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PREDICTED PERFORMANCE BENEFITS OF AN ADAPTIVE DIGITAL ENGINE CONTROL SYSTEM ON AN F-15 AIRPLANE

Frank W. Burcham, Jr.,* Lawrence P. Myers,† and Ronald J. Ray‡
NASA Ames Research Center
Dryden Flight Research Facility
Edwards, California

Abstract

The highly integrated digital electronic control (HIDEC) program will demonstrate and evaluate the improvements in performance and mission effectiveness that result from integrating engine-airframe control systems. Currently this is accomplished on the NASA Ames Research Center's F-15 airplane. The two control modes used to implement the systems are an integrated flightpath management mode and an integrated adaptive engine control system (ADECS) mode. The ADECS mode is a highly integrated mode in which the airplane flight conditions, the resulting inlet distortion, and the available engine stall margin are continually computed. The excess stall margin is traded for thrust. The predicted increase in engine performance due to the ADECS mode is presented in this report.

Nomenclature

ADECS	adaptive engine control system
CAS	control augmentation system
DEEC	digital electronic engine control
DEFCS	digital electronic flight control system
EMD	engine model derivative
EPR	engine pressure ratio, PT6M/PT2
FTIT	fan turbine inlet temperature, °C
HIDEC	highly integrated digital electronic control
KA2	instantaneous total pressure distortion factor for the F100 engine
M	Mach number
PLA	power lever angle, deg
PS2	engine inlet static pressure
PT2	fan inlet total pressure, lb/in^2
PT6M	mixed turbine discharge total pressure, lb/in^2
q	pitch rate
TSFC	thrust specific fuel consumption
TT2	engine inlet total temperature
UART	universal asynchronous receiver transmitter
WA	fan airflow, lb/sec
α	angle of attack, deg
β	angle of sideslip, deg
Δ	change in parameter
δ_s	stick position
$\hat{}$	estimated value

Introduction

Engines that power high performance airplanes are currently operated with a stall margin large enough to accommodate the worst case combination of inlet distortion, throttle transient, and engine-to-engine variation. Operation with this large stall margin requires the engine thrust to be reduced over what could be obtained if a smaller stall margin could be used. With the advent of digital engine control systems, digital flight control systems, and data buses, it may be practical to integrate the engine and flight control systems and implement an adaptive engine control system (ADECS), in which the engine control margins are continuously adjusted to match the needs of the airplane. For example, airframe data could be used to allow the engine to operate at higher performance levels (uptrim) at times when the inlet distortion is low and the full engine stall margin is not required. It may also be desirable to obtain additional engine stall margin (downtrim) during certain flight manuevers, such as during a STOL landing rollout with reverse thrust where reingestion could cause an engine stall, or for extreme attitude flight such as might be used for fuselage pointing.

NASA Ames Research Center's Dryden Flight Research Facility, in cooperation with other government agencies, is conducting a program called highly integrated digital electronic control (HIDEC). This program will develop and evaluate new digital engine control technology which is integrated with the digital flight control system of the airplane.[1] As part of the HIDEC program, an adaptive engine control system (ADECS) mode will be implemented. This paper describes the ADECS mode and the performance benefits predicted by simulation results.

Airplane

The NASA F-15 airplane (Fig. 1) is used for the HIDEC program. The F-15 is a high-performance air superiority fighter aircraft with excellent transonic maueuverability and a maximum Mach capability of 2.5. It is powered by two F100 afterburning turbofan engines. The F-15 airplane has also been used for the evaluation of the digital electronic engine control (DEEC) system on the F100

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*Chief, Propulsion Section, Member AIAA.

†F-15 Propulsion Engineer, Member AIAA.

‡Aerospace Engineer, Member AIAA.

engine, and the F100 engine model derivative (EMD) engine.

HIDEC System

The equipment that is installed on the F-15 airplane for the HIDEC program is shown in Fig. 2. The F100 EMD engines tested at NASA Ames-Dryden will be used, along with the DEEC engine controllers. A digital electronic flight control system (DEFCS) is installed in the airplane and will accommodate the HIDEC computations. A digital interface and bus control unit and a cockpit control and display are also installed. A telemetry uplink from ground-based computers is also available. The F-15 airplane is fully instrumented and equipped for propulsion and flight control integration research.

A block diagram of the HIDEC system on the F-15 is shown in Fig. 3. The various digital systems on the airplane will communicate with each other through a digital interface and bus controller. This unit will permit the HIDEC system to communicate with the equipment on the F-15 H009 data bus, the universal asynchronous receiver transmitter (UART) data bus, and the 1553 bus.

