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The High Stability Engine Control (HISTEC) Program: Flight Demonstration Phase

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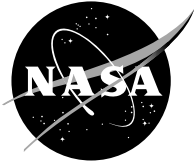
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THE HIGH STABILITY ENGINE CONTROL (HISTEC) PROGRAM: FLIGHT DEMONSTRATION PHASE

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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 objective of the High Stability Engine Control (HISTEC) program is to design, develop, and flight-demonstrate 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 decrease in fuel burn. The HISTEC concept has been developed and 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 phases, 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 significantly increased performance and/or decreased weight. Flight

demonstration of the HISTEC technologies has significantly reduced the risk of transitioning the technology to tactical and commercial engines.

NOMENCLATURE

A_j - Nozzle Area
ACTIVE - Advanced Control Technology for Integrated Vehicles
 α - Angle-of-Attack
 β - Angle-of-Sideslip
CEDU - Comprehensive Engine Diagnostic Unit
DES - Distortion Estimation System
EPR - Engine Pressure Ratio
HCF - High Cycle Fatigue
HSCT - High Speed Civil Transport
HISTEC - High Stability Engine Control
IDEEC - Improved Digital Electronic Engine Control
ID - Inner Diameter
OD - Outer Diameter
PLA - Power Lever Angle
SMC - Stability Management Control
WACC - Calculated Total Air Flow

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INTRODUCTION

Background

Future aircraft turbine engines, both commercial and military, must be able to successfully accommodate expected increased levels of steady-state and dynamic engine-face distortion. Advanced tactical aircraft are likely to use thrust vectoring for enhanced aircraft maneuverability. As a result, the propulsion system will see more extreme aircraft angle-of-attack and sideslip levels 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 is to base 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 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 known 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 HISTEC Approach

The distortion tolerant control approach developed for the High Stability Engine Control (HISTEC) program is shown in **Figure 2**. The approach 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. The HISTEC approach includes three major elements: Engine Face Pressure Sensors; the Distortion Estimation System (DES); and the Stability Management Control (SMC).

The engine face pressure sensors consist of a small number of high-response, wall static pressure transducers. There are five sensors at the engine face outer diameter (OD) and five sensors electrically averaged to a single measurement at the inner diameter (ID). The DES uses these high response pressure measurements to calculate in real time the indicators of type and extent of distortion.

The DES is an aircraft mounted, high speed processor that estimates the amount and type of distortion present and the impact of that distortion on the propulsion

