NASA/TM—1998-208655

SAE 985556

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Prepared for the
1998 World Aviation Congress and Exposition
cosponsored by the Society of Automotive Engineers International
and the American Institute of Aeronautics and Astronautics
Anaheim, California, September 28–30, 1998

National Aeronautics and
Space Administration

Lewis Research Center

September 1998

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# HIGH STABILITY ENGINE CONTROL (HISTEC): FLIGHT DEMONSTRATION RESULTS

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## ABSTRACT

Future aircraft turbine engines, both commercial and military, must be able to accommodate expected increased levels of steady-state and dynamic engine-face distortion. The current approach of incorporating sufficient design stall margin to tolerate these increased levels of distortion would significantly reduce performance. The High Stability Engine Control (HISTEC) program has developed technologies for an advanced, integrated engine control system that uses measurement-based estimates of distortion to enhance engine stability. The resulting distortion tolerant control reduces the required design stall margin, with a corresponding increase in performance and/or decrease in fuel burn. The HISTEC concept was successfully flight demonstrated on the F-15 ACTIVE aircraft during the summer of 1997. The flight demonstration was planned and carried out in two parts, the first to show distortion estimation, and the second to show distortion accommodation. Post-flight analysis shows that the HISTEC technologies are able to successfully estimate and accommodate distortion, transiently setting the stall margin requirement on-line and in real-time. Flight demonstration of the HISTEC technologies has significantly reduced the risk of transitioning the technology to tactical and commercial engines.

## INTRODUCTION

Advanced tactical aircraft are likely to use low observable inlets and, possibly, thrust vectoring for enhanced aircraft maneuverability. As a result, the propulsion system will see higher levels of distortion than currently encountered with present-day aircraft. Also, the mixed-compression inlets needed for the High Speed Civil Transport (HSCT) will likely encounter disturbances similar to those seen by tactical aircraft in addition to planar pulse, inlet buzz, and high distortion levels at low flight speed and off-design operation. The result of these increased levels of distortion is generally a decrease in propulsion systems performance, and more importantly, a lessening of the stable flow range of the compressor.[1] Current gas turbine engine design practice bases fan and compressor stall margin requirements on the worst case stack-up of destabilizing factors which include external factors such as inlet distortion as well as internal factors such as large tip clearances **(Figure 1)**. A stability audit is defined and maintained during the engine development process to account for the effects of each known destabilizing factor. The stability audit stacks up the worst case stall margin losses from each of the known factors, adds margin for engine-to-engine variability, and ensures that fan and compressor have some remaining stall margin under this worst case stack-up. However, this approach, especially in the case of future engines with increased levels of distortion, results in an increase in design stall margin requirement with a

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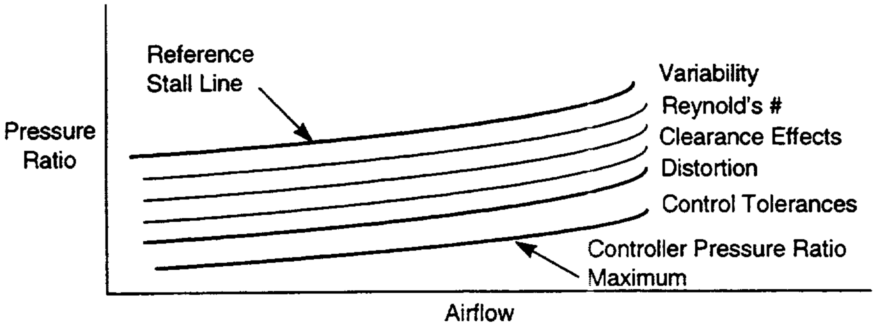


Figure 1 - Stall Margin Requirements

corresponding reduction in performance and/or increase in weight.

NASA is currently pursuing two research approaches which were confirmed beneficial by NASA's aircraft engine customers during the Advanced Control Concepts study sponsored by NASA.[2,3,4,5] The far term approach is to increase the amount of operational stall margin available by actively controlling the onset of stall, otherwise know as active stall control or active stability control.[6,7,8,9,10] The nearer term approach is to transiently increase the stall margin requirement on-line as the destabilizing effect, in this case engine face pressure distortion, is encountered. This approach, distortion tolerant control, allows a reduction in the required design stall margin by an amount on the order of the destabilizing impact of the distortion.

The distortion tolerant control approach developed for the High Stability Engine Control (HISTEC) uses a small number of engine-face pressure measurements to accurately estimate the actual distortion present. From this pressure-based distortion estimate, an onboard stability audit requests a time-varying stall margin requirement. The engine controller then accommodates the distortion by acting upon the current stall margin requirement supplied by the onboard stability audit.

In this paper, an overview of the HISTEC Program is given. The HISTEC approach and the hardware and software used to implement the approach for flight are described. Next, the planning and execution of the flight test program is discussed. Finally, a summary of the flight test results is provided along with conclusions concerning the HISTEC flight demonstration.

## THE HISTEC PROGRAM

HISTEC is a five year program sponsored by the NASA Lewis Research Center in Cleveland, Ohio. Program partners include NASA Dryden Flight Research Center, which accomplished the flight demonstration; Pratt &

