stability requirements shown in Fig. 5 include stall margin, combustor stability, augmentor stability, and control system stability.

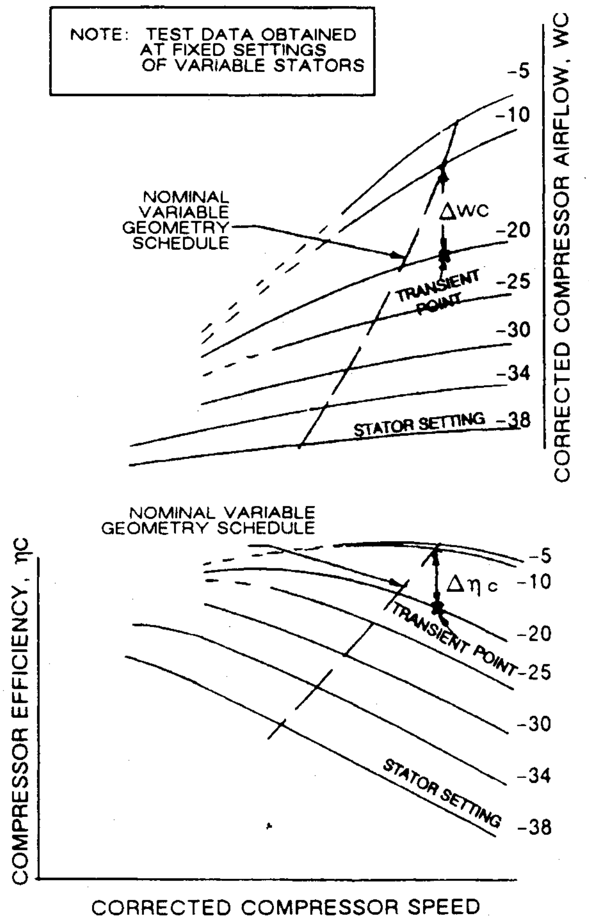

Fig. 3 Nonlinear compressor test data at fixed stator settings.

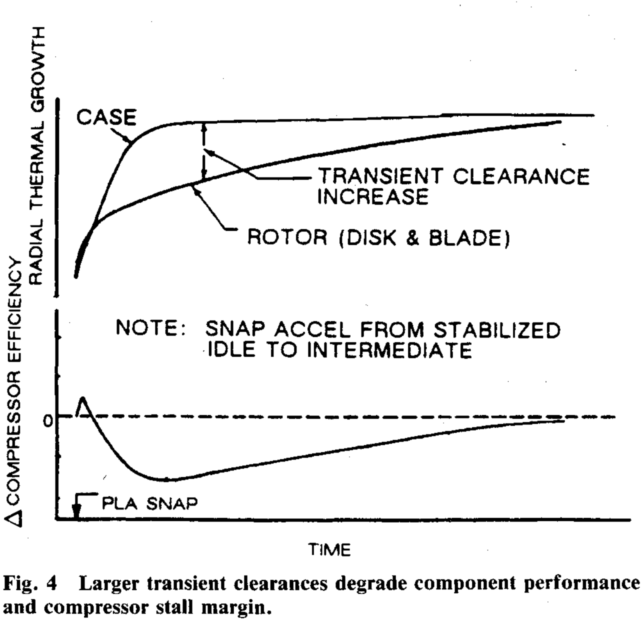

Fig. 4 Larger transient clearances degrade component performance and compressor stall margin.

Examples of Flow Path Design

Bypass Duct and Fan Deceleration Stall Margin

The fast deceleration rates of a fighter engine make the decrease in fan flow lag the decrease in compressor flow with a resulting increase in transient bypass ratio (Fig. 6). The bypass duct pressure loss is a nonlinear function of bypass duct entrance Mach number (Fig. 7) that increases with increasing bypass ratio. This nonlinearity causes large increases in duct pressure loss during the bypass ratio excursion of a deceleration (Fig. 7). There is approximately a one-to-one relationship between duct pressure loss increase and fan stall margin loss. Figure 8 shows the simulated deceleration fan operating lines, stall line, and steady-state operating lines with two duct loss representations evaluated on the F100-PW-229 engine model. It can be seen that the deceleration operating line with the ini-