The DEEC controllers on each engine will communicate with the HIDEC system through the UART bus. The normal throttle inputs to the DEEC controllers and the backup engine controls from the cockpit will be maintained.

The DEFCS is a digital implementation of the analog control augmentation system (CAS) currently on the F-15. It is a dual channel, fail-safe, high-authority system that operates in conjunction with a mechanical flight control system. The DEFCS replaces the analog computations in the CAS and has data bus input and output capability in Military-Standard (MIL-STD) 1553 format. It is programmable in higher-order language and currently has 80 percent excess capacity available for other control computations. For the early phases of the HIDEC program, the HIDEC control laws will be implemented in the unused portion of the DEFCS computers.

Initially, the pilot will communicate with the HIDEC system through a cockpit control and display panel. Later, a cockpit multifunction display will be added. This unit, which is currently produced for the F-18 airplane, communicates on the 1553 bus The pilot's normal stick, rudder, and throttle inputs will be handled as they are in the standard F-15 airplane.

The NASA uplink system is also MIL-STD 1553 compatible, and can be used to provide data to the HIDEC system. This will permit control algorithms to be processed in a ground-based computer.

Most of the airframe data required by the HIDEC system is available from the equipment currently installed and communicating on the F-15 H009 data bus, shown at the top of Fig. 3. Included is the air data computer, the inertial navigation set, the horizontal situation indicator, the attitude and heading reference set, and the central computer unit. The navigational control indicator panel is used to input data into the inertial navigation system, and can be used for keyboard entries into the HIDEC system.

For future system expansion, an additional onboard computer will be added. This computer will be 1553 compatible, and will provide additional flexibility and computational power.

The NASA data system will monitor parameters on the 1553 bus as well as other parameters that are recorded directly. This data will be recorded on board and also telemetered to the ground for real-time display, analysis, and use in control law computations that may be uplinked to the airplane.

Engine

The F100 EMD engine, Fig. 4, is an upgraded version of the F100-PW-100 engine that currently powers the production F-15 airplanes. These engines are built by Pratt and Whitney Aircraft and have a company designation of PW 1128. The engine incorporates a redesigned fan, revised compressor and combustor, single crystal turbine blades and vanes, a 16-segment augmentor with light-off detector, and a DEEC. More information on the F100 EMD engine is presented in Ref. 2.

The DEEC[3] is a key part of the HIDEC system. It is a full-authority digital control with an integral hydromechanical backup control. It controls the gas generator and augmentor fuel flows, the compressor bleeds, the variable inlet guide vanes, the variable stators, and the variable exhaust nozzle. The DEEC incorporates logic which provides closed-loop control of engine airflow (WA) and engine pressure ratio (EPR). It also limits fan turbine inlet temperature (FTIT). It has the capability to accept inputs from the airplane, in addition to the many engine sensors. Additional information on the DEEC logic is given in Refs. 3 and 4.

Two computer simulations of the F100 EMD engine are being used in the HIDEC program; a nonlinear, aerothermodynamic, steady-state engine performance program[5] and a nonlinear, aerothermodynamic, transient engine performance program. The steady-state model provides accurate values for many engine parameters including engine thrust, fuel flow, fan and core stall margins, and the DEEC parameters. Its inputs are inlet pressure, temperature, and power setting. The nonlinear transient model of the F100 EMD provides realistic dynamic response characteristics for engine transients.

ADECS Mode

The most significant engine variable that may be affected with the ADECS mode is the EPR. A simplifed view of the ADECS-mode EPR uptrim is shown in the block diagram of Fig. 5. For EPR uptrim, airframe data — such as flight conditions, attitudes, rates, and pilot commands — are input into logic to provide the current angles of attack and sideslip and a prediction of what these parameters will be in the future. It is planned, for example, to combine angle of attack, pitch rate, and stick position to generate an angle-of-attack estimate. These inputs are then used to determine current and predicted inlet distortion.

The inlet distortion data is presented as a function of angle of attack and angle of sideslip. At each flight condition, a value of distortion for which full EPR uptrim will be allowed and for which no uptrim will be allowed is generated. The output of this logic will be the allowable percent uptrim based on the inlet conditions.

Engine simulation data will be used to provide the maximum increase in EPR that is allowable at each flight condition. This data will be developed by using the F100 EMD simulation to determine the amount of EPR uptrim available for the low-distortion condition produced by the inlet.