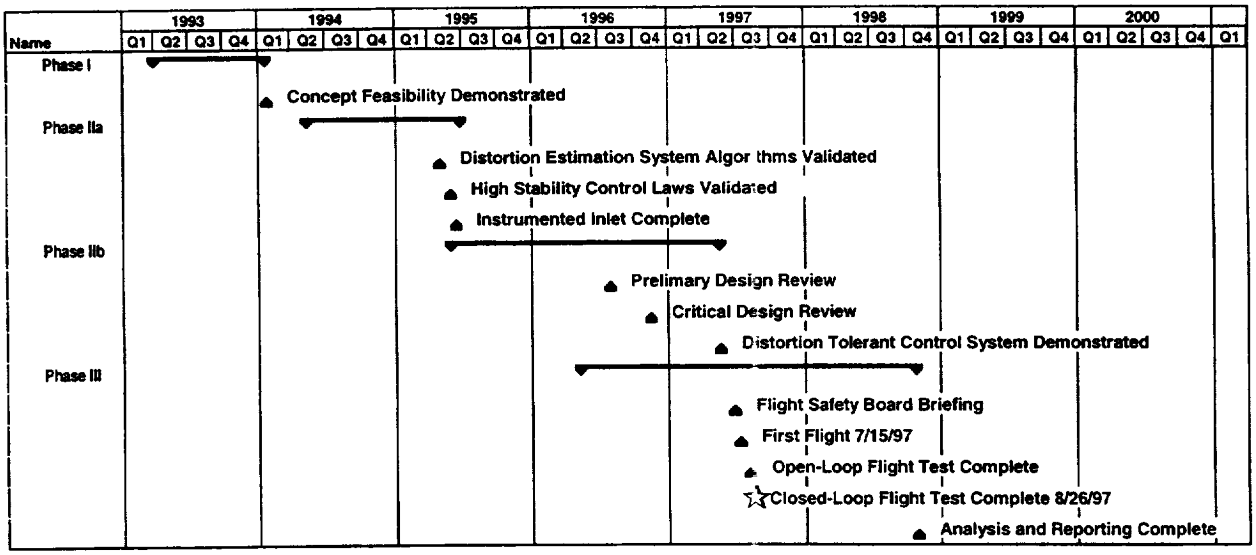


Figure 2 - HISTEC Program Timeline

Whitney, which developed the technical concepts and the systems for flight demonstration; Boeing (formerly McDonnell Douglas), which helped integrate the HISTEC systems onto the flight test vehicle; and the U.S. Air Force, which provided flight systems, engines, and the aircraft assets.

The HISTEC program consists of three phases: Phase I - Algorithm Development, Phase II - Concept Validation and System Development, and Phase III - Engine/Flight Demonstration. A timeline for the program is shown in **Figure 2.** HISTEC Phase I "Algorithm Development", completed in 1994, successfully defined the requirements for, and designed the algorithms necessary for the Distortion Estimation System (DES).[11] Under Phase IIA - "Concept Validation", the integrated DES algorithms and distortion accommodation algorithms (High Stability Control Laws) were designed and validated. This integration testing used a detailed nonlinear aero-thermal transient model of the F100-PW-229 engine and an emulator of the F-15 aircraft inlet which estimates engine inlet pressures based on aircraft flight condition, angle-of-attack, and angle-of-sideslip. The simulation testing confirmed that the HISTEC system is able to sense inlet distortion, determine the effect on engine stability, and accommodate for distortion by maintaining adequate engine surge margin.[12]

During HISTEC Phase IIb - Systems Development, and Phase III - Engine/Flight Demonstration, the systems necessary to flight demonstrate the HISTEC approach were developed and validated through systems testing and ground engine test. The systems were installed on the F-15 Advanced Control Technology for Integrated Vehicles (ACTIVE) aircraft at NASA Dryden and the HISTEC technologies were successfully flight demonstrated in the summer of 1997.[13,14,15]

## HISTEC APPROACH

The HISTEC distortion tolerant control approach includes three major elements: Engine Face Pressure Sensors; the Distortion Estimation System (DES); and the Stability Management Control (SMC) **(Figure 3)**. The engine face pressure sensors consist of a small number of high-response, wall static pressure transducers. The DES uses these high response pressure measurements along with maneuver information from the flight control to calculate indicators of the type and extent of distortion present and the sensitivity of the propulsion system to that distortion. The output of the DES consists of fan and compressor pressure ratio trim commands which are then communicated to the SMC. The SMC performs a stability audit online using the trims from the DES and then accommodates the distortion through the production engine actuators. The approach combining the DES and SMC results in a distortion tolerant control which enables a reduced design stall margin requirement.

To accomplish the HISTEC flight demonstration, systems for implementing the HISTEC approach on the F-15 ACTIVE aircraft were developed, validated, and installed on the aircraft. The following sections provide details on each of the elements of the HISTEC approach and their implementation for flight.

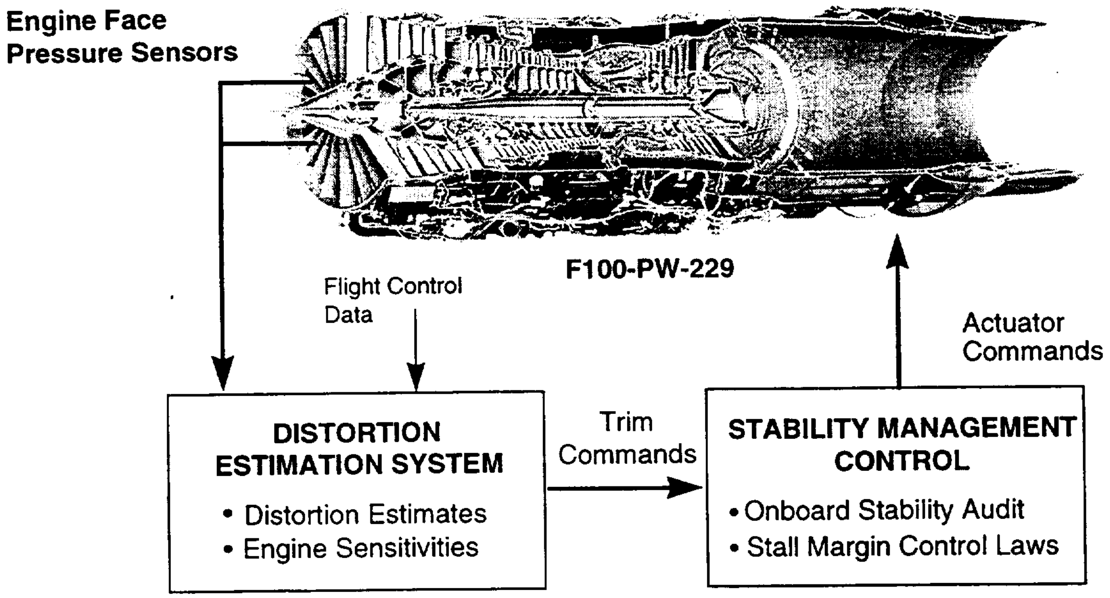
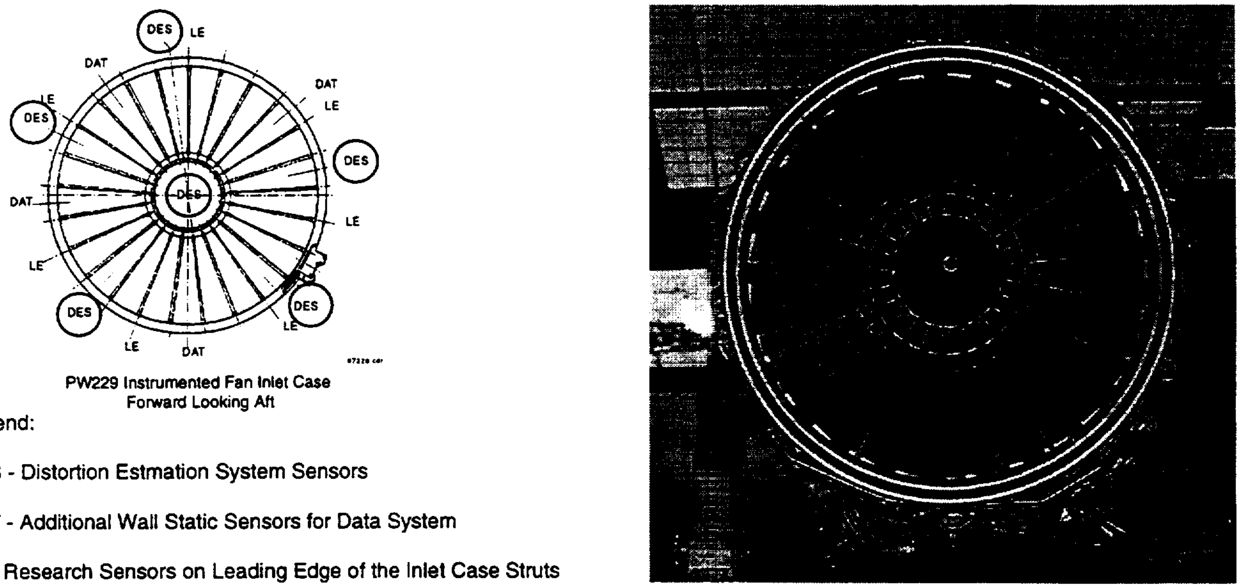


