N93-15169

Real-Time In-Flight Engine Performance and Health Monitoring Techniques for Flight Research Application

Ronald J. Ray
John W. Hicks
Keith D. Wichman

NASA Dryden Flight Research Facility
Edwards, California, U.S.A.

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Summary

Procedures for real-time evaluation of the in-flight health and performance of gas turbine engines and related systems have been developed to enhance flight test safety and productivity. These techniques include the monitoring of the engine, the engine control system, thrust vectoring control system health, and the detection of engine stalls. Real-time performance techniques were developed for the determination and display of in-flight thrust and for aeroperformance drag polars. These new methods were successfully demonstrated on various research aircraft at the NASA Dryden Flight Research Facility. The capability of NASA's Western Aeronautical Test Range and the advanced data acquisition systems were key factors for implementation and real-time display of these methods.

In Echtzeit arbeitende, bordgestützte Triebwerksleistungs- und -zustandsüberwachungstechniken für Anwendungen in der Flugforschung

Übersicht

Um die Sicherheit und Ergiebigkeit von Flugversuchen zu verbessern, wurden Verfahren entwickelt, die eine Echtzeit-Auswertung des Betriebszustandes und der Leistung von Strahlantrieben (mit den dazugehörigen Systemen) während des Fluges ermöglichen. Sie umfassen die Zustandsüberwachung des Triebwerkes, des Triebwerksreglers, der Schubvektoren-Steuerung und die Entdeckung von überzogenem Triebwerkszustand. Die Echtzeit-Auswertung wurde verwirklicht, um den Schub und die Widerstandspolaren während des Fluges bestimmen und anzeigen zu können. Diese neuen Methoden wurden erfolgreich bei mehreren Forschungsflugzeugen der NASA Dryden Flight Research Facility demonstriert. Die Fähigkeiten der NASA Western Aeronautical Test Range sowie des modernen Datenerfassungssystems waren Schlüsselfaktoren für den Einsatz und die Echtzeit-Anzeige mit Hilfe dieser Verfahren.

Table of Contents

Nomenclature

ALPHAT	true angle of attack, deg
AOA	angle of attack
BETAT	true angle of sideslip, deg
ComDev	Computing Devices Company
CRT	cathode-ray tube
DEEC	digital electronic engine control
EMD	engine model derivative
EPU	emergency power unit
ERCODE	error code
FM	frequency modulation
HARV	high alpha research vehicle
HIDEC	highly integrated digital electronic control
ICAEM	intelligent computer assistant for engine monitoring
MACHT	true Mach number
NASA	National Aeronautics and Space Administration
NPR	nozzle pressure ratio
PCM	pulse code modulation
PLA	power lever angle, deg
PSL	Propulsion System Laboratory (NASA Lewis)
RFCS	research flight control system
RTTM	real-time thrust method
SGTM	simplified gross thrust method
TTCP	The Technical Cooperation Program
TVCS	thrust vectoring control system
WATR	Western Aeronautical Test Range

Letter and Mathematical Symbols:

$A8$	nozzle throat area, ft^2
C_D	coefficient of drag
C_L	coefficient of lift
D	aircraft drag, lb
F_{ex}	excess thrust, lb
F_G	gross thrust, lb

FN	net thrust, lb
FNP	net propulsive force, lb
g	acceleration due to gravity
K	corrected parameter value
L	aircraft lift, lb
$N1$	fan rotor speed, rpm
$N2$	compressor rotor speed, rpm
n_x	aircraft longitudinal acceleration, g
n_z	aircraft normal acceleration, g
P_s	specific excess power, ft/sec
$PS0$	freestream static pressure
$PS3$	compressor discharge pressure, lb/in^2
$PS6$	afterburner inlet static pressure, lb/in^2 absolute
$PS7$	exhaust nozzle inlet static pressure, lb/in^2 absolute
$PT5$	turbine discharge total pressure, lb/in^2 absolute
q	dynamic pressure, lb/in^2
S	reference wing area, ft^2
$TT1°C$	engine inlet total temperature, °C
$TT5$	low-pressure turbine discharge temperature, °R
$TT5C$	turbine exhaust gas temperature, °C
Vt	true airspeed, ft/sec
W_t	aircraft gross weight, lb
α	angle of attack, deg

1. Introduction

The NASA Dryden Flight Research Facility (NASA Dryden) has conducted propulsion and performance flight research on a variety of aircraft. Because flight research typically involves exploring new state-of-the-art technologies, the aircraft or systems being tested are often one-of-a-kind. In addition, each research program has its own unique goals, resources, and requirements. To support these programs, engineers must assist flight activities by assuring that high-quality data are being obtained in a safe manner. Advanced aircraft and engines with new capabilities often require the development of new test techniques.

The goal of providing improved engine health monitoring capabilities extends beyond the flight test demand. Several new techniques for monitoring the health and performance of an engine and its related systems during flight are currently being pursued. For example, the Technical Cooperation Program (TTCP) in Australia, Canada, New Zealand, the United Kingdom, and the United States is coordinating international collaborative research and development activities in this area.[1] Although the flight test environment presents unique challenges, it also provides opportunities to evaluate new techniques not practical in an operational application.

The continual advancement of computer and display technologies has provided many opportunities to aid the flight test engineers in their task.[2] The X-29A program developed several innovative real-time analysis and display techniques to support the flight envelope expansion program and the subsequent flight research phase.[3] In support of propulsion and performance flight research, a variety of advanced real-time analysis techniques have been developed at Dryden for various flight research programs. These techniques include the monitoring of engine health, the engine control system, and the detection of engine stalls. Also included are the monitoring of systems associated with the engine such as a thrust vectoring system. Real-time performance techniques were also developed for the determination and display of in-flight thrust and for aeroperformance drag polars.

The development of sophisticated real-time analysis and displays required careful integration of the aircraft data acquisition and telemetry systems with the NASA Western Aeronautical Test Range (WATR) mission control facility.

This report describes various engine-related performance and health monitoring techniques developed in support of flight research at NASA Dryden. Techniques used during flight to enhance safety and to increase flight test productivity are summarized. A description of the NASA range facility is given along with a discussion of the flight data processing. Examples of data processed and the flight data displays are shown. A discussion of current trends and future capabilities is also included.