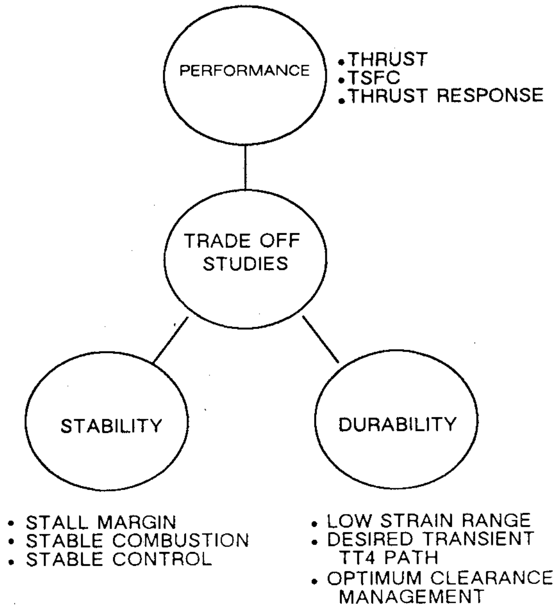

Fig. 5 Trade-off studies of key systems requirements.

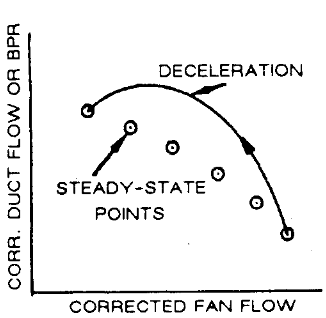

Fig. 6 BPR increases during deceleration.

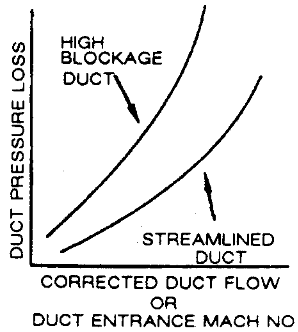

Fig. 7 Duct pressure loss characteristic.

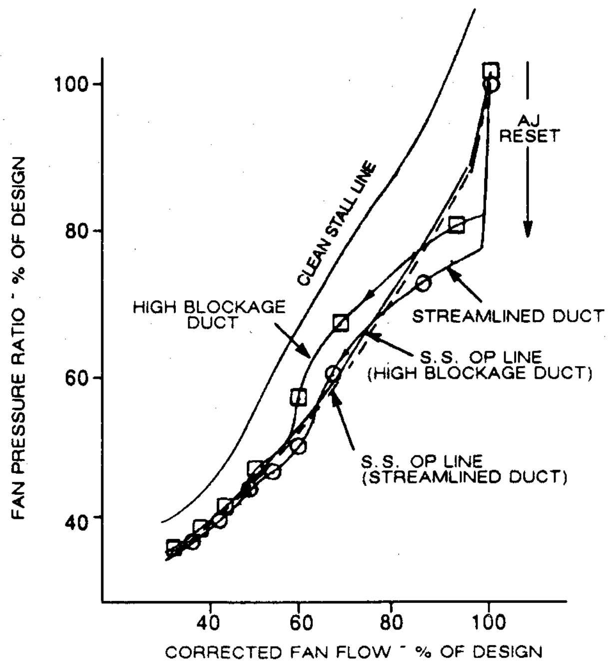

Fig. 8 Transient simulation of fan deceleration operating lines.

tially proposed high blockage duct rises significantly above the steady-state operating line (13%) in spite of opening the exhaust nozzle area (*AJ*). With a high blockage duct, a bigger *AJ* during deceleration further increases the duct Mach number, causing an increase in pressure loss. However, when the duct was streamlined to increase the effective flow area, the simulation showed a deceleration operating line rising only 2% above the steady-state level. A low duct loss also increases the effectiveness of exhaust nozzle action in increasing fan stall margin. It can be noted that the effect of duct pressure loss characteristic on the deceleration operating line is more pronounced than on steady-state operating line due to the higher duct corrected flow to fan corrected flow relationship during deceleration. F100-PW-229 engine test data of the deceleration operating line with the current duct configuration are shown in Fig. 9. It can be noted that with this configuration the deceleration operating line does not get much higher than the steady-state operating line. The above example shows the effectiveness of dynamic simulation studies in determining flow-path configurations. It must be remembered that the transient engine match requires careful scrutiny and by selecting engine configurations with favorable transient component matching at the very outset, operability problems can be effectively prevented in the follow-on development program.