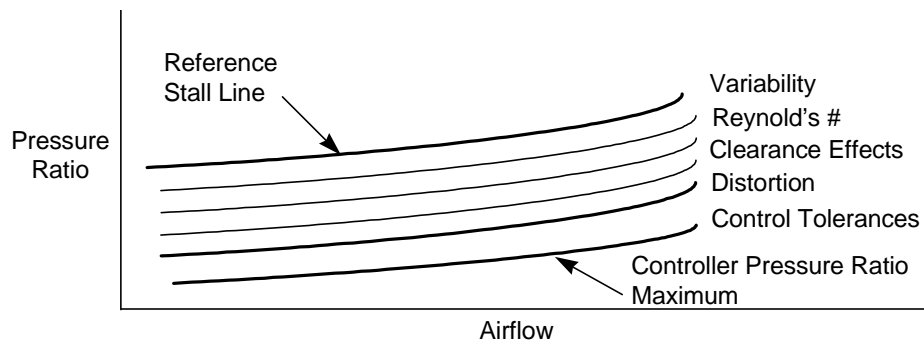


Figure 1 - Stall Margin Requirements

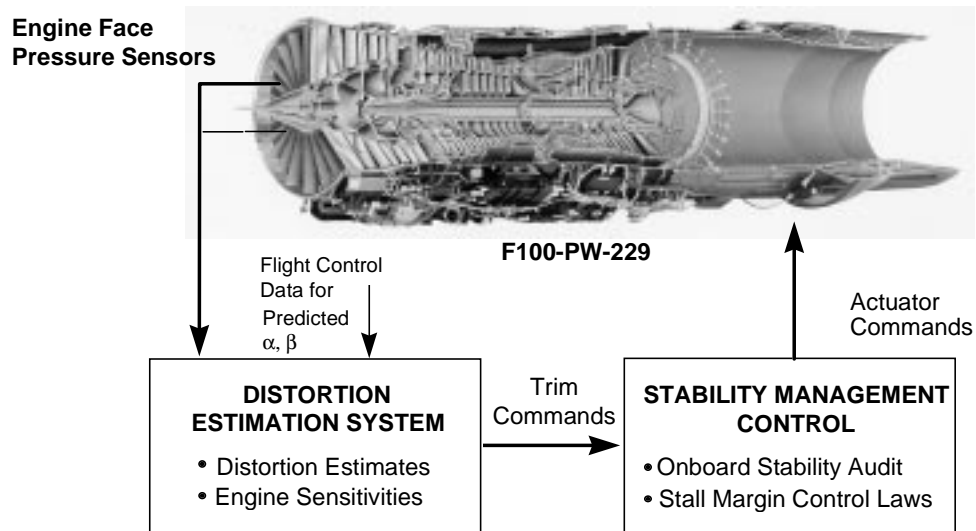


Figure 2 - HISTEC Distortion Tolerant Control Approach

system. The DES breaks the distortion, typically a three-dimensional phenomenon, into radial, circumferential, and planar components.¹¹ Each component is passed through an appropriate distortion sensitivity function to arrive at a fan and compressor pressure ratio surge margin debit or pressure ratio limit trim. Because the response of the engine and control is of lower bandwidth than the distortion phenomenon and because there is an additional delay for the distortion algorithm computations, the DES also uses maneuver information from the flight control to predict angle-of-attack and angle-of-sideslip in order to anticipate high inlet distortion conditions. Dynamic compensation using the maneuver information is applied to the fan and compressor ratio limit trims. From the measurements, and from the maneuver information, the DES determines the effects of the distortion on the propulsion system and the corresponding engine match point necessary to accommodate it.

The output of the DES consists of fan and compressor pressure ratio trim commands which are then communicated to the SMC. The SMC is contained in the engine mounted Improved Digital Electronic Engine Control (IDEEC). 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 with a corresponding increase in performance and decrease in fuel burn.

The HISTEC Program

HISTEC is a five year program sponsored by NASA Lewis Research Center in Cleveland, Ohio. Program partners include NASA Dryden Flight Research Center, which accomplished the flight demonstration; Pratt & 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 3**. HISTEC Phase I "Algorithm Development", completed in 1994, successfully defined the requirements for, and designed the algorithms necessary for the Distortion Estimation System (DES).¹² 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 should be able to sense inlet distortion, determine the effect on engine stability, and accommodate for distortion by maintaining adequate engine surge margin.¹³