2. Aircraft Description

Propulsion and performance research on a variety of unique test aircraft has recently been conducted at NASA Dryden. The research aircraft discussed in this report are shown in figure 1. They include the X-29A advanced technology demonstrator, the F-15 highly integrated digital electronic control (HIDEC), and the F-18 high alpha research vehicle (HARV).

The X-29A advanced technology demonstrator is an experimental aircraft developed by the Grumman Aerospace Corporation, Bethpage, New York, in partnership with the Defense Advanced Research Projects Agency, NASA, and the U.S. Air Force. Technologies of this small single-seat fighter-type aircraft include a 30° forward-swept wing consisting of a thin supercritical airfoil section with graphite-epoxy upper and lower wing coverings configured to inhibit wing structural divergence. Other technologies are the close-coupled canard–wing configuration, a three-surface pitch control system, an automatic wing camber control mode, a large negative static margin, and a triplex digital fly-by-wire flight control system. The X-29A aircraft is powered by a single F404-GE-400 (General Electric, Lynn, Massachusetts) afterburning turbofan engine. The engine is rated at 16,000-lb static thrust at sea level. Details of the X-29A configuration and its technologies is in [4].

The NASA F-15 HIDEC aircraft is a specially modified high-performance vehicle used for conducting integrated propulsion controls research. Its current configuration includes two engine model derivative (EMD) F100 engines with digital electronic engine control (DEEC), a digital electronic flight control system, a digital inlet control system, and a central computer that can communicate with all systems on a Military Standard 1553 data bus. The aircraft has the capability of measuring, recording, and telemetering over 1,000 parameters, including high-frequency parameters up to 20,000 Hz. Integrated propulsion and flight-control system experiments have been conducted on the F-15 aircraft to optimize vehicle performance. One experiment, for example, has demonstrated a 5- to 10-percent increase in engine thrust. This increase was done by uptrimming the engine pressure ratio while reducing excess engine stall margin to a minimum safe level based on flight condition and pilot inputs. Additional information on propulsion research related to the F-15 HIDEC aircraft is in [5] and [6].

The F-18 HARV aircraft (McDonnell Douglas Corporation, St. Louis, Missouri) is a high-performance twin-turbofan jet fighter-attack airplane equipped with a thrust vectoring control system (TVCS). The TVCS hardware uses three vanes mounted around each engine of the F-18 aircraft. This configuration allows three-dimensional thrust vectoring capability. Thrust turning vanes replace the standard divergent nozzle and external nozzle flaps. The convergent part of the nozzle remains on the engine. The F-18 HARV is powered by two F404-GE-400 engines. Additional information on the F-18 HARV and its TVCS is in [7] and [8].

3. Aircraft Data Acquisition Systems

The flight research vehicles in this report incorporate a data acquisition system for acquiring and recording the desired aircraft measurements. Although each instrumentation system is uniquely configured to best accomplish the operational safety and research goals of the project, some commonality also exists. For example, each aircraft employs a pitot-static noseboom system for obtaining accurate airdata information including angles of attack and sideslip. Each aircraft also measures vehicle gross weight, accelerations; vehicle attitudes, angular rates and angular accelerations; control surface positions; and flight control system performance parameters.

On the X-29A aircraft, all pulse code modulation (PCM) data were encrypted and telemetered to the ground as a single uncalibrated serial PCM stream along with some high-response frequency modulation (FM) data. The PCM system sampled the 10-bit data words at 25 to 400 samples/sec, depending on the data frequency content desired for the particular measurement. Including the FM system, a total of 691 aircraft parameters were measured. The thrust-calibrated engine of the X-29A aircraft was fully instrumented for real-time thrust calculation as well as for postflight analysis using the traditional gas generator thrust calculation method.[9] An illustration of the real-time data acquisition system for the X-29A aircraft is shown in figure 2. The data acquisition of the F-15 HIDEC and F-18 HARV aircraft are similar.

The data acquisition of the F-15 HIDEC vehicle uses two PCM systems and an onboard tape recorder. Both PCM's are 10-bit/data word systems gathering data at up to 400 samples/sec. Over 1200 data values, including many from the digital flight and digital engine controls, are measured and downlinked on the F-15 aircraft. More information on the F-15 instrumentation and data acquisition system is in [10].

The F-18 HARV data acquisition system has two PCM data streams and two video streams. Data rates are from 40 to 800 samples/sec. Many strain gauges, thermocouples, and vibration accelerometers are installed on the F-18 aircraft for health monitoring of the thrust vectoring system. In addition to the standard engine health monitoring instrumentation, the right engine is equipped with a diagnostic instrumentation system to determine the exact cause of an engine stall if one should occur. The normal engine instrumentation is sampled at 40 samples/sec and the diagnostic set is at 800 samples/sec.

Four video cameras are used for visual data: two on the vertical tails, one on the right wing tip, and one on the turtleback behind the canopy. At any one time, two of the video signals are recorded onboard and the other two videos are transmitted to the ground. A switch in the cockpit provides the ability to select which video signals are recorded or transmitted. The two tail-mounted video cameras can be positioned to monitor part of the thrust vectoring hardware during flight. This positioning allows the engineers to visually monitor the system from the ground. More information is provided [11] on the use of onboard cameras on the F-18 HARV aircraft.

4. Western Aeronautical Test Range

The NASA Western Aeronautical Test Range, or WATR, is a large, highly integrated facility that provides aircraft and telemetry tracking; communications systems; a real-time data acquisition, processing, and display system; and a mission control center.

Capabilities of the WATR include reception of up to two simultaneous downlink data streams from each research aircraft at a maximum rate of 1 Mbit/sec/stream. The data stream is decrypted (X-29A aircraft used encrypted telemetry), time tagged, compressed, converted to engineering units, limit checked, and stored in real time at a maximum of 200,000 words/sec/data stream. This storage area can hold 4096 calibrated parameters plus 3200 computed parameters for recording, further processing, or display.

There are three dedicated real-time minicomputers for on-line data processing and control of display apparatus. Two of the computers are Gould 32/6780 (Gould Electronics, Inc., Cleveland, Ohio) machines and one is a Gould 32/9780 machine.