**Figure 3 - HISTEC Distortion Tolerant Control Approach**



PW229 Instrumented Fan Inlet Case
Forward Looking Aft

Legend:

DES - Distortion Estmation System Sensors

DAT - Additional Wall Static Sensors for Data System

LE - Research Sensors on Leading Edge of the Inlet Case Struts

**Figure 4 - Instrumented Inlet Case**

INSTRUMENTED INLET CASE - The HISTEC instrumented inlet case, designed and fabricated during HISTEC Phase IIa, is a production F100-PW-229 fan inlet case modified to incorporate the HISTEC engine face pressure sensors **(Figure 4)**. The sensors which are used by the Distortion Estimation System include five wall static pressure transducers at the engine face outer diameter (OD) and five at the inner diameter (ID) electrically averaged to a single measurement. In addition to the DES sensors, thirty-five total pressure sensors are located on 7 inlet case struts, 5 sensors per strut, distributed radially on each strut by equal flow path area. These research sensors provide a reference for validating the DES sensors. For temperature compensation, seven total temperature probes are located approximately mid-span on the same inlet struts as the total pressure sensors. Finally, wall static pressure sensors located at nine locations (5 locations the same as the DES sensors, 4 additional locations) provide additional spatial resolution for investigating if the number of DES pressure sensors is sufficient.

DISTORTION ESTIMATION SYSTEM (DES) - The DES algorithms follow the basic concepts of traditional stability audit methodology [16] **(Figure 5)**. This methodology consists of standards for measurement, pattern classification, and computation of stability debits and relies on the key assumption of superposition of stability debits for individual circumferential, radial, and planar dynamic distortion components. For the DES, a Fourier transform formulation of the distortion classification allows implementation of the distortion estimation using digital signal processing techniques. The DES algorithms first convert the wall static DES pressure measurements into equivalent total pressure measurements **(Figure 6)**. The DES algorithms then perform spatial Fourier transforms to classify the distortion present into circumferential, radial, and planar components. Temporal Fourier transforms (FFT) then obtain the frequency content of each of the spatial distortion components. Finally, frequency domain sensitivity functions are applied to find the impact of the distortion components on stall pressure ratio for the fan and compressor. Dynamic maneuver compensation, using maneuver information from the flight control, provides look-ahead capability to anticipate high

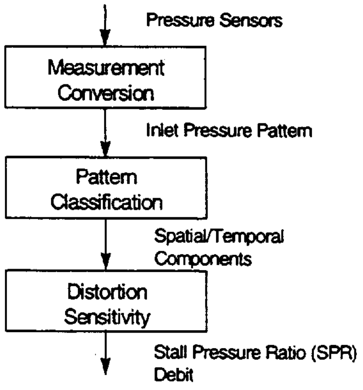


**Figure 5 - Traditional Stability Audit Methodology**

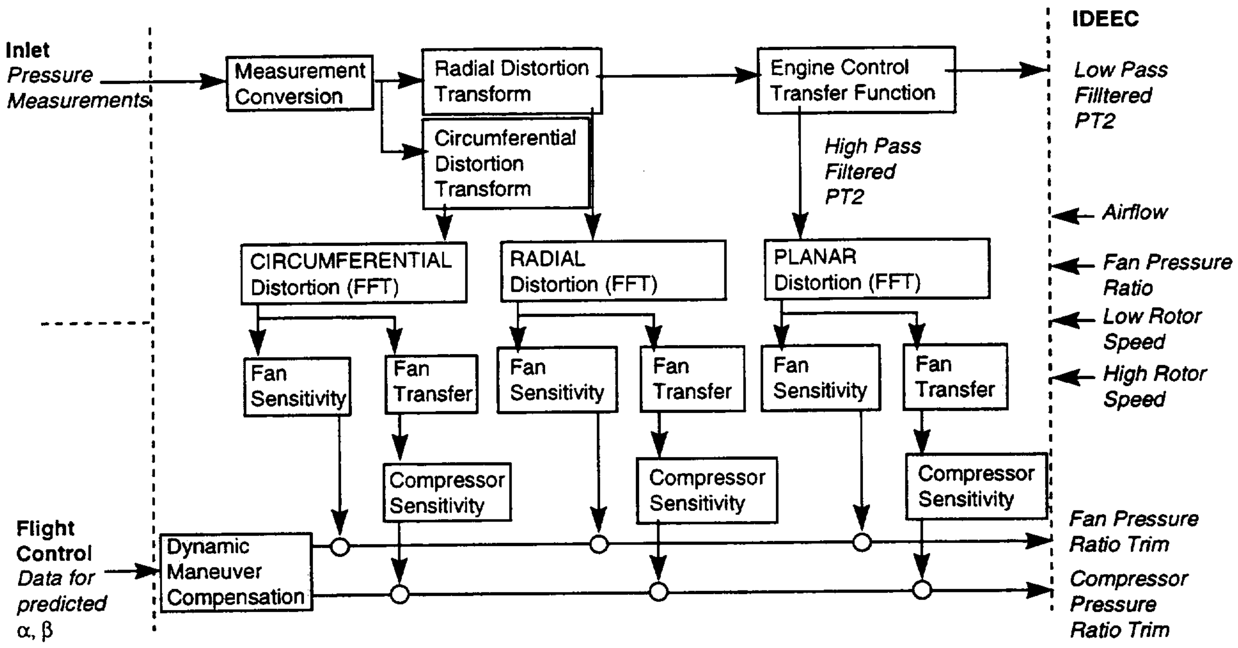


**Figure 6 - Distortion Estimation System (DES) Algorithms**

distortion conditions. A detailed description of the DES algorithms is contained in **Reference 12.**

The F119 Group 1 Comprehensive Engine Diagnostic Unit (CEDU) was chosen during HISTEC Phase IIa to implement the DES for flight testing. The CEDU has a flight-quality design and sufficient I/O and throughput capability. The CEDU also contains a digital signal processor to efficiently implement the signal processing techniques used in the DES algorithms. For HISTEC the CEDU was airframe mounted.