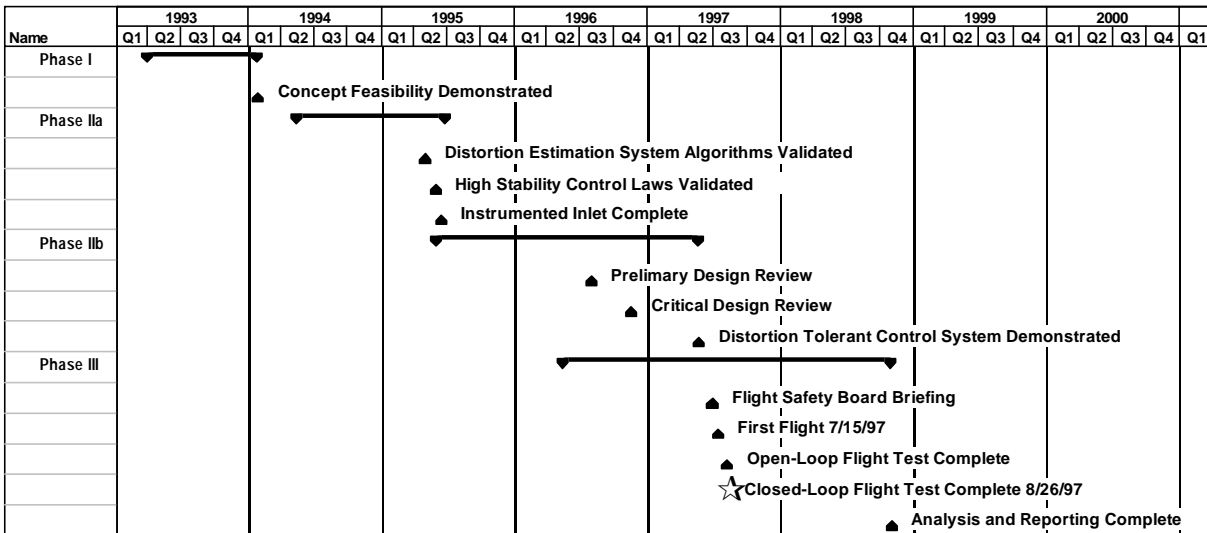


Figure 3 - HISTEC Program Timeline

This paper provides a summary of HISTEC Phase IIb - Systems Development, and Phase III - Engine/Flight Demonstration. During these final phases of the HISTEC program, 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 flight demonstration was accomplished in the summer of 1997. In this paper, the background and objectives for the flight demonstration are given. The HISTEC flight systems hardware and software are described and the efforts necessary to validate these systems are discussed. An overview of the flight test planning is given. Finally, a summary of the flight testing and flight test results is provided. In companion papers, the details of the effort necessary to install and demonstrate the HISTEC systems are given,¹⁴ and the detailed flight test results are presented.¹⁵

FLIGHT TEST OBJECTIVES

The overall objective of the HISTEC program is to develop and flight demonstrate an advanced high stability integrated engine control system which uses real-time, measurement-based estimation of distortion to enhance engine stability. For the flight demonstration phase of the program, there are two specific objectives. The first specific objective is to demonstrate the distortion tolerant control approach developed for HISTEC. This demonstration includes 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 in flight the amount and type of distortion and its impact on engine stability; and to demonstrate 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 second specific objective is to augment the available database of dynamic flight distortion data.

FLIGHT SYSTEMS DEVELOPMENT

In order 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. These systems include the instrumented inlet case, the Distortion Estimation System hardware and software, and the Stability Management Control software.

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. 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

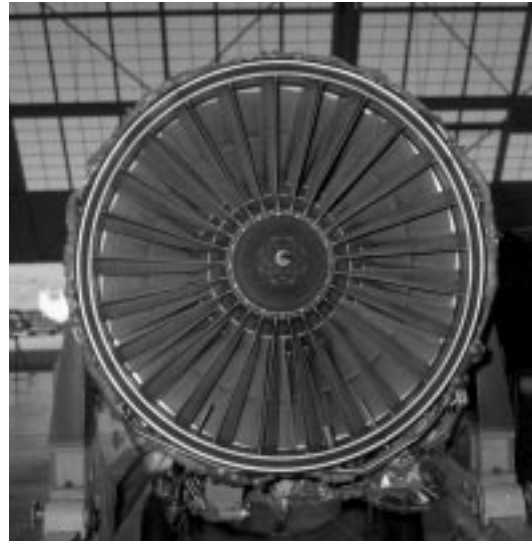
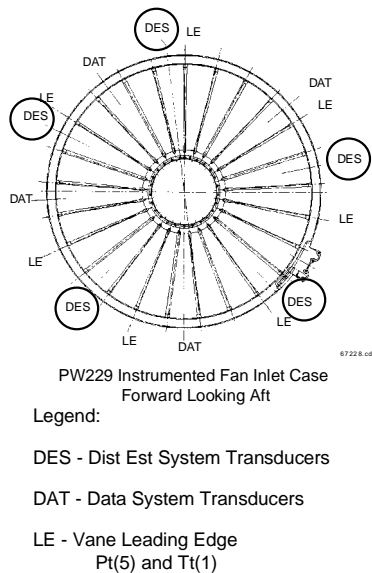