The percent uptrim command will be multiplied by the maximum change in EPR to generate the ΔEPR command. This command will be sent to the DEEC. The DEEC will incorporate protect logic to eliminate any uptrim requests larger than the maximum ΔEPR. The effect of the ΔEPR request will be to have the DEEC request a higher EPR, which will be accomplished by closing the nozzle. The higher EPR will increase the thrust.

Inlet Distortion Data

Distortion data for the F-15 inlet, operating at the maximum airflow of the F100 EMD engine, will be used to generate the percent uptrim logic. The maximum instantaneous distortion, the KA2 distortion factor, represents the combined effect of radial and circumferential distortion on the F100 engine, and is formulated so that KA2 is linearly related to loss of stall margin. Figure 6 shows typical KA2 contours, as a function of angle of attack (α) and angle of sideslip (β) at Mach 0.9, for the left inlet. KA2 values range from 0.4 to 1.1. The distortion values are not symmetric with respect to β because of the side fuselage-mounted inlets on the F-15 airplane; the right inlet would have the sign of β reversed. The engine stall tolerance at this flight condition is specified to be 1.0, providing stall-free operation at all conditions except for the one extreme condition of $\alpha = -10^\circ$ and $\beta = 10^\circ$. Data is only available at α from -10° to +40°, and for β from -10° to +10°. The results could be extrapolated to larger values of α and β, but this does not appear to be warranted for the F-15 airplane.

For the ADECS logic, the inlet data of Fig. 6 must be converted to percent allowable uptrim, as shown in Fig. 7. The KA2 contour of 1.0 is set to a 0-percent uptrim value (full-stall margin required). Except for the $\alpha = -10^\circ$ and $-\beta = 10^\circ$ point, the limits of the test data are used to define the remainder of the 0 percent uptrim. The KA2 contour of 0.4 is then set to a 100-percent uptrim value for this case. In general, a table could be provided to define the percent uptrim contours in whatever detail would be required. For the F-15 airplane, this may be simplified by using linear interpolation between the 100-percent and 0-percent uptrim boundaries. To provide a transition region, the 100-percent uptrim boundary may be moved to $\beta = \pm 5^\circ$ even though the data indicate that it could be at ± 10°. The actual contours may also be represented by a series of straight lines, as shown in Fig. 7. Inlet data will be stored in the HIDEC computer at several flight conditions, and linear interpolation will be used at other flight conditions.

Maximum ΔEPR

The maximum ΔEPR is a function of inlet total temperature (TT2) and power lever angle (PLA). Maximum ΔEPR is determined using the following procedure. The engine stall margin is determined from a stability audit of the engine, shown in Fig. 8. The stability audit data is derived from component rig tests, sea-level and altitude engine test results, flight results, and analytical methods. For example, at Mach 0.9 and at an altitude of 40,000 ft, the total stall margin is 22 percent, of which 11 percent is required for augmentor allowance, Reynolds number effects, engine-to-engine variation, and control tolerance. The remaining 11 percent is available for distortion tolerance and stall margin remaining. The distortion tolerance is required to accommodate the distortion shown in Fig. 6, where the maximum allowable KA2 was 1.0, and the minimum that occurred was 0.4. Therefore, to accommodate the minimum distortion of 0.4, 40 percent of the distortion tolerance is needed. This requires that the stall margin maintained at 14 percent, as shown in Fig. 8.

Predicted Performance Improvements

As shown in Fig. 9, the engine steady-state simulation has been run at the subsonic high-altitude condition at the normally scheduled EPR and with EPR uptrim for maximum power at Mach 0.9 and at an altitude of 40,000 ft. The EPR is increased by closing the nozzle. The increased back pressure on the fan decreases stall margin, as shown. It also requires more fan work, which in turn requires an increase in fan turbine inlet temperature, FTIT, to hold the scheduled fan speed. The thrust increases as shown. The desired 14-percent stall margin can be maintained with a 10-percent EPR uptrim, and a resulting thrust increase of 5.6 percent. The efficiency of the fan and the augmentor combustion increase for the EPR uptrim, up to 10-percent, is shown in Fig. 9. This results in a decrease of thrust specific fuel consumption (TSFC) of 0.06 (3 percent) for the uptrim.