STABILITY MANAGEMENT CONTROL (SMC) - The SMC algorithms build on the bill-of-material F100-PW-229 control laws. For HISTEC, the SMC algorithms added an onboard stability audit to account for the destabilizing influence of distortion (as computed by the DES) and other factors **(Figure 7)**. Advanced control laws manage the amount of stall margin remaining in the fan and high pressure compressor. The SMC algorithms were incorporated into a production, engine mounted F100-PW-229 Improved Digital Electronic Engine Control (IDEEC). The IDEEC on the right-hand engine on the F-15 ACTIVE was replaced with the IDEEC containing the HISTEC SMC algorithms. Communications between the IDEEC and DES were accomplished through the aircraft 1553 data bus.

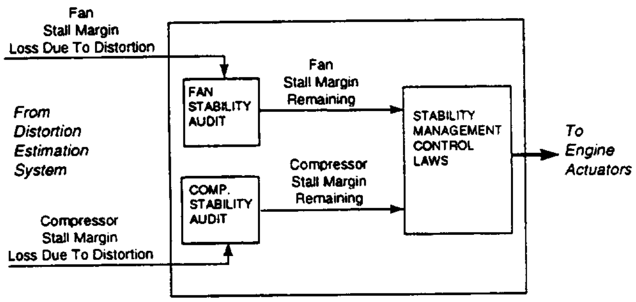


**Figure 7 - Stability Management Cotrol (SMC)**

## FLIGHT TEST PROGRAM

PLANNING - The flight test program was designed to methodically demonstrate the HISTEC approach to high stability engine control and to provide a significant amount of high-quality inflight dynamic inlet distortion data. The flight demonstration included: validating the ability of the measurement system to provide sufficient information to the DES to reconstruct the engine face pressure profile; validating the ability of the DES to accurately estimate on-line and in real-time the amount and type of distortion and its impact on engine stability; and finally, validating the ability of the SMC to conduct an accurate on-line stability audit and provide good distortion accommodation in the stability management control laws.

The flight test program was divided into two parts. Part 1 included an extensive matrix of test points to obtain the distortion database and determine the ability of the DES to accurately estimate stall margin loss due to inlet distortion. Although the stall margin control laws within

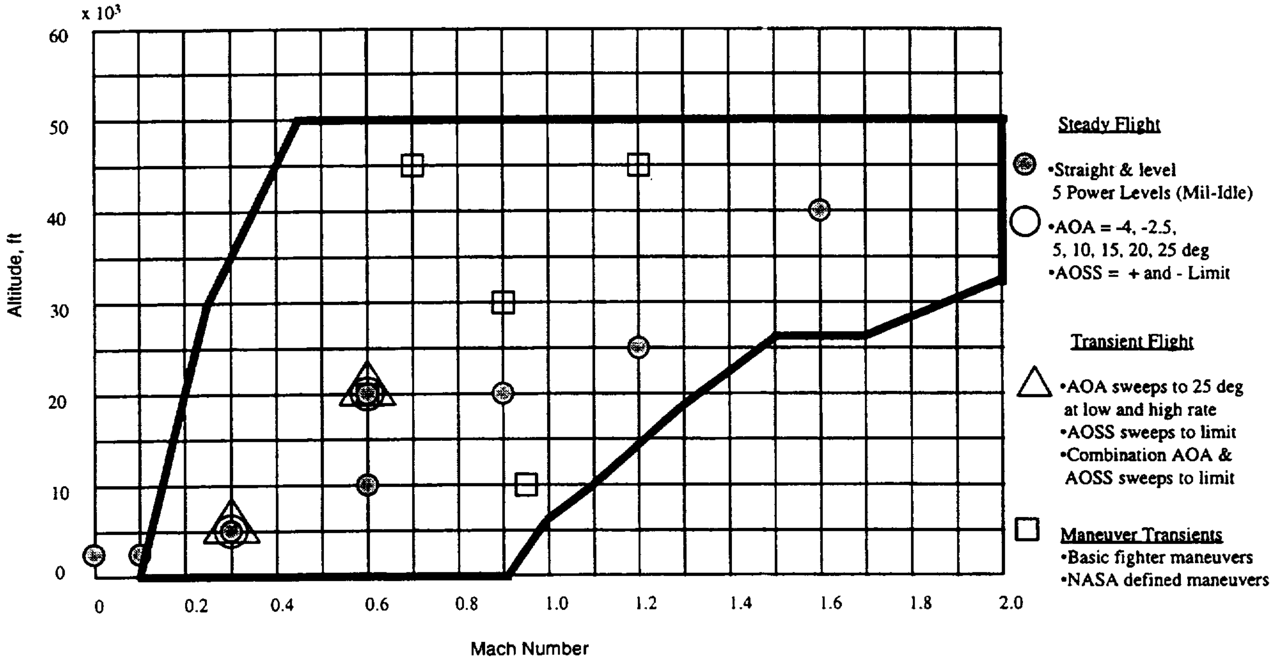


Figure 8 - HISTEC Flight Envelope

the SMC were executing for evaluation purposes, the control did not send trim data to the engine for stability accommodation during Part 1 of the flight testing. This is referred to as *open-loop* operation. At the conclusion of Part 1, flight test data analysis was performed to determine the need to fine-tune the HISTEC algorithms prior to proceeding with Part 2 of the flight test. Part 2 of the HISTEC flight test program focused on *closed-loop* operation where the control modified engine operation to maintain engine stability based on inputs from the DES.

The HISTEC flight test envelope is shown in **Figure 8**. A test point matrix consisting of 106 test points at various subsonic and supersonic flight conditions was developed to carry out the two part flight test discussed above. Flight conditions were chosen so that the majority of testing would be accomplished with inlet pressures in the middle of the transducers' range. This inlet pressure (~13 psia) also approximates the pressure on the ground where transducer calibrations were done. Mach numbers were chosen which approximated typical stability audit points. Engine operating points were chosen to provide a variety of airflows, which in turn provided a wide variation in distortion pressure patterns. Included in the test point matrix were aircraft maneuvers to generate high levels of distortion. These included steady and transient high angle-of-attack (AOA) and angle-of-sideslip (AOSS) flight, wind-up turns, split-S maneuvers, and take-offs. These allowed a thorough demonstration of distortion estimation in the first part and of distortion accommodation in the second part of testing.