Transient Intermediate Case Aeroloading

Dynamic simulation was also valuable in ascertaining the cause of a transient flowfield anomaly observed during experimental engine testing under the F100 Engine Model Devel-

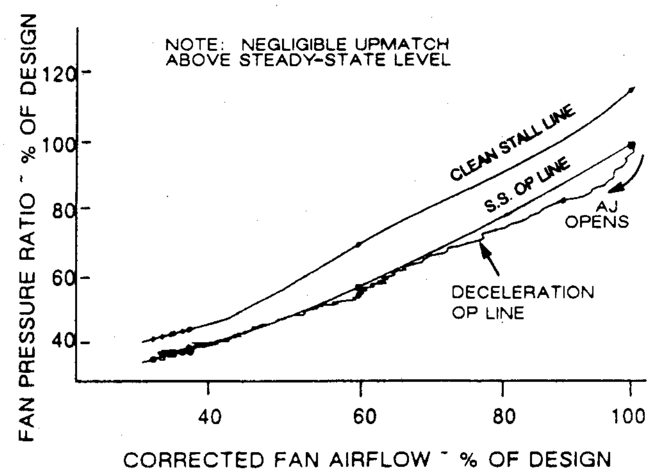

Fig. 9 Test data of PW229 deceleration fan operating line.

opment Program (EMDP).[7,8] One of the objectives of the EMDP was to screen out components not meeting system requirements during test evaluation. In the above testing, random pressure fluctuations were observed during snap decelerations at the inner diameter (ID) of the intermediate case (fan/compressor interface diffusing structure) (Fig. 10) indicating ID flow separation. Pressure fluctuations were absent at the fan exit but were very pronounced downstream in the intermediate case near the compressor inlet. This ID flow defect originating in the intermediate case was not acceptable since it could, when coupled with inlet distortion, serve as a trigger for internally-generated heavy distortion. It was required to determine the transient engine match and flow conditions responsible for the onset of the observed pressure fluctuations in the cascade formed by the 16 intermediate case struts at the ID wall. This was done by simulating the deceleration, which showed a high transient bypass ratio. The simulation results including bypass ratio (BPR), corrected fan airflow, and fan pressure ratio were then input in the component design group's streamline deck to calculate the diffuser loading parameter $\Delta P/(P_T - P_S)$. At the point of onset of pressure fluctuations, the calculated $\Delta P/(P_T - P_S)$ at the ID was 0.6, which is close to a typical cascade stall limit.

The lesson learned in the EMDP was applied to advantage in the design of the PW229 intermediate case. A set of stators was incorporated behind the fan's third rotor to share the diffusion load. In conjunction with the reduced radial turning resulting from the larger compressor ID, this reduced the transient aeroloading. To determine the worst case aeroloading, PW229 dynamic simulation was exercised at various flight conditions. The calculated transient BPR and other flow-path parameters were then input in the component design group's streamline deck and showed that the worst case $\Delta P/(P_T - P_S)$ for the third stator/intermediate case was less than 0.5. This was evident from the absence of any pressure fluctuations in PW229 (Fig. 10). This is an example of how dynamic simulation results help the detailed flow-path design.

Examples of Control-System Design

The fidelity of the dynamic engine model due to accurate off-design component characteristics and engine dynamics permitted dependable control-system design studies. The results were so accurate that the simulation designed control system required only minor changes during engine test verification. This is illustrated in the first example presented here. The second example shows the design of a new control mode for a full authority digital control system.

Verification of the Simulation Designed Control System

High-fidelity simulations are used for the complete control-system design, including steady-state performance schedules, loop gains, leads, and trim schedules. To show the effectiveness of this process, engine/control model prediction of an acceleration transient of the F100-PW-229 engine is compared with engine test data of the initial flight release (IFR) configuration in Fig. 11. The flight condition selected was an altitude of 20,000 ft and Mach number of 0.8, which is within the combat "box" (Leeds box). The transient selected was flight idle to maximum augmentation. Thrust is increasing in this transient not only from rotor spoolup but also from augmentor turnon during the rotor spoolup. This results in fast thrust response. It can be noted from Fig. 11 that the response characteristics predicted by the dynamic engine/control model are close to the IFR engine test data obtained during the first checkout at an altitude facility. The overall compression system pressure ratio (OPR) is also shown in Fig. 11 in addition to net thrust (FN). The engine data are very close to prediction, and the digital control required only the expected refinements to leads, trims, and gain schedules. The fidelity evident from Fig. 11 is a result of accurate modeling inclusive of off-design characteristics, engine dynamics, and sensor/actuator dynamics as well as augmentor system dynamics. F100-PW-229 augmentor incorporates an advanced fuel management (AFM) system that has 11 small volume spray rings (segments) to effect smooth thrust transients with minimal segment sequencing back pressure. To make dynamic simulation an effective augmentor logic design tool, the AFM spray ring fill/drain process was modeled. This makes the simulation a good indicator of transient augmentor blowout margin and sequencing fan upmatch during the augmentor logic design process.