In general, augmentor combustion efficiency increases with uptrim due to the higher pressures in the augmentor. The fan efficiency also generally increases with uptrim. A fan map for the F100 EMD engine is shown in Fig. 10. It shows that the normal operating line for the F100 EMD fan, set by stall margin considerations, is below the line of optimum fan efficiency at all except the lowest fan speeds. The EPR uptrims to higher fan pressure ratio therefore increase fan efficiency, in some cases, up to 3 percent.

The combination of increased thrust and decreased TSFC in augmentation results in the ability to achieve a desired thrust at considerably reduced fuel flow. Figure 11 shows the thrust-TSFC curve for the F100 EMD engine at Mach 0.9, with and without uptrim, for intermediate power and for five augmented power settings. At maximum augmentation and the partial augmentation power settings shown, the TSFC decreases as the thrust increases. With uptrim, the same thrust level can be achieved at lower TSFC, and hence, a lower fuel flow. For example, the 100-percent thrust level without uptrim may be achieved at a lower power setting with uptrim, and the resulting TSFC is reduced by 0.18 (approximately 9 percent).

The steady-state simulation deck has been used to predict the thrust increases due to the ADECS EPR uptrim for the F100 EMD engine over the flight envelope of the F-15 airplane. The results for maximum augmented thrust are shown in Fig. 12. At low Mach numbers, the percent thrust increase ranges from 4 to 10 percent. At supersonic speeds, the increase is 2 to 4 percent. Slightly larger increases are predicted at lower augmented power settings. At intermediate power, the percent thrust increases are in the 6- to 8-percent range.

Figure 13 summarizes the reductions in fuel flow with EPR uptrim that have also been determined at several flight conditions to achieve the nonuptrimmed maximum thrust (as shown in Fig. 11). The percent reductions in fuel flow average 5 percent at supersonic Mach numbers, 10 percent at Mach 0.9, and as much as 18 percent at static conditions.

EPR Uptrim Dynamics

The dynamics of the ADECS EPR uptrim mode have been investigated with the F100 EMD dynamic engine simulation. The EPR uptrim can be introduced gradually and does not pose a dynamic problem. However, the uptrim may have to be rapidly removed in case of a rapid aircraft maneuver in which the full engine stall margin is needed. To investigate rapid EPR downtrims, a 10-percent EPR downtrim request was input into the simulation as shown in Fig. 14. The downtrim request caused the nozzle to open at its maximum rate, decreasing thrust and increasing stall margin. The fan speed increased slightly as the fan back pressure was decreased, but the core fuel flow cut back rapidly and the fan speed increase was only 100 rpm. Stall margin increased 5 percent in less than one sec with no tendency to overshoot or oscillate. This response appears to be more than adequate for the expected airplane maneuvers. Closed-loop simulations are being developed to more fully investigate the interactions between the pilot, airplane, and engine.

Concluding Remarks

Predictions of the performance benefits of an adaptive engine control system on an F100 EMD engine in an F-15 airplane have been made. Based on inlet distortion data and engine stability audits, a significant amount of stall margin is available to trade for thrust. At maximum augmented power, thrust increases of 4 to 10 percent may be obtained from the ADECS mode. To achieve the nonuptrimmed maximum thrust with uptrim, the ADECS mode permits reductions of fuel flow of 5 to 10 percent. Preliminary transient simulation results show that EPR uptrim can be rapidly removed without dynamic instabilities.

References

[1] Burcham, Frank W., Jr., and Haering, Edward A., "Highly Integrated Digital Engine Control System on an F-15 Airplane," AIAA Paper 84-1259, June 1984.

[2] Myers, Lawrence P., and Burcham, Frank W., Jr., "Preliminary Flight Test Results of an F100 EMD Engine in an F-15 Airplane," AIAA Paper 84-1332, June 1984.

[3] Burcham, Frank W., Jr., Myers, Lawrence P., and Walsh Kevin R., "Flight Evaluation Results for a Digital Electronic Engine Control System in an F-15 Airplane," AIAA Paper 83-2703, Nov. 1983.

[4] "Digital Electronic Engine Control (DEEC) Flight Evaluation in an F-15 Airplane," NASA CP-2298, 1984.

[5] F100 EMDP Prototype Engine Flight Demonstration Performance Model, User's Manual for Deck CCD 1194.2, Pratt and Whitney Report FR-16212, Mar. 1983.