Figure 4 - Instrumented Inlet Case

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 methodology¹¹ (**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. The DES algorithms as implemented rely on digital signal processing techniques to perform spatial transforms for classifying the amount and type of distortion present, and temporal transforms (FFT) to then obtain the frequency content of each of the spatial distortion components. A detailed description of the DES algorithms is contained in **Reference 13**.

The F119 Group 1 Comprehensive Engine Diagnostic Unit (CEDU) was chosen during HISTEC Phase IIa from among several candidates for the DES because of its flight-quality design and sufficient I/O and throughput capability. The CEDU contains a digital signal processor which accommodated the signal

processing techniques used in the DES algorithms very well. For HISTEC the CEDU was airframe mounted.

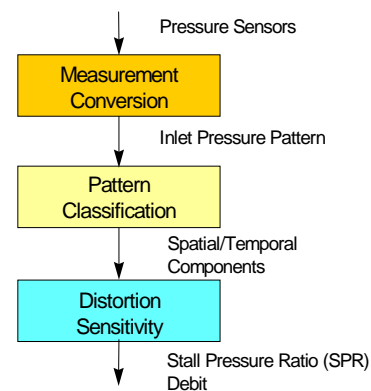


Figure 5 - Traditional Stability Audit Methodology

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. Advanced control laws manage the amount of stall margin remaining in the fan and high pressure compressor (**Figure 6**). The SMC algorithms were incorporated into a production 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.

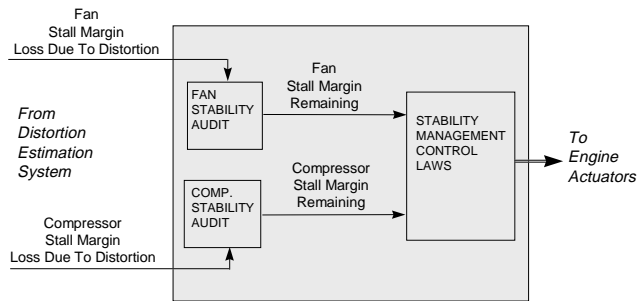


Figure 6 - Stability Management Control

FLIGHT SYSTEMS VALIDATION

During the systems development phase of HISTEC (Phase IIb), the design of the instrumented inlet case fabricated during Phase IIa was refined in response to some minor structural deficiencies discovered during High Cycle Fatigue (HCF) testing of an inlet case strut modified and instrumented like the flight inlet case. At resonant modes and frequencies typical of on-engine operation, minor cracking was discovered at some of the sites where the research total pressure transducers are installed in the leading edge of the inlet guide vane struts. The electro discharge machining used to install the holes to house the HISTEC instrumentation had produced a local through-wall heat-affected zone. The cause of the cracking was attributed to the concentrated stresses exceeding the capability of the locally degraded material. Re-design and re-work of the transducer installations alleviated the cracking problem during HCF testing. The repair scheme was then applied to the flight inlet case. Flight clearance of the inlet case was accomplished through engine ground testing on the M37 sea-level stand at Edwards Air Force Base.