Data display capabilities in each of two identical mission control rooms include 12 eight-channel strip charts, numerous cathode-ray tube (CRT) digital data displays of either the fixed update or continuous scroll type, color graphics displays, conventional analog meters, and discrete lights. A photograph of the mission control center is shown in figure 3. A terminal, located in the mission control center, controls the selection of several different engineering color graphics displays, including those developed for propulsion system health monitoring, stall detection, TVCS configuration, and aeroperformance research. This system stores many predefined display formats that can be selected by an operator, as required. The graphic displays include digital parameters such as basic engine and performance parameters that can be set to change colors to indicate when a limit has been reached. Graphic parameters are updated at up to 10 samples/sec, and the column of digital data displayed next to the graphics is set to update at 1 sample/sec. Details of the graphic display system are in [12], and the WATR configuration and operation are in [13] and [14].

5. Real-Time In-Flight Analysis and Monitoring Techniques

The real-time analysis techniques discussed in this report were developed to aid in the health monitoring of the engine or to improve the efficiency and productivity of the flight research activity. Although these techniques were developed for flight test use, the basic technologies have other potential applications such as the onboard monitoring of engine health and performance.

6. General Engine Health Monitoring

All flight research activities at NASA Dryden have a fundamental first priority of assuring that flight safety is adequately monitored. Basic engine safety monitoring is conducted on all the research aircraft discussed in this report. Because of the significance of flight safety, techniques have been developed to aid in the detection of relevant engine safety problems. For most programs this involves the use of CRT's and strip charts to display basic engine parameters and warning lights to indicate when a parameter limit has occurred. Figure 4 shows the real-time displays used on the F-15 HIDEC program to monitor engine and aircraft safety. Two CRT data pages were used to digitally display engineering parameters, including the critical measured parameters, calculated functions, and engine control system faults. Strip charts were used to provide a real-time history of selected engine parameters. A color graphics display and color alarm display were also used to provide a status of pertinent aircraft systems and to provide a warning signal if a failure or system emergency was detected.

The X-29A program developed a special graphics display for engine health monitoring. The display combined many of the features of a CRT, strip chart, and color graphics–warning display for engine health monitoring. This new display provides a 60-sec time history of critical engine parameters for display at high sample rates along with a column of digital parameters updated at one sample/sec (fig. 5). The display is color based and can be set up to change colors as a function of parameter values. For example, a parameter (digital or graphical) that is within its normal range can be shown in green. It can be set to become yellow to provide a warning if a limit is approached and red if a specified limit is exceeded. Because this display provides all the functions of the CRT display, strip chart, and color warning display on one convenient terminal, it is a more efficient use of the control room resources.

7. Engine Stall Detection

Engine stalls are a potential hazard of some flight test experiments. A former NASA Dryden F-14 program evaluating spin recovery logic resulted in over 100 engine stalls. Because of the potential engine problems associated with high angle-of-attack testing, an engine stall detection algorithm and display were developed for use on the X-29A aircraft.

Figure 6 shows the real-time display developed for use on the X-29A high angle-of-attack aircraft. The display provides a combination of high resolution graphics and digital data to present a complete story to the engine health monitor in the control room. The top graph shows corrected turbine exhaust gas temperature (*TT5C_K*) as a function of corrected fan rotor speed (*N1_K*). The "stall line" is displayed as a solid line. Normal engine operation occurs below the stall line and any engine transient should result in a data trace that runs parallel to it. An engine stall would result in a data trace that crosses above the stall line. This display provides a simple visual approach to detecting engine stalls. The middle graph provides a time history of the compressor discharge pressure (*PS3*) and turbine exhaust gas temperature (*TT5C*). This graph can be used to confirm that an engine stall has occurred as it will result in a sudden, rapid drop in *PS3*. Because stalls can result in an over temperature, *TT5C* is monitored along with *PS3*. The bottom graph provides a unique trace of the maneuver. Both angle of attack and angle of sideslip are displayed as a function of Mach number.

Thus, the propulsion system health monitor can quickly visualize what the flight conditions of the aircraft are during a maneuver and identify when the aircraft is in a critical or more stall-prone condition. Engines are typically more stall prone at low airspeeds and at extreme attitudes. The digital portion of the display provides a 1-sec update of all the essential engine system parameters for normal health monitoring. A more advanced version of the X-29A stall detection algorithm is being developed for use on the F-18 HARV. This method will have the ability to distinguish between a hung and "pop" stall. The F-15 HIDEC program has demonstrated the ability to predict engine stall margin in real time as part of its integrated controls research. In this case excess stall margin is traded for improved engine performance.[4] Real-time fan and compressor stall margins are computed based on engine, inlet, and aircraft measurements. The program demonstrates the potential for onboard engine stall avoidance algorithms.

8. Real-Time Thrust

A real-time thrust method (RTTM) was developed to compute accurate engine gross and net thrust for the X-29A aircraft. This computation was a requirement for implementation of real-time aeroperformance, as discussed in the following section. The RTTM was specially developed for the X-29A program by the Computing Devices Company (ComDev) of Ottawa, Canada, in conjunction with NASA.

Over the past 15 years, ComDev has developed and patented a unique capability to compute accurate engine gross thrust (F_G) in real time over the entire aircraft operating flight envelope. This simplified gross thrust method (SGTM) has advantages over the traditional methods like the manufacturer's in-flight thrust program. The SGTM requires much less instrumentation and computational power while remaining reliable and accurate. It requires only free-stream static air pressure and simple gas pressure measurements at three locations in the engine afterburner duct. Because all engine pressures are measured downstream of the rotating machinery, gross thrust accuracy is not affected by engine degradation or intake distortion.

The extension of the SGTM to the RTTM involved the addition of a simplified net thrust calculation procedure based on the real-time calculation of ram drag from true airspeed and inlet mass flow. Net thrust was also corrected for estimated nozzle and spillage drag yielding the net propulsive force (F_{NP}).

The RTTM was developed and calibrated for an F404-GE-400 engine using data obtained during testing at the NASA Lewis Propulsion System Laboratory (PSL). A comparison of computed RTTM net thrust values to the measured PSL values indicate an accuracy of ±2.74 percent. Analysis predicts a 2- to 4-percent uncertainty in flight. A detailed description of the RTTM is in [15].