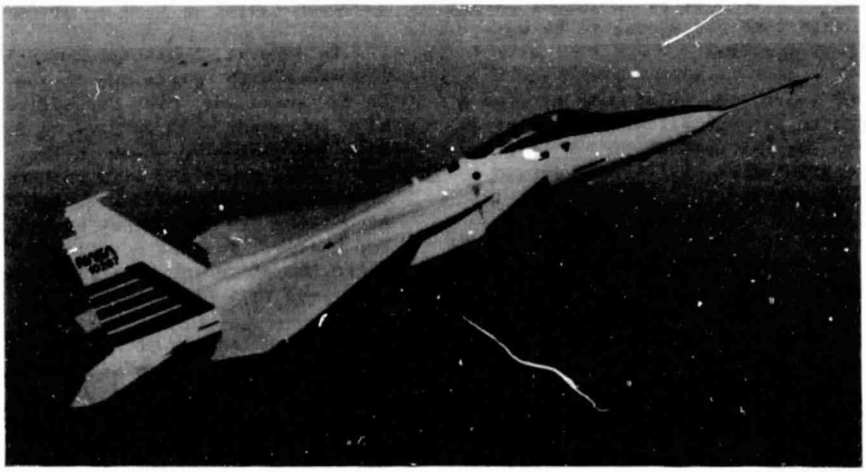

Fig. 1 F-15 airplane.

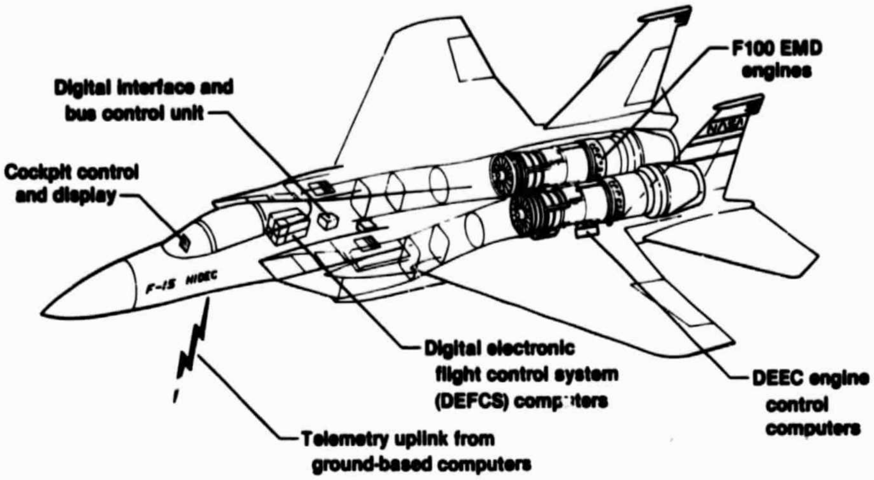

Fig. 2 Features of the F-15 HIDEC research airplane.

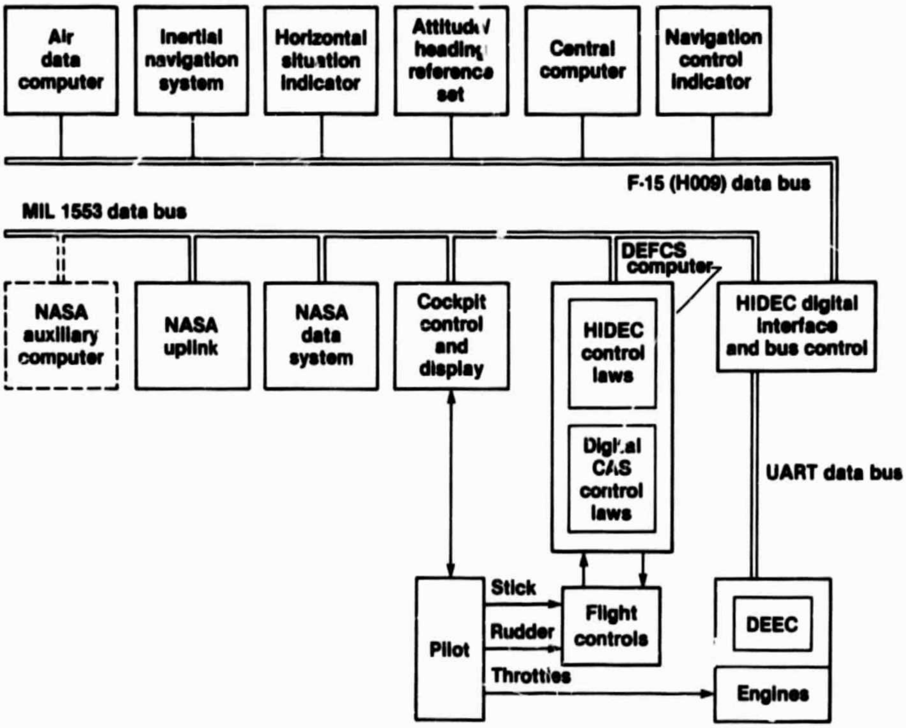

Fig. 3 Block diagram of the HIDEC system.