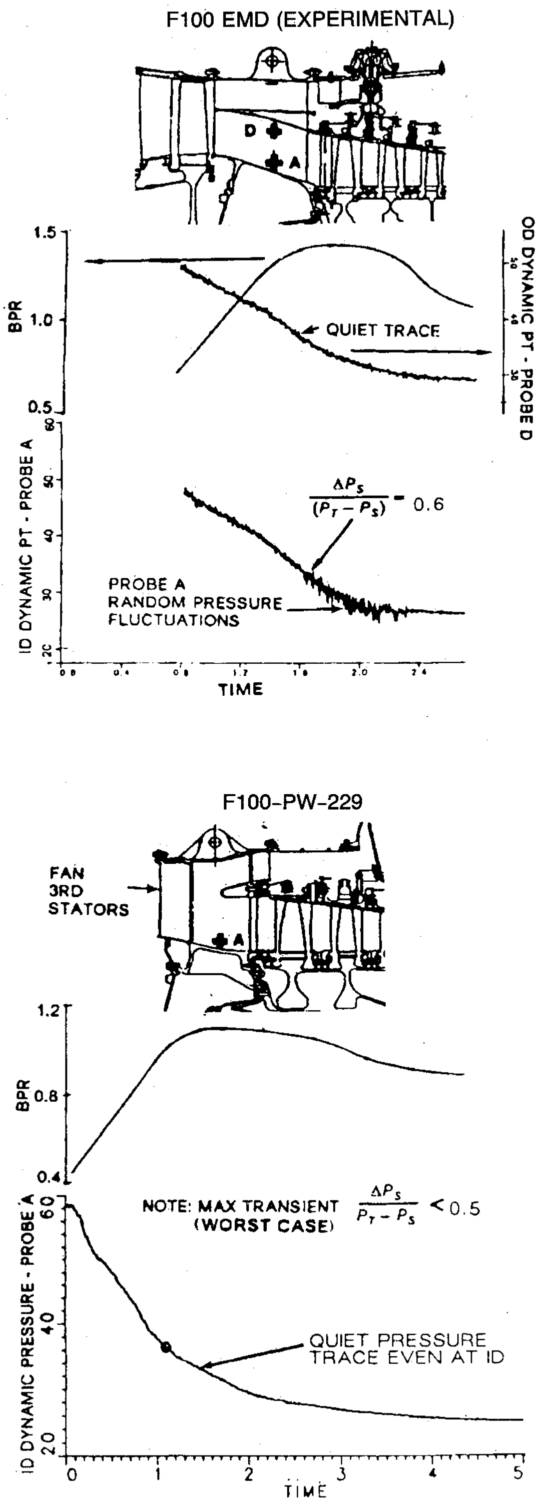

Fig. 10 Benefiting from lessons learned in intermediate case design.

Design of a New Transient Control Mode

The use of full authority digital control with the increased computational and logic capability allows implementation of new control concepts that dared not be entertained with hydromechanical systems. However, the practices followed during the hydromechanical days tend to persist due to the inertia effect. An open mind has to be kept to realize the full potential of the multiple-input and multiple-output digital control system of the modern afterburning turbofan engine. The availability of high-fidelity dynamic simulation permits exploring novel control modes under all possible operating conditions to determine if certain specific systems requirements can be met.

From these studies one can quantify the benefits and identify regions where a particular control mode can have an adverse impact requiring its selective deactivation. The transient control mode described below was designed using dynamic simulation and is being evaluated for a retrofit F100 engine (F100-PW-220E) to enhance thrust response in combat situations and also to increase LCF life. For tactical advantage during combat, a pilot has to perform Bodie transients when power is chopped to idle, and after a dwell time the gas generator is spooled back to full speed. Thrust response is considerably enhanced if AJ is opened in a controlled manner during the deceleration and closed during the follow-on acceleration.[9] Thrust reduction due to nozzle opening (nozzle exit velocity reduction) means that idle rotor speeds can be maintained high for the same idle thrust (Fig. 12). This reduction in rotor speed excursion has the double payoff of enhanced thrust response (Fig. 13) and increased LCF life due to the reduced strain range of rotating parts.