Also during Phase IIb, the DES and SMC were incorporated into the F-15 ACTIVE aircraft flight systems architecture, and the detailed hardware/software design and implementation was accomplished to incorporate the HISTEC systems onto the aircraft. In the DES, the executive software, distortion estimation algorithms, and data communication software were coded and tested. In the SMC, the onboard stability audit, stability management control laws, and modified data communications software were coded and tested. To validate the SMC control laws, a ground engine test was conducted on a sea-level test stand at Pratt & Whitney. The SMC was

evaluated for the correct distortion accommodation response to signals emulating pressure ratio trims from the DES. In addition, the functioning of the onboard stability audit was evaluated. Finally, verification testing was done to ensure that production engine functionality was maintained with the HISTEC stability accommodation inactive. To validate the integrated DES and SMC, system integration testing was first conducted stand-alone using an emulator of the aircraft and its associated communications systems. Next, operation of the integrated HISTEC systems was verified during uninstalled ground engine testing. This was the same test that flight cleared the instrumented inlet case. Vehicle integration testing was then done using the aircraft hardware-in-the-loop bench at McDonnell Douglas Aircraft (now Boeing Phantom Works). Finally, installed ground testing was performed in the F-15 ACTIVE aircraft to test correct integration of the HISTEC systems onto the aircraft, to verify correct operation of the flight data systems, and to clear all HISTEC systems for flight. Detailed descriptions of the ground testing and ground test results are provided in **Reference 14**.

FLIGHT TEST

Planning

As mentioned earlier, the overall objective of the HISTEC program is to develop and flight demonstrate an advanced high stability integrated engine control system which uses real-time, measurement-based estimation of distortion to enhance engine stability. Specific objectives for the flight test included:

- 1) Augmenting the existing databases for distortion data by gathering inflight dynamic distortion data from the instrumented inlet case and engine; and 2) Flight validating a distortion tolerant engine control consisting of the engine face pressure measurements, distortion estimation in the DES, and distortion accommodation in the SMC. In order to satisfy these specific objectives, the flight test program was divided into two phases. The first phase would quantify inlet distortion at steady state and transient flight conditions; correlate measured inlet distortion from total pressure measurements to DES pressure measurements; demonstrate acceptable DES accuracy; and define any DES software changes required before the second phase. The second phase would then demonstrate accurate inlet distortion estimation at steady state and transient flight conditions; demonstrate functional engine trim capability to accommodate inlet distortion; and demonstrate adequate transient aircraft angle of attack and sideslip prediction based on aircraft control inputs and adequate resultant