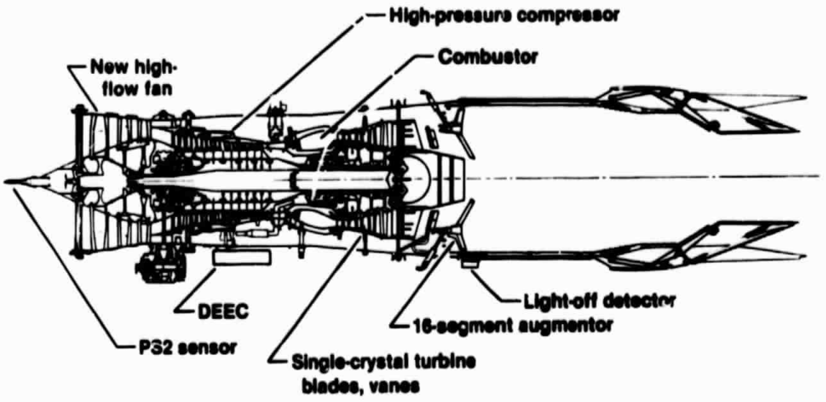

Fig. 4 Features of the F100 EMD engine for the HIDEC program.

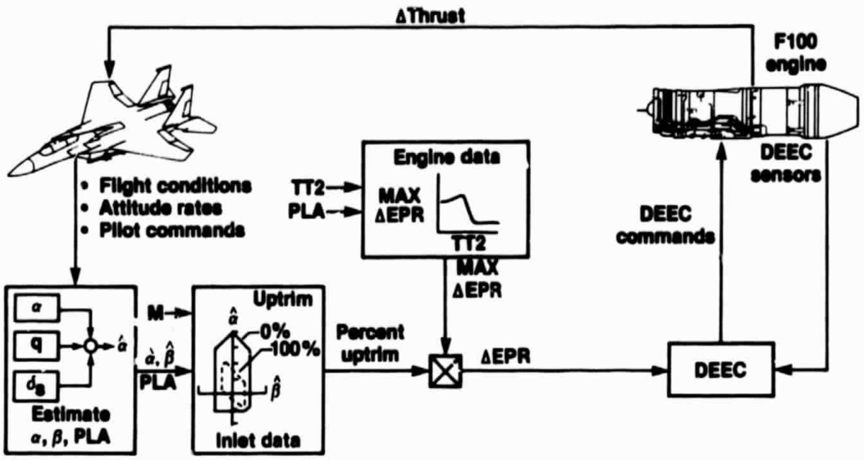

Fig. 5 Block diagram of the HIDEC ADECS mode.

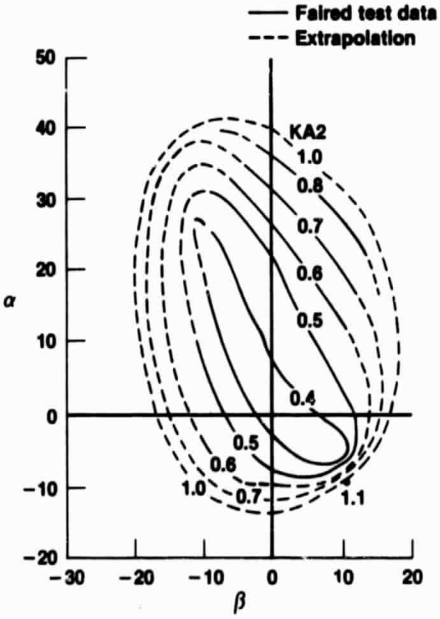

Fig. 6 Inlet distortion contours. M = 0.9; WA = 230 lb/sec, left inlet.