Displays were developed to monitor the RTTM input and output values, including time histories of gross thrust and the average engine pressure rake values. An example display format is shown in figure 7. The display includes digital parameters like the aircraft measured flight conditions, basic engine health parameters, engine performance parameters, and information on individual pressure values of each rake. Logic was also developed to continually monitor the status of the ComDev thrust calculation methods and to display a coded message (ERCODE) when an error occurred, describing the nature of the error.

Currently, the RTTM is being evaluated by the TTCP for potential use as an onboard engine health monitor.[1]

9. Aeroperformance

The X-29A aeroperformance real-time analysis technique was developed to increase flight efficiency and productivity through maneuver technique evaluation and data quality control. Direct real-time evaluation of the final data analysis product minimized the flight repeats that often arise when postflight data reduction reveals poor data quality or poor flight maneuver technique such as unacceptably high maneuver dynamics. One example is the drag polar coefficients of lift and drag. In addition to the value of immediate in-flight aircraft performance evaluation and immediate hard copy of flight results for postflight evaluation, the technique has the potential added bonus of use for real-time in-flight aerodynamic optimization. That is, the onboard calculation of real-time lift and drag allows them to be used in performance optimization schemes.

The real-time aeroperformance data analysis method is based on the in-flight calculation of net thrust, highlighted in the previous section, and vehicle excess thrust from accelerometer and weight measurements. Aircraft coefficients of lift (C_L) and drag (C_D) were calculated from the equations

$$C_D = D/qS = F_{NP} - F_{ex}/qS$$

where excess thrust is computed from

$$F_{ex} = n_x W_t$$

and

$$C_L = L/qS = n_z W_t - F_G \sin \alpha/qS$$

Aircraft specific excess power (P_s) is also computed from the equation

$$P_s = F_{ex}\ Vt/W_t$$

The maneuver techniques used were the dynamic pushover-pullup and the constant thrust, constant Mach windup turn to sweep out a wide range of angles of attack at a given Mach number in two short maneuvers. These maneuvers were flown back to back at a nominal 0.20-g/sec g-onset rate at fixed Mach number increments over the speed range of Mach 0.40 to 1.30. The maneuver pair could be completed in less than 1 min. The real-time data inputs were neither filtered nor thinned.

Figures 8(a) and (b) show the representative displays of the quality of drag polars reached. Good data quality is evident by the small amount of data scatter. These real-time results were compared with later postflight-reduced drag polar results and were in very good agreement. Because of the decision not to digitally filter the aircraft accelerometers in real time, aerodynamic buffet onset was seen as a function of angle of attack and coefficient of lift on the drag polar and lift curves. A detailed description of the real-time aeroperformance technique is provided in [16].

10. Thrust Vectoring System Configuration

Because of the unique configuration of the F-18 HARV TVCS, a real-time monitoring display was developed by the flight controls engineer to give a prompt qualitative status of the system. Figure 9 shows the real-time graphic display of the TVCS on both engines. This display gives an implicit understanding of vane deflections and the resulting thrust vector. It also provides instant configuration updates and important engine performance information pertinent to the TVCS. Most noticeable is the indication of each postexit vane position.

Vane position is shown on the display by the amount of shading of each vane outline and by the digital value associated with each vane. For the TVCS to be active, the research flight control system (RFCS) must be engaged. The engagement is indicated by the letters RFCS in the upper left corner of the screen surrounded by a green box. The top center portion of the display shows the pilot's current stick, rudder, and throttle positions. Below this is an illustration showing the direction and magnitude (arrow direction and size) of the resulting thrust vector. The six-sided figure shows a representative maximum possible effective thrust vector envelope. Here, the two jets combine to provide a vectored jet that is pointed to the right and slightly upward. Below the figure is a digital display of important TVCS engine performance parameters including nozzle pressure ratio (NPR), nozzle area (*A8*), power lever angle (PLA), and the estimated net thrust (*FN*). These digital values are calculated onboard the aircraft for use in the thrust vectoring control laws. The bottom two bar graphs below each vane diagram display the vane rates and direction of travel. This display gives a comprehensive view of the TVCS configuration and its performance.

11. Advanced Health Monitoring

The continuing advancements in computer hardware, software, and display technology will provide new capabilities for engine performance and health monitoring. In particular, artificial intelligence techniques combined with modern display technologies promise enhanced safety monitoring. The programmable workstation has the ability to put some of the engineers' knowledge into the system. This input can be done through the use of expert systems that use the declarative knowledge contained in rules that evaluate the system monitored. In this way, data, as well as other useful information, are displayed to the user.

Also, the use of programmable workstations for graphic displays substantially reduces the workload, allows for sophisticated graphics without impacting critical acquisition software, and provides greater flexibility in display and reconfiguration.

A preliminary intelligent computer assistant for engine monitoring (ICAEM) was developed and evaluated for use on the X-29A and F-18 HARV aircraft.[17] This expert system operates as an "expert aid" to the propulsion health monitor. The ICAEM has the capability of determining the current operational state of the engine, recognizing a systems-level anomaly, and displaying the corrective action required of both the pilot and the propulsion system monitor. For example, this system can recognize when the pilot is beginning to start an engine, identify if a normal or a "hung" or "hot" start is occurring, and display related critical parameters. The ICAEM can also recommend corrective actions to the propulsion monitor.

The displays developed with this system are also unique. Figure 10 shows a typical display for the monitoring of two engines on the F-18 aircraft. The ICAEM display is partitioned into three major sections. The bottom portion of the display shows a cross-sectional view of two engines, left and right. This section of the display shows parameters that are always monitored. Thermometerlike displays are at respective engine stations. A set of two vertical bars provide an indicated and a predicted value for each parameter. The predicted value is based on many previous data samples and indicates a trend. The box containing digital data at each station will change to yellow when a parameter is near a predetermined limit and will turn red when the limit is reached.