By exercising dynamic simulation, the constraints of this control mode were determined. Opening AJ too far is detrimental due to the constraints of bypass duct choking and

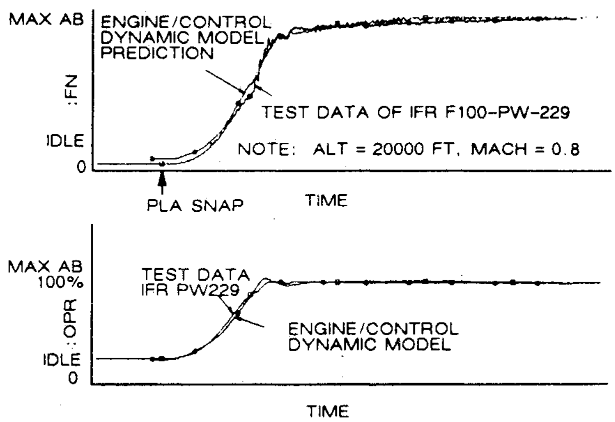

Fig. 11 Idle to Max AB test data duplicates model prediction.

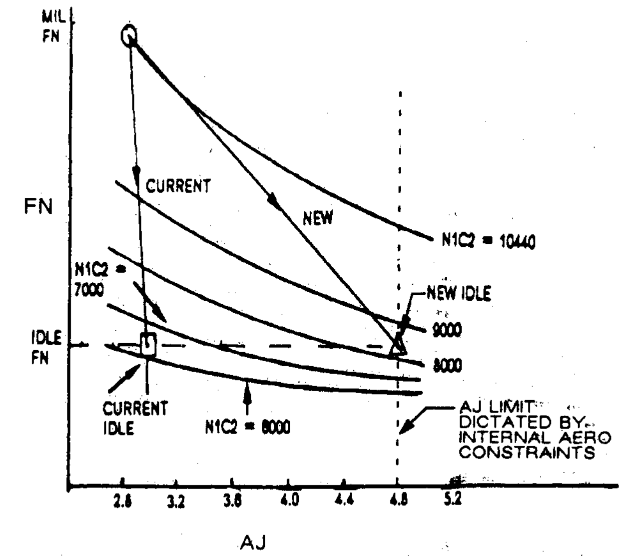

Fig. 12 Reduced rotor speed excursion with larger idle AJ.

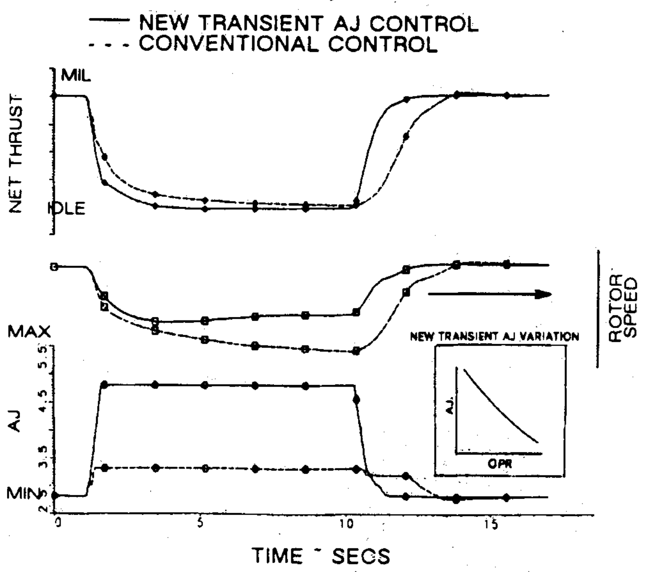

Fig. 13 New transient AJ control provides fast thrust response.

transient intermediate case aeroloading discussed earlier. Even after staying within those constraints, significant benefits can be realized in engine operability and durability. Of course, bigger AJ causes an increase in transient fuel consumption. However, by proper control-mode activation criteria implementable through digital control logic capability, this control mode can be made active only under certain operating conditions. This way the impact on total mission fuel burn is made insignificant.