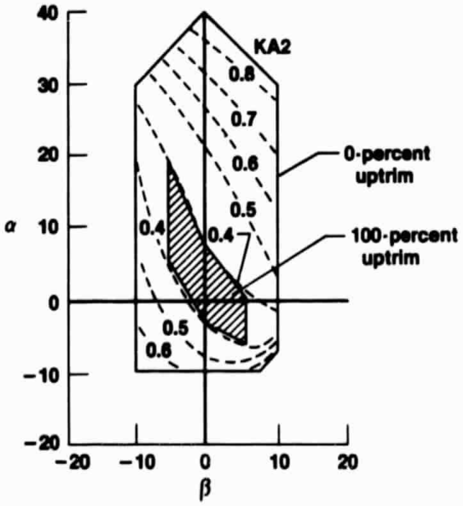

Fig. 7 Uptrim contours for ADECS mode at 0 and 100 percent. M = 0.9; left inlet.

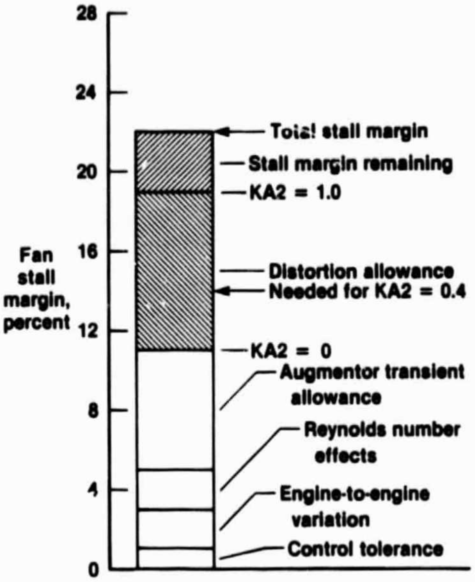

Fig. 8 Stability audit for F100 EMD engine. M = 0.9; altitude = 40,000 ft.

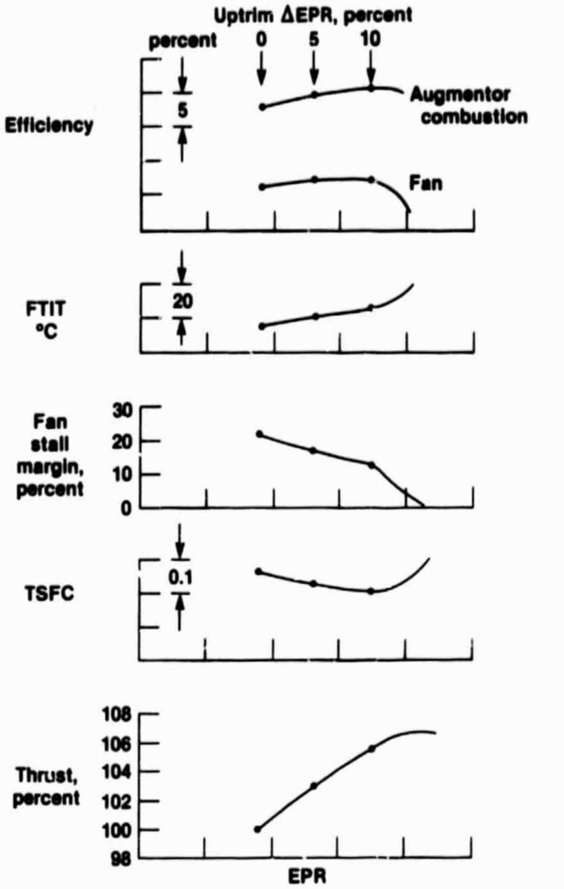

Fig. 9 ADECS-mode EPR uptrim. M = 0.9; altitude = 40,000 ft; maximum power.

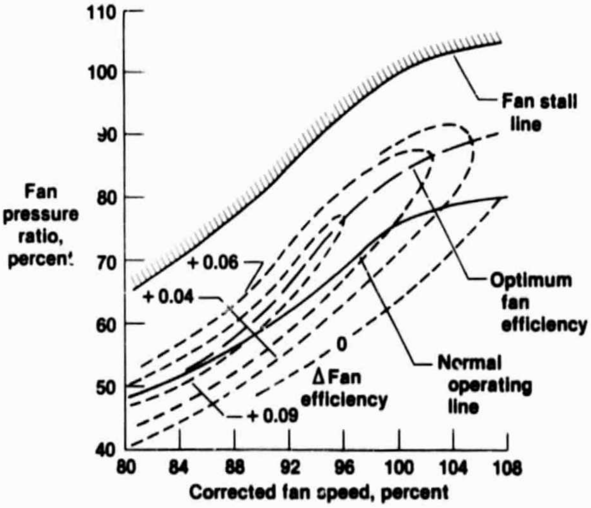

Fig. 10 Fan efficiency map for F100 EMD.