The center display is two colored horizontal bars containing text. These bars show the actual state of the engine; that is, ground start, takeoff, normal flight operation, stall, and airstart. Any nominal condition is displayed in a green background, while a warning condition or a condition of potential concern is displayed with a yellow background. Any serious condition is displayed with a red background. The top portion of the display is used to show user-requested information. The user can request digital strip charts on any predefined parameter desired and pop up a display with a procedure on it such as the spooldown airstart procedure.

The ICAEM can provide a better monitoring environment because it uses the knowledge and experience of several propulsion engineers. It is always attentive and never distracted as a human may be. Because the system displays information, not raw data, it enhances safety of flight and improves the efficiency of the propulsion system monitor.

12. Concluding Remarks

Procedures for real-time evaluation of the in-flight health and performance of gas turbine engines have been developed to enhance flight test safety and productivity. These techniques include the monitoring of the engine, the engine control system, thrust vectoring control system health, and the detection of engine stalls. Real-time performance techniques were developed for the determination and display of in-flight thrust and for aeroperformance drag polars. These new methods were successfully demonstrated on various research aircraft at the NASA Dryden Flight Research Facility. A new technique for engine health monitoring based on expert system technology promises enhanced safety of flight and improved efficiency for the propulsion system monitor. The capability of NASA's Western Aeronautical Test Range and the advanced data acquisition systems were key factors for implementation and real-time display of these methods.

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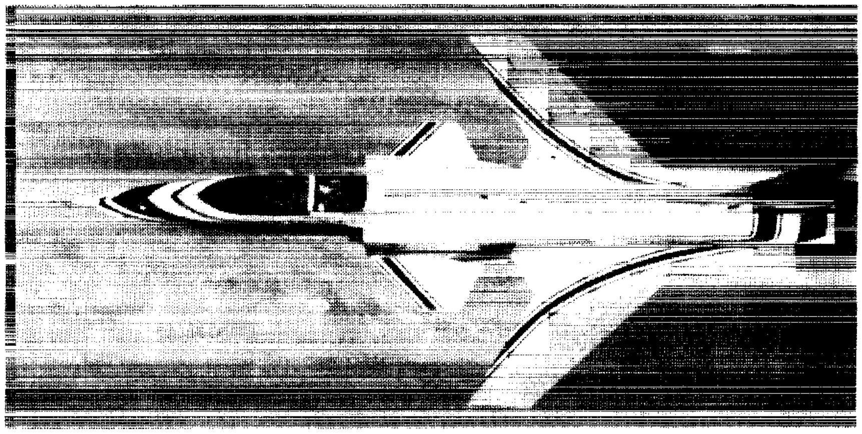


(a) X-29A advanced technology demonstrator.

(b) F-15 HIDEC.

(c) F-18 HARV.

Figure 1. NASA aircraft used to develop engine health monitoring and performance techniques.

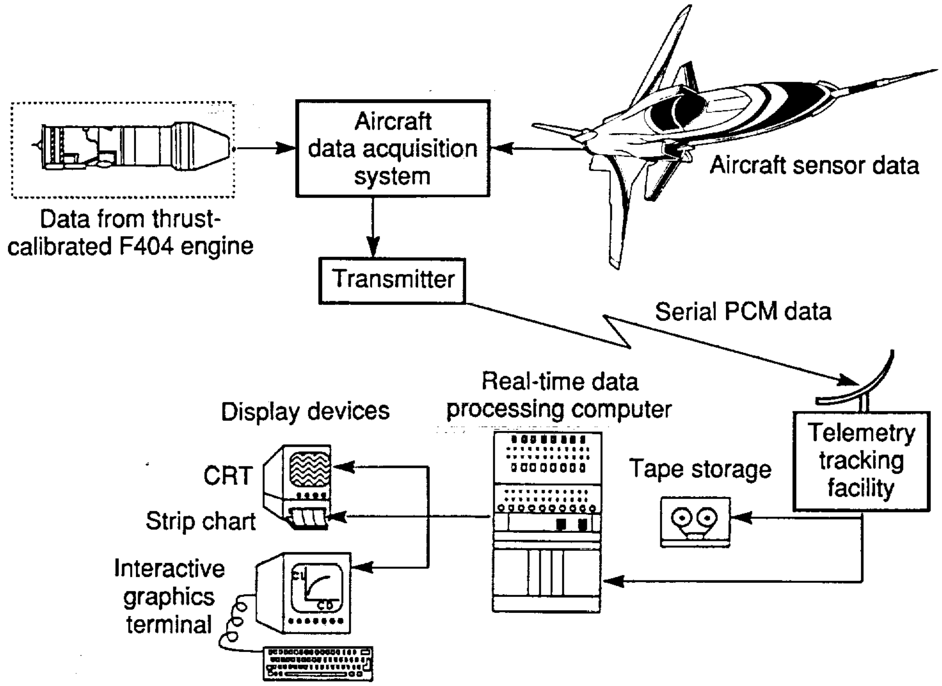


Figure 2. X-29A real-time data acquisition system.

Figure 3. Western Aeronautical Test Range mission control center.