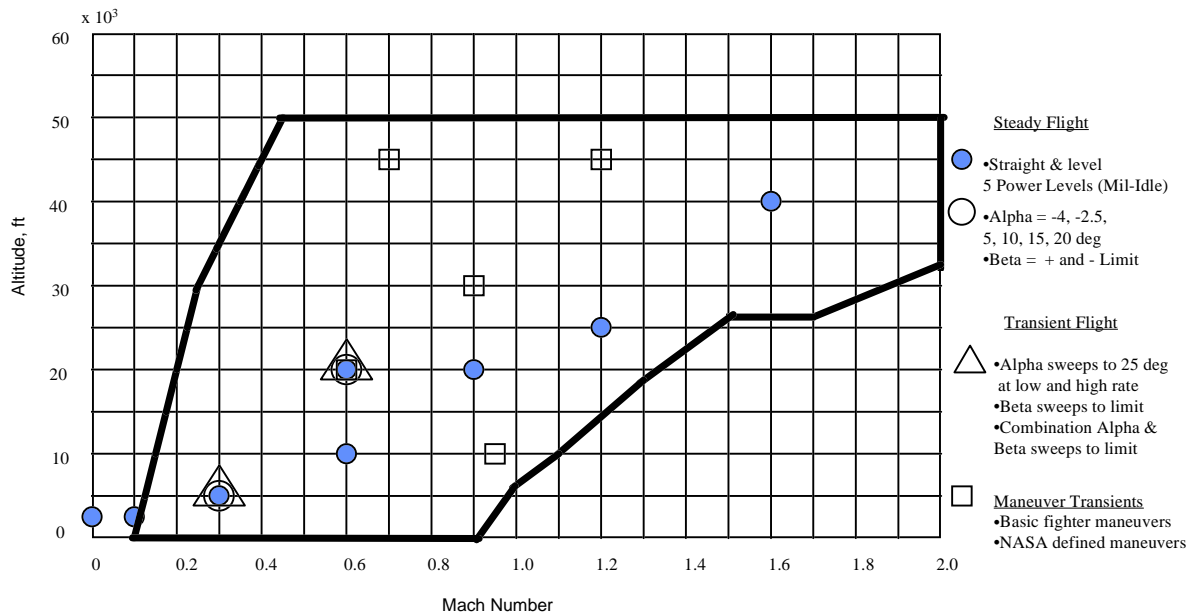


Figure 7 - HISTEC Flight Envelope

engine trim lead terms to ensure inlet distortion accommodation.

The HISTEC flight test envelope is shown in **Figure 7**. A test point matrix consisting of 106 test points at various subsonic and supersonic flight conditions was developed to carry out the two phase 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 aiflows, 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 (α) and angle-of-sideslip (β) flight, wind-up turns, split-S maneuvers, and take-offs. These allowed a thorough demonstration of distortion estimation in the first phase and of distortion accommodation in the second phase of testing.

Demonstration

Flight testing commenced on July 15, 1997, and the first phase was completed after 6 flights (~7 flight hours) over a 3½ week period. The second phase, 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**.

SUMMARY OF FLIGHT DEMONSTRATION RESULTS

Analysis of the flight test data indicates that both the Distortion Estimation algorithms and the stability margin management elements of the overall HISTEC control system performed as designed. Post-flight analysis has been divided into three main areas. First, it was necessary to determine if the DES wall-static 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. A summary of the post-flight analysis is presented here. Detailed analysis results are contained in **Reference 15**.

HISTEC Flight Test Data Analysis, flt1775 adr1023
 20K/0.6, $\alpha=21^\circ$, $\beta=0^\circ$, wacc = 100% of mil power
 Right Hand Engine, Aft Looking Forward