FLIGHT TEST CONFIGURATION - The HISTEC flight tests were conducted at the NASA Dryden Flight Research Center at Edwards, California, on the NASA F-15 ACTIVE aircraft **(Figure 9)**. The HISTEC instrumented inlet case and IDEEC with SMC algorithms were mounted on the right-hand engine. The DES was aircraft mounted in an avionics bay near the front of the right engine. The DES computer communicated with the engine control through the aircraft flight-control 1553 data communications bus. In order to fit functionally

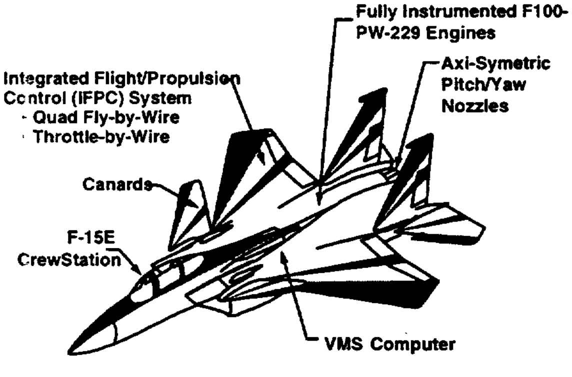


Figure 9 - F-15 ACTIVE Testbed

within the existing bus architecture, the DES was installed in place of one of the channels of the Vehicle Management System Computer (VMSC). This required additional software in the DES to emulate the VMSC on the data bus and also required disabling some of the functionality of the VMSC. Although the aircraft was equipped with thrust vectoring nozzles, they were not used during HISTEC testing due to these data bus constraints in accommodating the HISTEC control hardware.

DEMONSTRATION - Flight testing commenced on July 15, 1997, and the first part of testing was completed after 7 flights (~7 flight hours) over a 3½ week period. The second part of testing, consisting of 4 flights (~3 flight hours), was completed on August 26, 1997. Overall, the execution of the flight test was extremely successful. All test points were flown except some negative angle-of-attack points which were precluded due to aircraft systems problems at negative g-forces. Over 65 Gbytes of high-quality data were recorded onboard the aircraft and/or telemetered to ground recording stations. All HISTEC flight research objectives were successfully accomplished. A detailed description of the flight test execution is contained in **Reference 14**.

## FLIGHT DEMONSTRATION RESULTS

Analysis of the flight test data indicates that the measurement system, the Distortion Estimation algorithms, and the Stability Management Control elements of the overall HISTEC control system all performed as designed. Post-flight analysis has focused on three main areas, corresponding to the three elements of the HISTEC approach. First, it was necessary to determine if the DES wall-static pressure transducers were able to reconstruct the engine face pressure profile with enough fidelity to determine the amount and type of distortion present. Second it was necessary to show that the DES is able to compute distortion descriptors and apply the appropriate sensitivity functions to provide the correct stall margin pressure ratio debit to the onboard stability audit in the SMC. And finally, it was necessary to show that the onboard audit was able to apply the distortion stability debit to the control laws in order to accommodate conditions of high distortion. Representative results are given in the following sections.

*Table I - Summary of HISTEC Flight Test Instrumentation Drift Analysis*

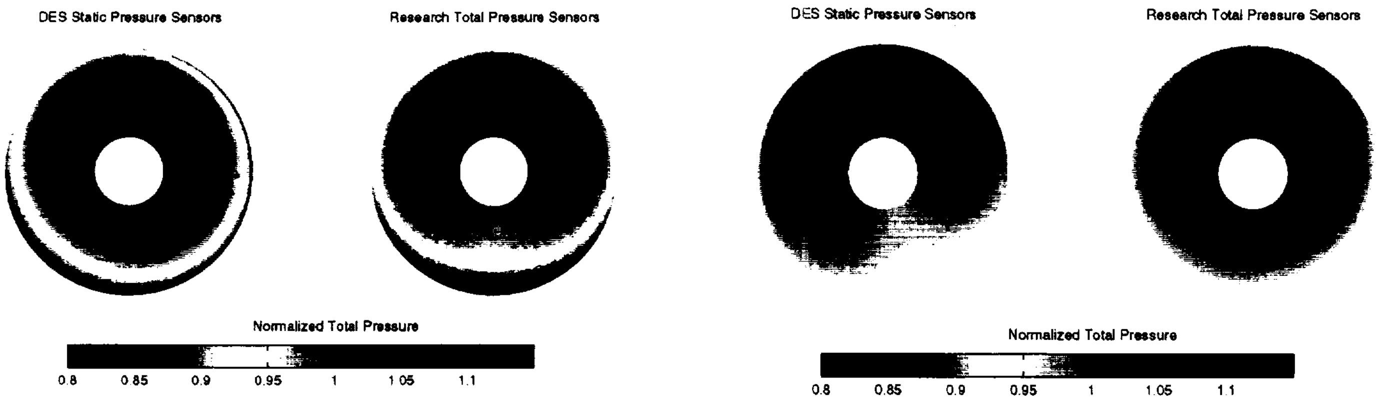
| *Transducer* | *Average* | *Slope* | *Standard Deviation* |
|---|---|---|---|
| *PTIGV9-5 (Max. Slope)* | *0.4533* | *0.3181* | *1.1492* |
| *PTIGV19-3 (Min. Slope)* | *-0.0728* | *0.0001* | *0.0128* |
| *PSW20 (Median Slope)* | *0.0065* | *0.0107* | *0.0497* |

ENGINE FACE PRESSURE MEASUREMENTS - The HISTEC flight test instrumentation performed exceptionally well during the flight test. All high response pressure transducers were checked for drift during testing. This was accomplished through a pre-flight engine-off data point taken at the beginning of each day of testing. This information was then compared to an independent atmospheric pressure measurement, with the difference (psi) applied to the transducer for the remainder of the day. The difference, known as the ambient offset, was plotted verses test day and fit with a linear least squares curve fit. The slope of the linear fit is a measure of the transducer drift. The slope was always small compared to the standard error of the data indicating the system uncertainty masked any transducer drift that may have occurred. **Table I** shows the slope and standard error (psi) for the transducer with the largest drift, the least drift, and the transducer that fell in the middle. In the table, transducers with a PTIGV header were the high response total pressure type, located on the fan inlet guide vane struts while PSW20 was one of the high response wall static transducers.