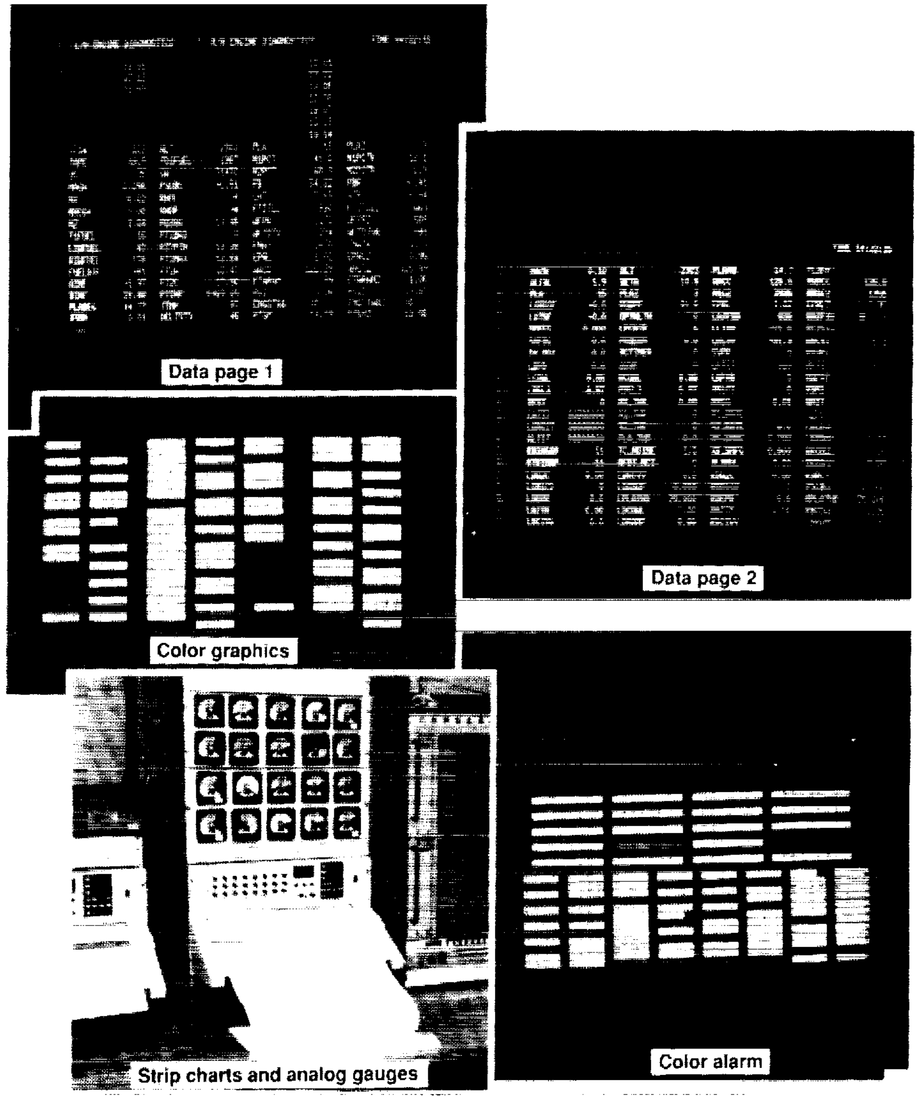


Figure 4. Real-time displays used for engine health monitoring of the F-15 HIDEC.

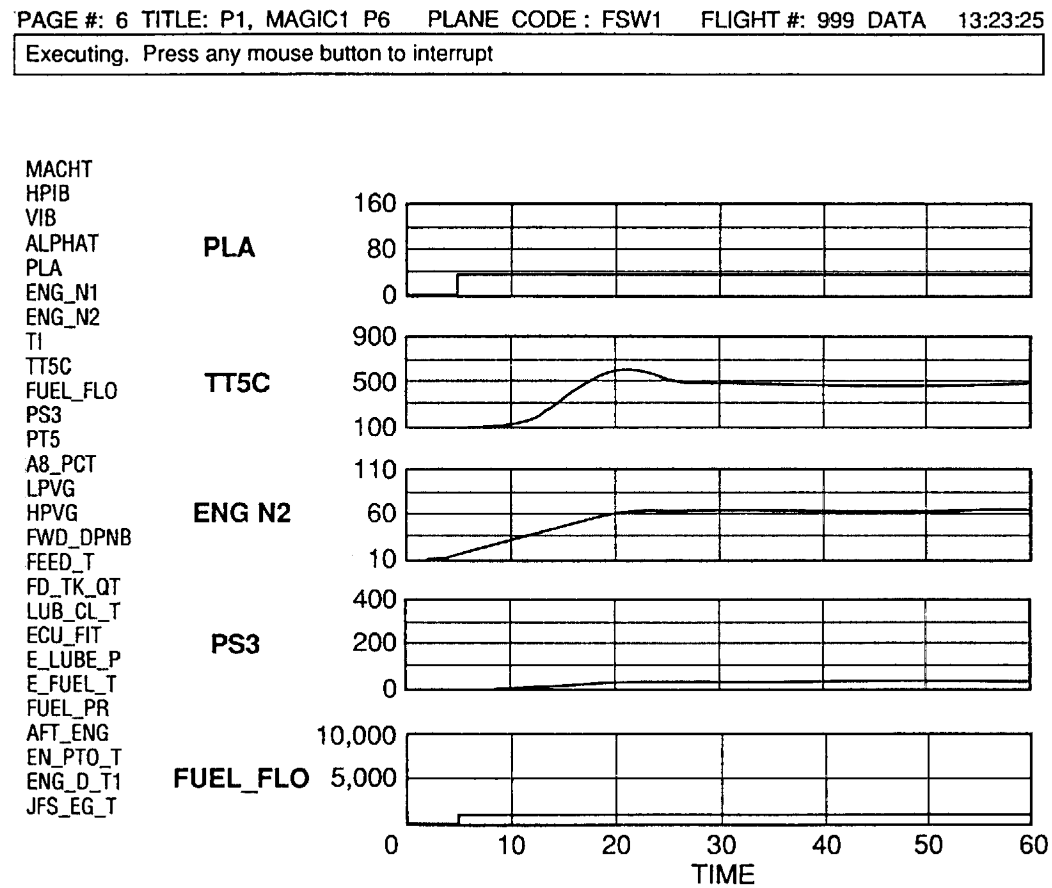


Figure 5. X-29A real-time engine health monitoring display.