Test Data Driven Engine Model (TDDM) Applications in Development/Flight Testing

The aforementioned analytical process of system design assures problem prevention during the development program. During the development test period, it is required to verify the design quantified by the various measures of merit and to refine the design. The test engines are instrumented with both steady-state and dynamic instrumentation to evaluate, for example, engine performance and operability. Determining measures of merit from engine measurements is not always easy and practical. For example, turbine inlet gas temperature used in engine performance analysis is based on flow-path area weighted average. To determine this parameter from measurements is a very difficult if not an impossible task. It would require, first, a large number of temperature probes covering the gas path station, and second, the temperature probes must be capable of withstanding high temperature. The objective of determining this measure of merit can be met by using the described method, which is a hybrid of test data reduction and

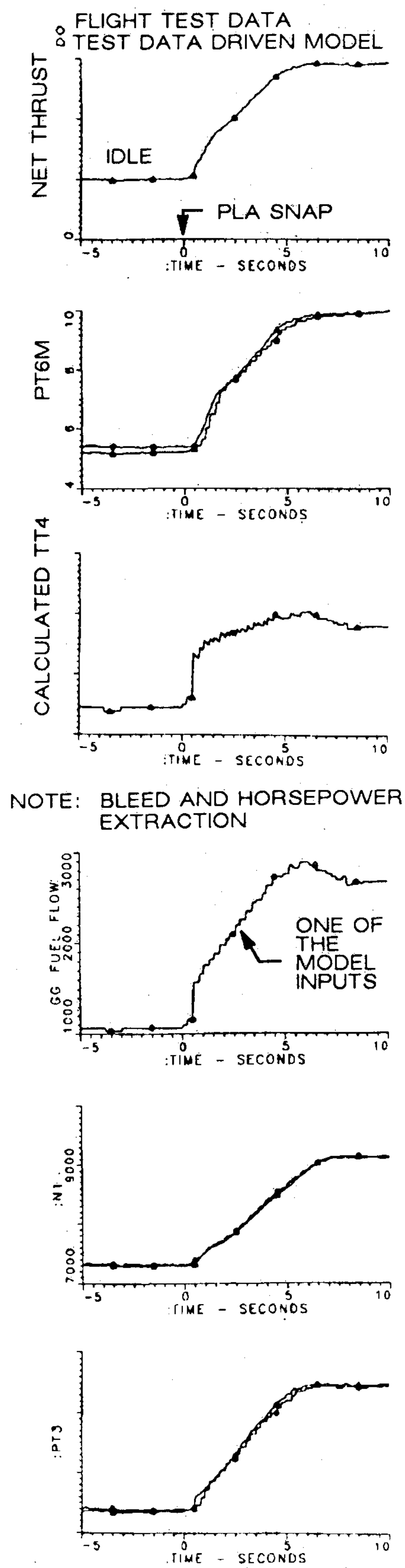

Fig. 14 In-flight transient thrust and combustor exit temperature, idle to mil snap, altitude 40,000 ft, Mach number 0.52.

simulation (Fig. 2). Test engine's fuel flow, variable geometry, and flight conditions when input into a high-fidelity dynamic engine model result in representative transient performance and internal engine parameters. Test data input is low pass filtered to eliminate noise before being used in calculations. This prevents convergence failures during cycle balance iterations.

In-Flight Transient Thrust Determination

The aforementioned method has been successfully used to calculate the in-flight transient thrust of a modern fighter engine installed in the F-15 flight-test aircraft. The first example is of a snap engine acceleration from flight idle to military power performed at an altitude of 40,000 ft and Mach number of 0.52 with installation effects of compressor bleed and horsepower extraction. The measured flight-test data for flight conditions, engine fuel flow, variable geometry, and exhaust nozzle area are used as input to the dynamic engine model. Model calculations for transient thrust, *PT6M* and *N*1, are shown in Fig. 14 together with flight test gas generator fuel flow, which is one of the inputs. The traces for *PT6M* and *N*1 are compared with flight-test data and show excellent agreement. Since *PT6M* is reflective of gross thrust and *N*1 is reflective of total engine airflow, it can be inferred that the calculated net thrust *FN* (gross thrust − ram drag) is representative. Also, it can be inferred from Fig. 14, based on the accuracy of *PT*3 (reflective of compressor airflow) and use of actual fuel flow, that the calculated combustor exit temperature *TT*4 is representative. The *TT*4 path and level were as originally predicted for the case with bleed and horsepower extraction.