Each flight, there was also a pressure calibration data point taken at an altitude of 20,000 feet, Mach 0.6 (20K/0.6), straight and level at full power. All total pressure transducers were repeatable to within 2.5% while all static pressure transducers were repeatable to within 5%.

To qualitatively assess if the DES sensors were able to reconstruct the engine face pressures, the face pressure profile computed from the six DES pressure measurements was compared to the corresponding pressure profile computed from the thirty-five research total pressure sensors. Both pressure profiles were calculated by first fitting Fourier series descriptors to the sensor data, similar to the calculations done in the DES. The engine face pressure profile was then back-calculated from the resulting spatial Fourier series coefficients. **Figure 10** shows two such comparisons.

In **Figure 10(a)**, the pressure profiles from the DES sensors and research sensors for high airflow, high angle-of-attack (and thus high-distortion) conditions are



(a) AOA=21 deg, AOSS=0 deg, Mil Power

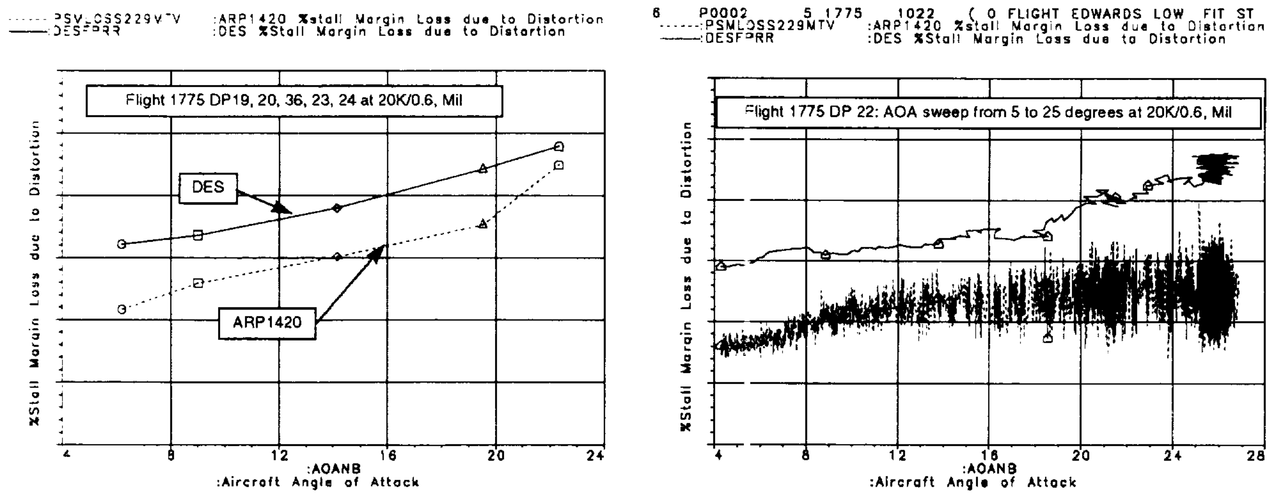
(b) AOA=11 deg, AOSS=2 deg, Part Power

**Figure 10 - Measurement System Results, Altitude=20000 feet, Mach Number=0.6**
*(Right Hand Engine, Aft Looking Forward)*

shown to compare favorably. This indicates that the DES wall static pressure sensors are able to pick up the important features for estimating distortion. The circumferential distortion in the DES surface is rotated slightly relative to the research surface. This is believed to be due to the DES static pressure transducers being located in a slightly different axial plane than the research instrumentation.

**Figure 10(b)** shows the same comparison for a lower airflow and lower angle-of-attack (and thus lower distortion) condition. Again, the pressure profile calculated from the DES wall static pressure sensors compares favorably to that computed from the research total pressure sensors.

DISTORTION ESTIMATION - Next the stall margin debit due to distortion as calculated by the DES in flight from the DES sensors was compared to the stall margin debit calculated off-line from flight data for the 35 research sensors using the industry-standard ARP1420 methodology.[16] In **Figure 11(a)**, this comparison is shown for time-averaged data for five levels of steady angle-of-attack (AOA) between approximately 5 and 23 degrees. The first important result seen in the figure is that the stall margin debit due to distortion is correctly



(a) Steady angle-of-attack

(b) Angle-of-attack sweep

**Figure 11 - Distortion Estimation Results**
*(vertical scale omitted to protect proprietary data)*

estimated as increasing with increasing AOA. Second, the stall margin debit calculated in flight by the DES is quite similar in magnitude and slope to that computed by the ARP1420 method. In **Figure 11(b)**, this same comparison is made for time-history data for an AOA sweep maneuver from approximately 5 to 25 degrees. Again the estimated stall margin debit due to distortion is correctly shown to be increasing for increasing angle of attack, and the DES in-flight results compare favorably to the ARP1420 results. One additional result is shown in the time-history data. The ARP1420 method, computed at each time sample, shows that as AOA and average distortion level increase, the time-varying nature of the distortion increases as well. However, the DES signal processing algorithms tend to smooth the calculated stall margin debit even at high distortion levels.

DISTORTION ACCOMMODATION - The F100-PW-229 engine is designed with sufficient stall margin to operate stall-free anywhere in the F-15 flight envelope even under worst case distortion conditions. Thus, distortion accommodation is not normally required to maintain stability. However, to allow flight evaluation of the HISTEC distortion tolerant control approach, a simulated stability audit limit was incorporated into the SMC to force control action to downmatch the engine to accommodate for high levels of inlet distortion. This simulated audit limit represents the stability limit of an advanced fan or compressor component designed with reduced stall margin, as would be possible for an engine incorporating the HISTEC technologies.

Closed-loop operation of the complete HISTEC approach was demonstrated in flight by having the DES and SMC accommodate the high levels of distortion encountered during aggressive aircraft maneuvers. One such maneuver is the "Split-S" **(Figure 12).** During this maneuver, the pilot inverts the aircraft and then pulls the stick back to get a sustained high angle-of-attack (AOA) while diving towards the ground.

**Figure 13** shows the successful in-flight distortion accommodation during a Split-S maneuver. **Figure 13(a)** shows the angle-of-attack (AOA) for the maneuver. As can be seen, close to 25 degrees AOA is achieved for almost 10 seconds. **Figure 13(b)** shows that for this maneuver, Power Lever Angle (PLA) is held constant. Therefore any transient in the control is due to the maneuver, and not due to an engine power transient.