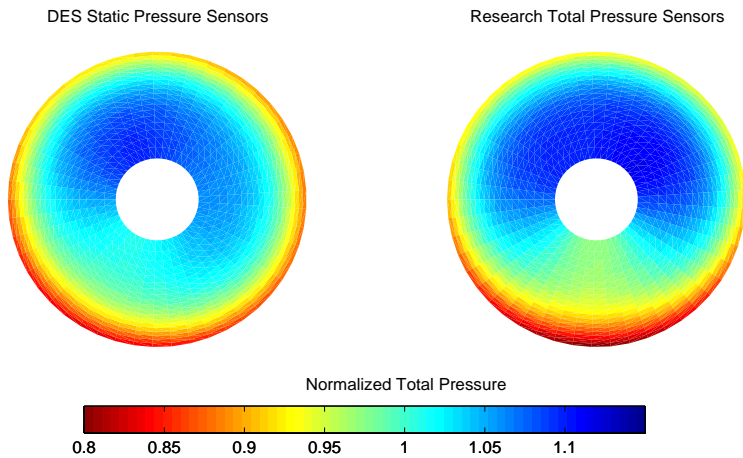


Figure 8 - Measurement System Results

Engine Face Pressure Measurements

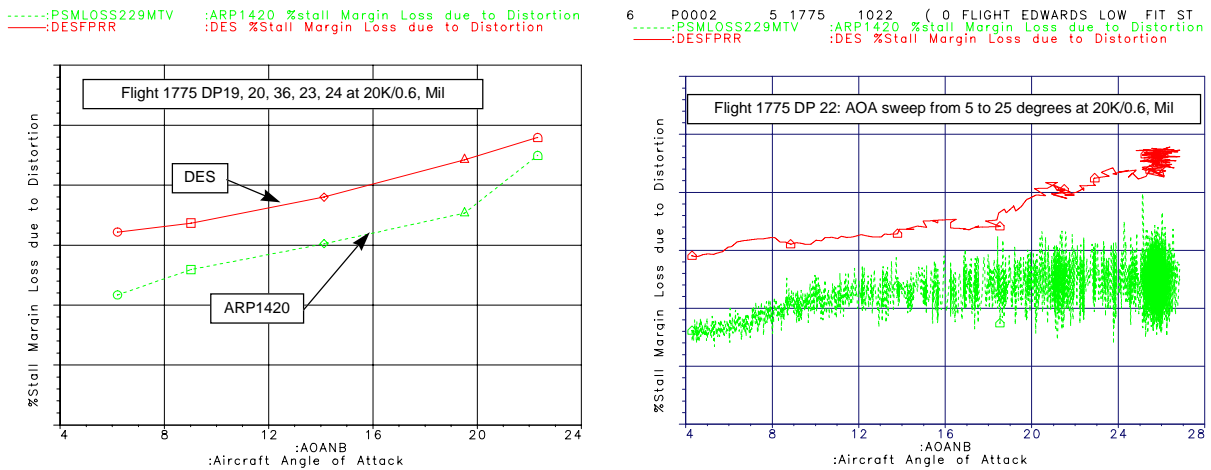
Figure 8 shows a comparison of the face pressure profile computed from the six DES pressure measurements and the corresponding pressure profile computed from the thirty-five research total pressure sensors.

The pressure profiles were calculated by first fitting Fourier series descriptors to the sensor data, similar to the calculations done in the DES. The pressure profile was then back-calculated from the resulting spatial

Fourier series coefficients. As can be seen from the qualitative comparison in the figure, the pressure profiles for this high airflow, high angle-of-attack (and thus high-distortion) condition compare favorably. This indicates that the DES wall static pressure sensors are able to pick up the important features for estimating distortion.

Distortion Estimation

Next the stall margin debit due to distortion as calculated by the DES in flight from the DES sensors



(a) Steady angle-of-attack

(b) Angle-of-attack sweep

Figure 9 - Distortion Estimation Results
 (vertical scale omitted to protect proprietary data)

was compared to the stall margin debit calculated off-line from flight data for the 35 research sensors using the industry-standard ARP1420 methodology.¹¹ In **Figure 9(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 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 9(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. The time-history data also shows that the DES signal processing algorithms tend to smooth the calculated stall margin debit. The ARP1420 method, computed at each time sample, shows the increased time-varying nature of the distortion as the level of the distortion increases.

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 10**). 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.

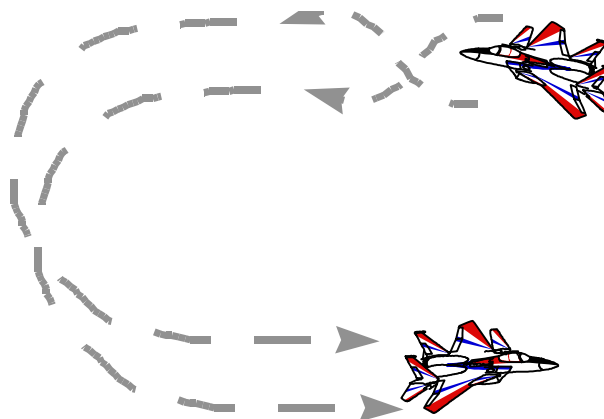
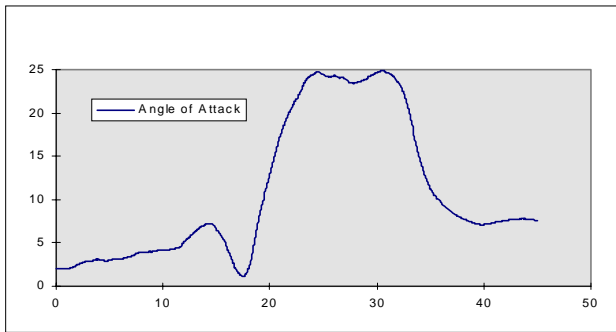