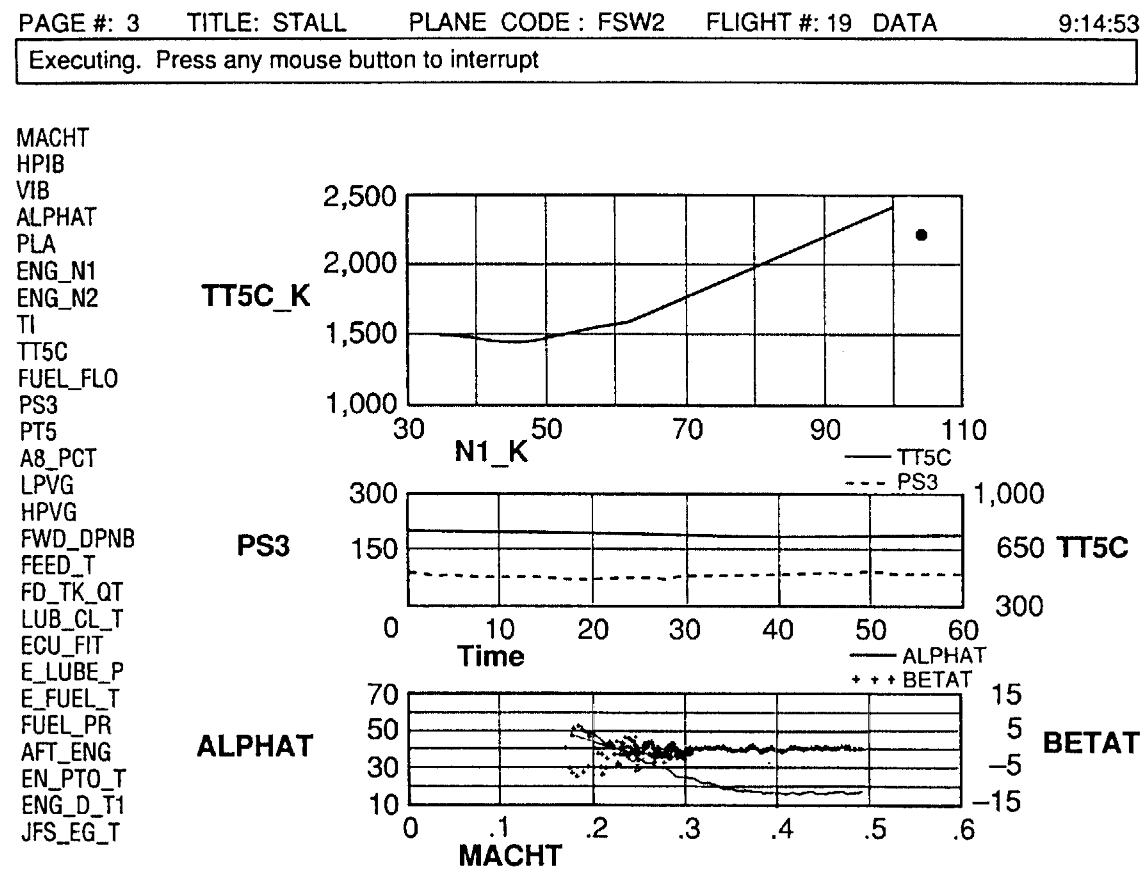


Figure 6. X-29A engine stall detection display.

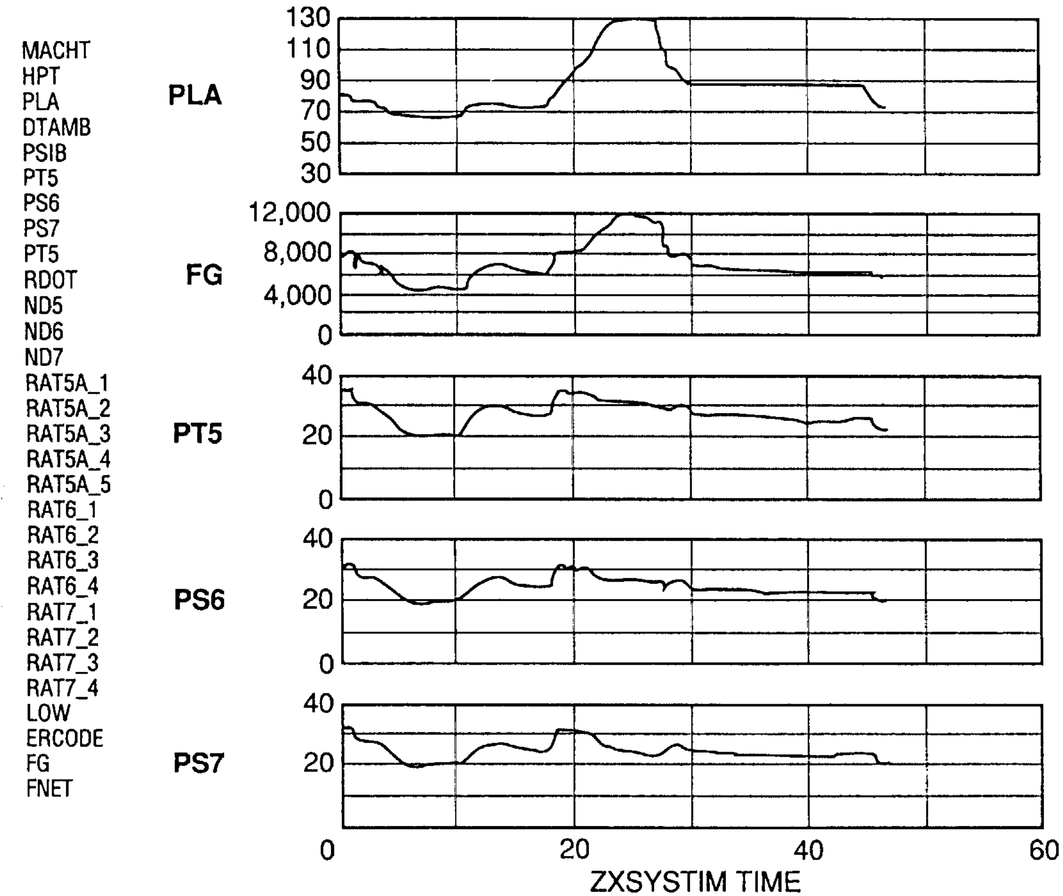
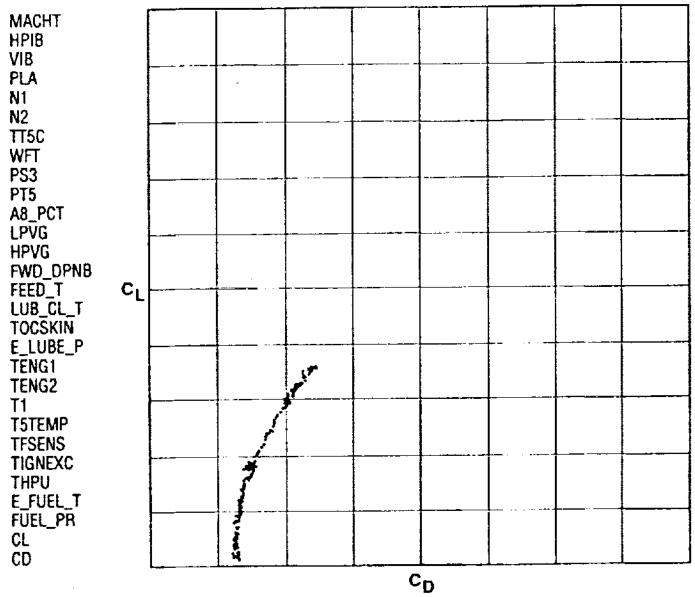
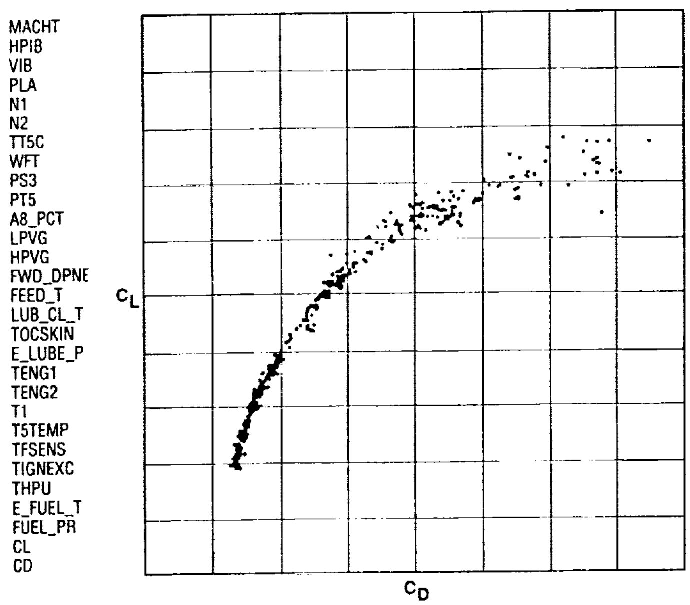