The second example of Fig. 15 presents calculated in-flight transient thrust during a pilot-selected transfer from Max *AB* in primary control to secondary control (SEC) at a Mach number of 1.2, 30K. Again, the good agreement between measured and calculated augmentor pressure (*PAB*), and use of actual control outputs, is indicative of representative transient thrust. The closely duplicated *PAB* and use of actual flight conditions means accurate calculation of nozzle pressure ratio (NPR).

Since ideal gross thrust function $FG_i/(P_T A_J)$ is unique with NPR, gross thrust is representative, and since nozzle mass flow functions $[\dot{m}\sqrt{T}/(P_T \cdot AJ)]$ is unique with NPR, total engine airflow and, hence, ram drag are representative, making net thrust representative.

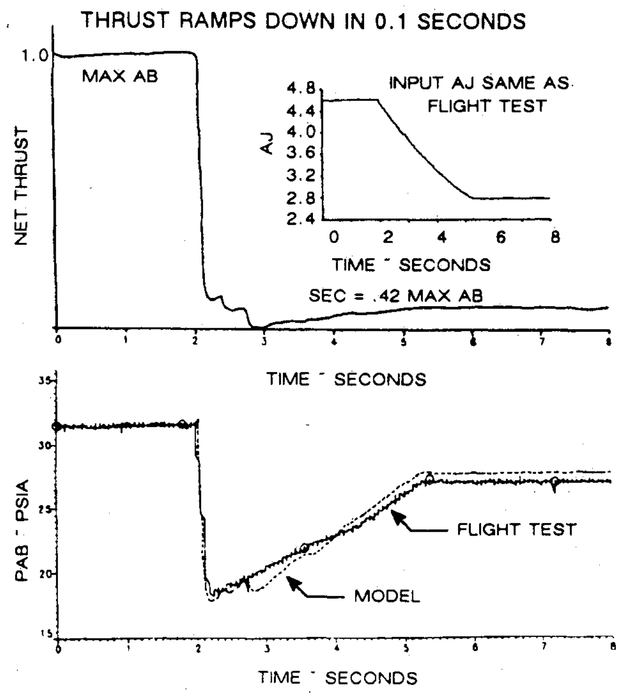

Fig. 15 In-flight transient thrust calculation during transfer from Max *AB* primary to SEC control.

Evaluating Augmentor Stability During Transients

The augmentor blowout susceptibility is indicated by the augmentor stability parameter[10] $V/(P_S{*}T^{1.7})$. For flight conditions when duct segments are turned off, augmentor stability parameter is based on average low pressure (LP) turbine exhaust properties (*SPMXE*). When augmentor stability parameter is based on local augmentor entrance measurements, it has not been a reliable indicator of blowout. This could be due to the scatter associated with the variation in local flow properties at the turbine exhaust swirl. To obtain transient stability parameters based on average flow properties, test data driven engine model was utilized. This is illustrated with the example of an augmentor transient from military power to maximum augmentation performed with a non-bill-of-material control logic at an altitude facility condition of 50,000 ft and Mach number of 0.6 using JP4 jet fuel (Fig. 16). The control was intentionally set to lower the fan match by lowering the engine pressure ratio (EPR) schedule 6% for this test. The engine achieved maximum augmentation, but the augmentor transiently encountered a blowout during segment sequencing and then recycled to get back on track. The blowout is indicated by the momentary drop-off in *PT6M* and the light-off

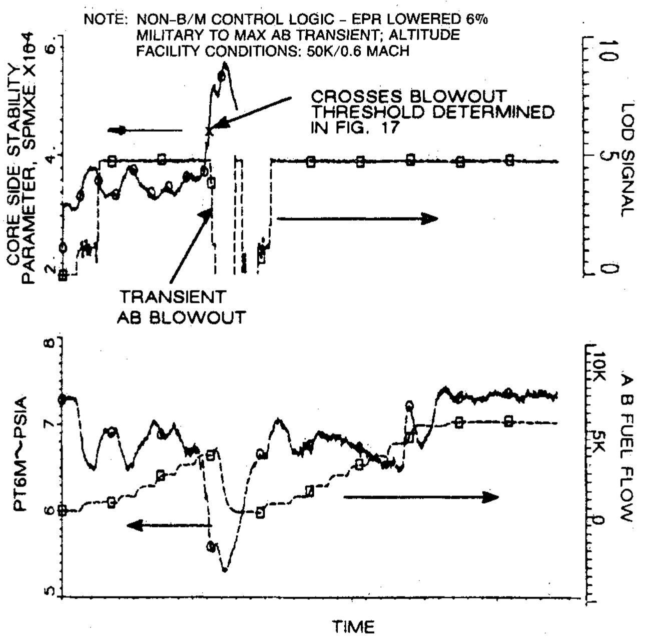

Fig. 16 Non-bill-of-material control mil to max *AB* transient.