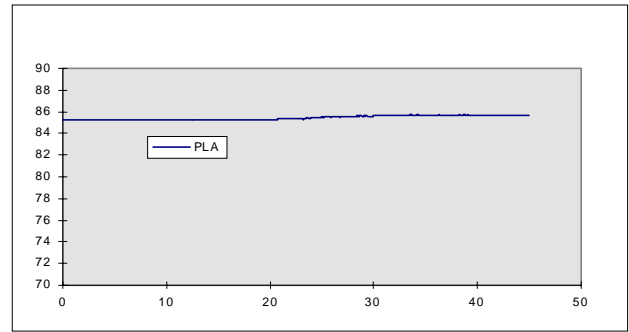
Figure 10 - Split-S Maneuver

Figure 11 shows the successful in-flight distortion accommodation during a Split-S maneuver. **Figure 11(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 11(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.

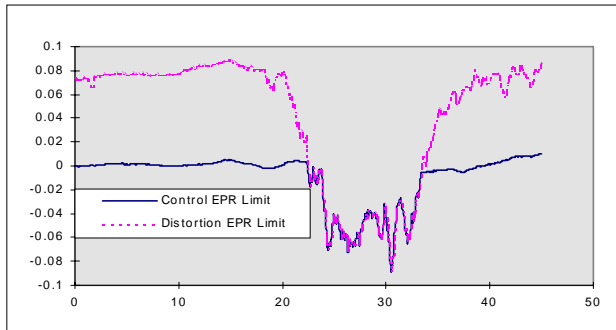
Figure 11(c) shows the desired engine pressure ratio (EPR) limit as computed by the SMC and provided as a request to the control's regulator logic. **Figure 11(c)** also shows the HISTEC modifier to the EPR request as computed from the stall margin debit provided by the DES. For a controller without 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 11(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 11(d)** shows that, in response to the lowered EPR request at high distortion conditions, the SMC control laws successfully accommodate the distortion by opening the nozzle area (A_j) to downtrim EPR.



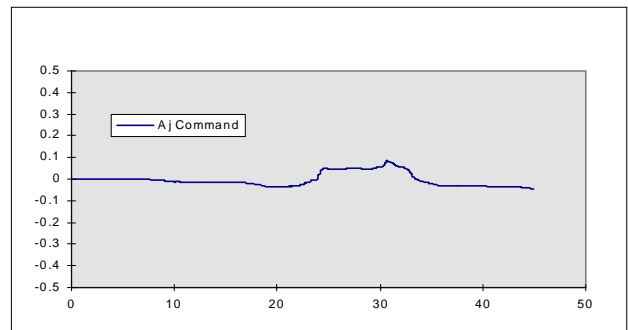
(a)



(b)



(c)



(d)

Figure 11 - Fan Distortion Accommodation: 27,000ft, $M_n=0.6$, Split-S Maneuver to 25 degrees Angle of Attack

CONCLUSIONS

Under the High Stability Engine Control (HISTEC) Program, a distortion tolerant control system has been designed, developed, and flight demonstrated on the F-15 ACTIVE aircraft. The control system uses measurement-based inlet pressure distortion estimation to enhance engine stability. Flight systems to implement the HISTEC distortion tolerant control for flight test were developed and validated through integration testing and engine ground testing and the flight demonstration was accomplished in the summer of 1997. The flight demonstration was carried out in

two phases, 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 significantly increased performance and/or decreased weight. Flight demonstration of the HISTEC technologies has significantly reduced the risk of transitioning the technology to tactical and commercial engines.

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13. ABSTRACT (<i>Maximum 200 words</i>) 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 objective of the High Stability Engine Control (HISTEC) program is to design, develop, and flight-demonstrate 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 decrease in fuel burn. The HISTEC concept has been developed and 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 phases, 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 significantly increased performance and/or decreased weight. Flight demonstration of the HISTEC technologies has significantly reduced the risk of transitioning the technology to tactical and commercial engines.			
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