**Figure 13(c)** shows the desired engine pressure ratio (EPR) limit as computed by the SMC and provided as a request to the control's regulator logic. **Figure 13(c)** also shows the HISTEC modifier to the EPR request as computed from the stall margin debit provided by the DES. For a controller without the HISTEC distortion accommodation logic, since there is no engine transient, the EPR limit request would remain essentially flat throughout the maneuver. As shown in **Figure 13(c)**, early in the maneuver, while at low AOA, the EPR request remains at this nominal value. However, as AOA (and thus distortion) increases, the HISTEC EPR modifier requests a lower EPR, that is, increased stability in the presence of distortion. At the end of the maneuver as AOA returns to near zero, the HISTEC EPR modifier allows the EPR request to again increase to its nominal value. **Figure 13(d)** shows that, in response to the lowered EPR request at high distortion conditions, the SMC control laws successfully accommodate the distortion by commanding open the nozzle area ($A_j$) to downtrim EPR.

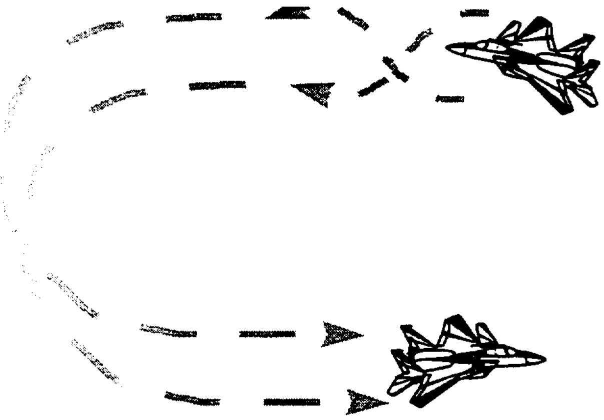
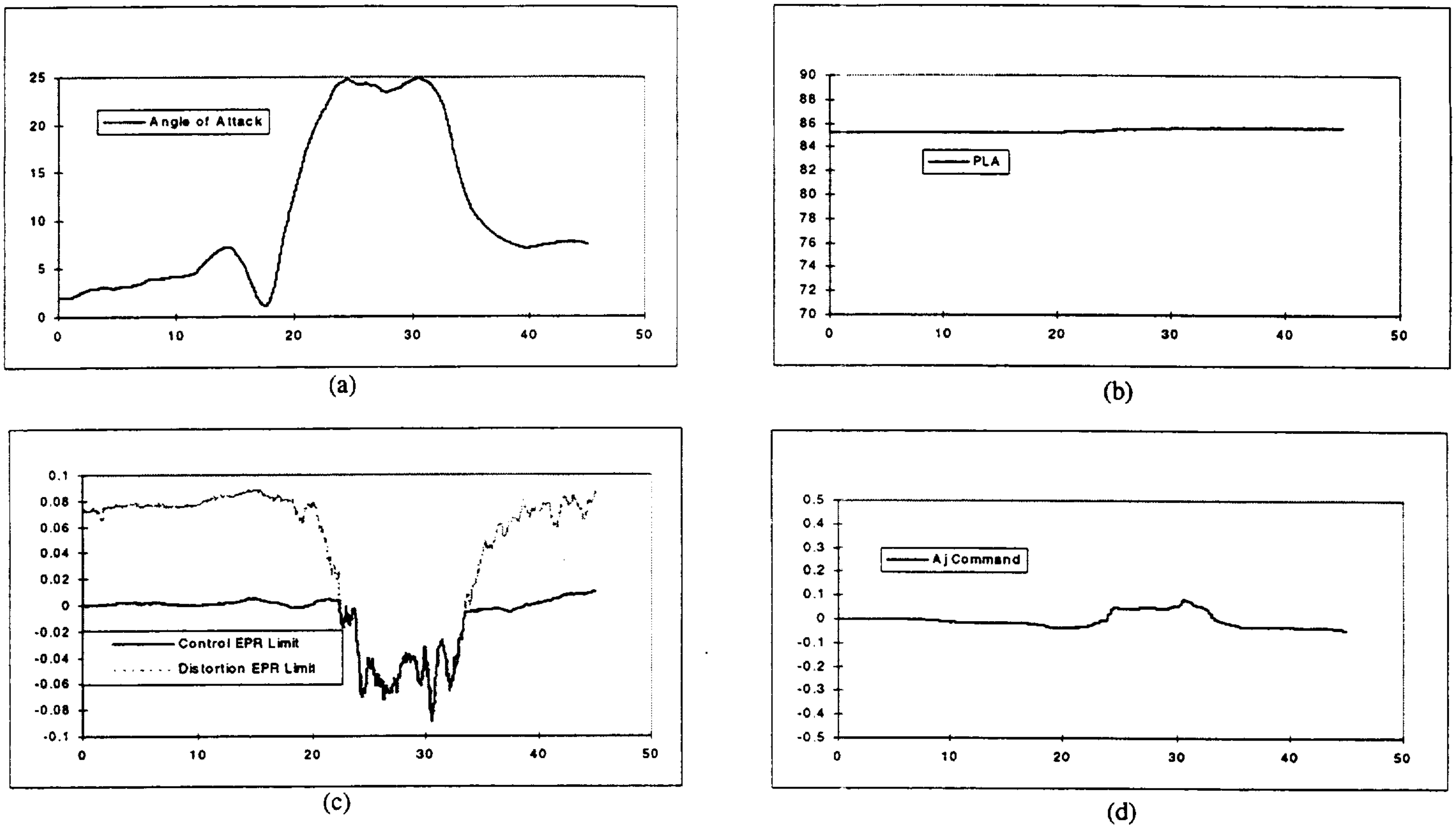


**Figure 12 - Split-S Maneuver**

**CONCLUSIONS**

Under the High Stability Engine Control (HISTEC) Program, technologies for a distortion tolerant control system have been developed and flight demonstrated on NASA's F-15 ACTIVE aircraft. The control system uses measurement-based inlet pressure distortion estimation to enhance engine stability. Flight demonstration was accomplished in the summer of 1997. The flight demonstration was carried out in two parts, the first to show distortion estimation and the second to show distortion accommodation. Post-flight analysis shows that the HISTEC technologies are able to successfully estimate and accommodate distortion, transiently setting the stall margin requirement on-line and in real-time. This allows the design stall margin requirement to be reduced, which in turn can be traded for increased performance and/or decreased weight. Flight demonstration of the HISTEC technologies has significantly reduced the risk of transitioning these technologies to tactical and commercial engines.