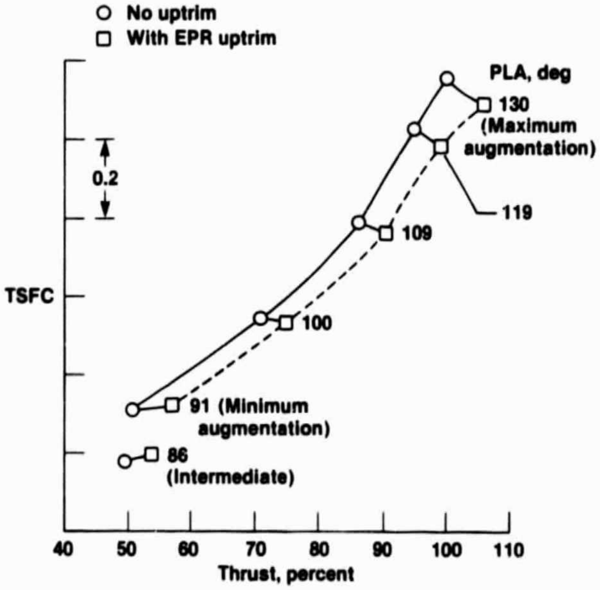

Fig. 11 Thrust-TSFC data for F100 EMD engine with and without EPR uptrim. M = 0.9; altitude = 40,000 ft.

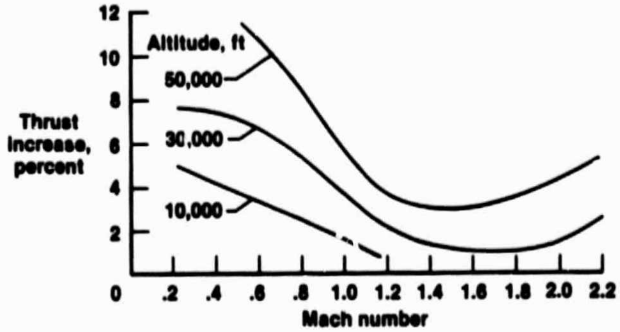

Fig. 12 Thrust increase for ADECS mode, maximum power.

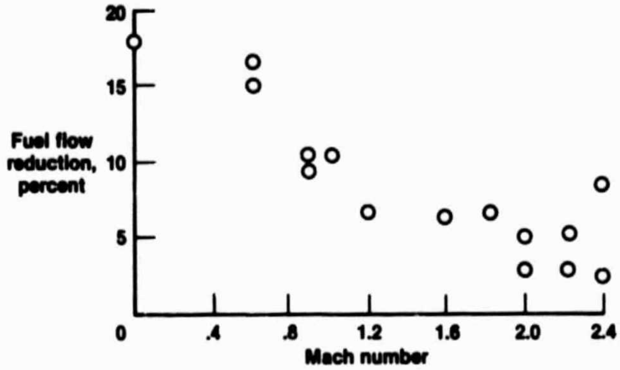

Fig. 13 Reduction in fuel flow with EPR uptrim to obtain nonuptrimmed maximum thrust.

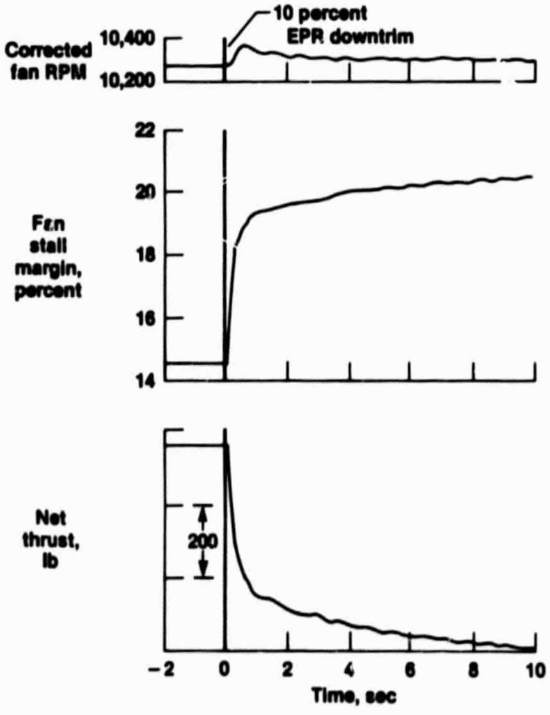

Fig. 14 F100 EMD transient simulation results for a rapid EPR downtrim. M = 0.9.