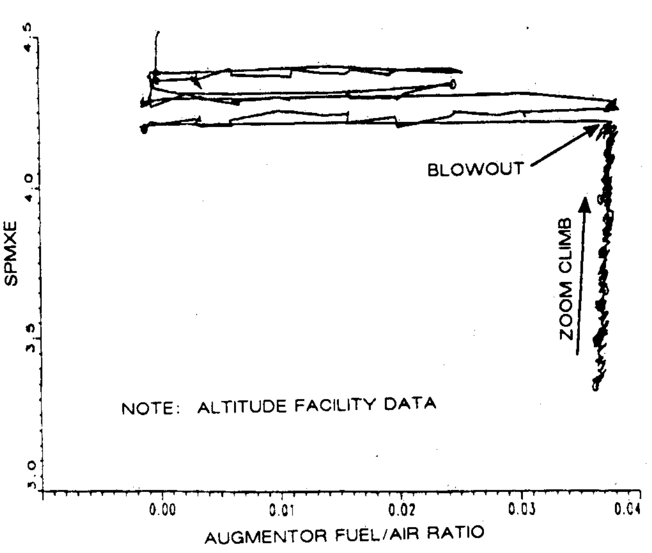

Fig. 17 *AB* core side stability parameter during zoom climb.

detector (LOD) signal and is a result of transient *AJ*/temperature rise mismatch. The restoration of *PT6M* and LOD signal is indicative of recovery from blowout. To calculate the stability parameter, measured engine data of *PT6M*, *N*1, fuel flow, and other test parameters were input in the engine model. The cycle was balanced at each transient point to make the model output match the measured test data. The resultant engine model calculation of the *SPMXE* during the transient is shown plotted vs time in Fig. 16, together with *PT6M* and LOD. It can be noted that when *SPMXE* rises sharply and crosses a threshold of 4.4×10^{-4}, the LOD signal drops, indicating a quenched flame. The blowout threshold was determined by processing the altitude facility test data for a zoom climb to blowout using the same method as the military to Max *AB* transient. The model calculated *SPMXE* for the zoom climb is shown plotted vs augmentor fuel-air ratio in Fig. 17, and the value of *SPMXE* when blowout is first encountered is also 4.4×10^{-4}.

Concluding Remarks

The analytical process described in this article proved to be valuable during engine design and development programs. The key results and conclusions include the following:

1) High-fidelity dynamic engine models permitted the selection of flow-path configurations that ensured component flow compatibility. Steady-state models are not adequate for configuration design since favorable transient component matching has to be ascertained for stable engine operation. The applications of this method to a fast-response modern fighter engine were very effective as evidenced by the excellent flight-test results of both F15 and F16 aircraft.

2) Comprehensive dynamic simulation studies resulted in control system optimization to meet operational requirements. Also, more tolerant control modes, with flexibility to accommodate changing requirements, were designed well ahead of engine tests.

3) Novel control modes were dependably evaluated across the operating spectrum to quantify the benefits and to determine the constraints. Appropriate activation criteria were identified that, when programmed in the digital control, made the novel control modes practicable.

4) Early identification of control requirements allowed the lead time to procure the state-of-the-art control hardware.

5) Accurate engine simulations provided pretest predictions that ensured safe and meaningful test investigations.

6) Data driven engine models aided design verification by calculating hard-to-measure parameters. The calculated average flow-path section parameters, such as augmentor stability parameter, were found to be good measures of merit since they were better indicative of engine match. Flight-test data driven model results on transient thrust also helped the airframer in integrating the engine and flight-control systems.

In summary, the use of representative dynamic engine models during engine flow-path design, engine control-system design, and development testing played a key role in problem prevention, in reducing development cost, and in ensuring timely weapons system procurement.

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