(a)

(b)

(c)

(d)

**Figure 13 - Fan Distortion Accommodation: 27,000ft, Mach Number=0.6, Split-S Maneuver to 25 degrees Angle of Attack**

## References

1. Longley, J.P.; and Greitzer, E.M.: "Inlet Distortion Effects in Aircraft Propulsion System Integration.", Cambridge University, Cambridge (England), 1992.
2. Ralph, J.A.: Advanced Control for Airbreathing Engines, Volume 1, Pratt & Whitney." NASA CR 189203, July 1993.
3. Bansal, Indar: "Advanced Control for Airbreathing Engines, Volume 2, General Electric Aircraft Engines." NASA CR 189204, July 1993.
4. Bough, R.M.: Advanced Control for Airbreathing Engines, Volume 3, Allison Gas Turbine." NASA CR 189205, July 1993.
5. Ouzts, P.J.; Lorenzo, C.F.; and Merrill, W.C.: "Screening Studies of Advanced Control Concepts for Airbreathing Engines." Prepared for the 28th Joint Propulsion Conference and Exhibit, July 6-8, 1992, NASA TM 106042.
6. Bright, M.M.; Qammar, H.K.; Weigl, H.J.; and Paduano, J.D.: "Stall Precursor Identification in High-Speed Compressor Stages Using Chaotic Time Series Analysis Methods." Journal of Turbomachinery, Vol. 119, July 1997.
7. Eveker, K.M.; Gysling, D.L.; Nett, C.N.; and Sharma, O.P.: "Integrated Control of Rotating Stall and Surge in Aeroengines." In proceedings: SPIE's International Symposium on Aerospace/Defense Sensing & Control and Dual-Use Photonics "AeroSense", 4/17-4/21/95. Proceedings volume 2494.
8. Owen, A.K.; Braun, D.C.; Le, D.K.; and Mattern, D.L.: "Results of Forced Response Testing Using Air-Jet Injectors on an Axi-Centrifugal Gas Turbine Engine." Presented at 33rd Joint Propulsion Conference and Exhibit, July 6-9, 1997, AIAA 97-2770.

9. Berndt, R.G.; Weigl, H.J.; Paduano, J.D.; and Epstein, A.H.: "Experimental Techniques for Actuation, Sensing and Measurement of Rotating Stall Dynamics in High Speed Compressors." In proceedings: SPIE's International Symposium on Aerospace/Defense Sensing & Control and Dual-Use Photonics "AeroSense", 4/17-4/21/95. Proceedings volume 2494.

10. Weigl, H.J.; Paduano, J.D.; Frechette, L.G.; Epstein, A.H.; Greitzer, E.M.; Bright, M.M.; and Strazisar, A.J.: "Active Stabilization of Rotating Stall and Surge in a Transonic Single Stage Axial Compressor." Presented at the 1997 ASME Turbo Expo, Orlando, FL., June 1997.

11. Southwick, R.D.; Gallops, G.W.; Larkin, L.J.; and Sobanski, K.J.: "High Stability Engine Control (HISTEC) Phase I: Algorithm Development, Volume I: Final Report and Appendix A." NASA CR 198399, September 1995.

12. DeLaat, John C.; Southwick, Robert D.; and Gallops, George W.: "High Stability Engine Control (HISTEC)." Prepared for the 32nd Joint Propulsion Conference and Exhibit, July 1-3, 1996, NASA TM 107272, AIAA-96-2586.

13. DeLaat, J.C.; Southwick, R.D.; Gallops, G.W.; and Orme, J.S.: "The High Stability Engine Control (HISTEC) Program: Flight Demonstration Phase." Prepared for the 34th Joint Propulsion Conference and Exhibit, July 13-15, 1998, NASA TM 1998-208482, AIAA-98-3756.

14. Orme, J.S.; DeLaat, J.C.; Southwick, R.D.; Gallops, G.W.; and Doane, P.M.: "Flight Test of the High Stability Engine Control (HISTEC) System." Prepared for the 34th Joint Propulsion Conference and Exhibit, July 13-15, 1998, AIAA-98-3715.

15. Southwick, R.D.; Gallops, G.W.; Kerr, L.J.; Kielb, R.; Welsh, M.; DeLaat, J.C.; and Orme, J.S.: "High Stability Engine Control (HISTEC) Flight Test Results." Prepared for the 34th Joint Propulsion Conference and Exhibit, July 13-15, 1998, NASA TM 1998-208481, AIAA-98-3757.

16. Society of Automotive Engineers: "Gas Turbine Engine Inlet Flow Distortion Guidelines", Aerospace Recommended Practice (ARP) 1420, 1978.

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
September 1998

**3. REPORT TYPE AND DATES COVERED**
Technical Memorandum

**4. TITLE AND SUBTITLE**
High Stability Engine Control (HISTEC): Flight Demonstration Results

**5. FUNDING NUMBERS**
WU-523-53-13-00

**6. AUTHOR(S)**
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**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

**8. PERFORMING ORGANIZATION REPORT NUMBER**
E-11375

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
National Aeronautics and Space Administration
Washington, DC 20546-0001

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
NASA TM—1998-208655
SAE 985556

**11. SUPPLEMENTARY NOTES**
Prepared for the 1998 World Aviation Congress and Exposition cosponsored by the Society of Automotive Engineers International and the American Institute of Aeronautics and Astronautics, Anaheim, California, September 28–30, 1998. John C. DeLaat, NASA Lewis Research Center; Robert D. Southwick and George W. Gallops, United Technologies Corporation, Pratt & Whitney, P.O. Box 109600, West Palm Beach, Florida 33410; John S. Orme, Dryden Flight Research Center, Edwards, California 93523. Responsible person, John C. DeLaat, organization code 5530, (216) 433-3744.

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Unclassified - Unlimited
Subject Category: 07 Distribution: Nonstandard

This publication is available from the NASA Center for AeroSpace Information, (301) 621-0390.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** ***(Maximum 200 words)***

Future aircraft turbine engines, both commercial and military, must be able to accommodate expected increased levels of steady-state and dynamic engine-face distortion. The current approach of incorporating sufficient design stall margin to tolerate these increased levels of distortion would significantly reduce performance. The High Stability Engine Control (HISTEC) program has developed technologies for an advanced, integrated engine control system that uses measurement-based estimates of distortion to enhance engine stability. The resulting distortion tolerant control reduces the required design stall margin, with a corresponding increase in performance and/or decrease in fuel burn. The HISTEC concept was successfully flight demonstrated on the F-15 ACTIVE aircraft during the summer of 1997. The flight demonstration was planned and carried out in two parts, the first to show distortion estimation, and the second to show distortion accommodation. Post-flight analysis shows that the HISTEC technologies are able to successfully estimate and accommodate distortion, transiently setting the stall margin requirement on-line and in real-time. Flight demonstration of the HISTEC technologies has significantly reduced the risk of transitioning the technology to tactical and commercial engines.

**14. SUBJECT TERMS**
Aircraft engines; Engine control; Flow distortion; Stability augmentation

**15. NUMBER OF PAGES**
17

**16. PRICE CODE**
A03

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102