Figure 7. X-29A real-time thrust display.



(a) Pushover-pull up.



(b) Windup turn.

Figure 8. X-29A real-time aeroperformance display.

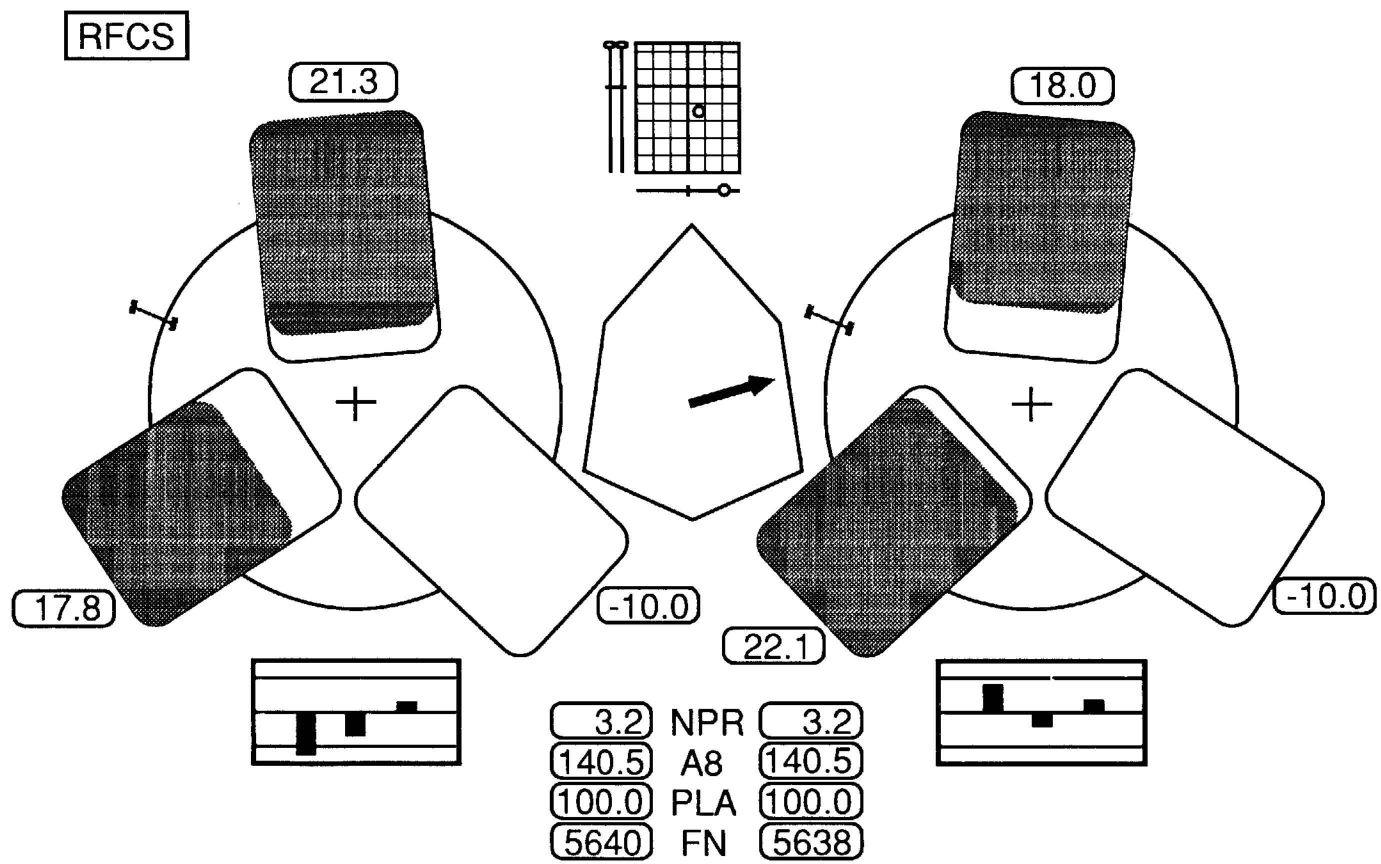


Figure 9. F-18 HARV real-time thrust vectoring system configuration display.

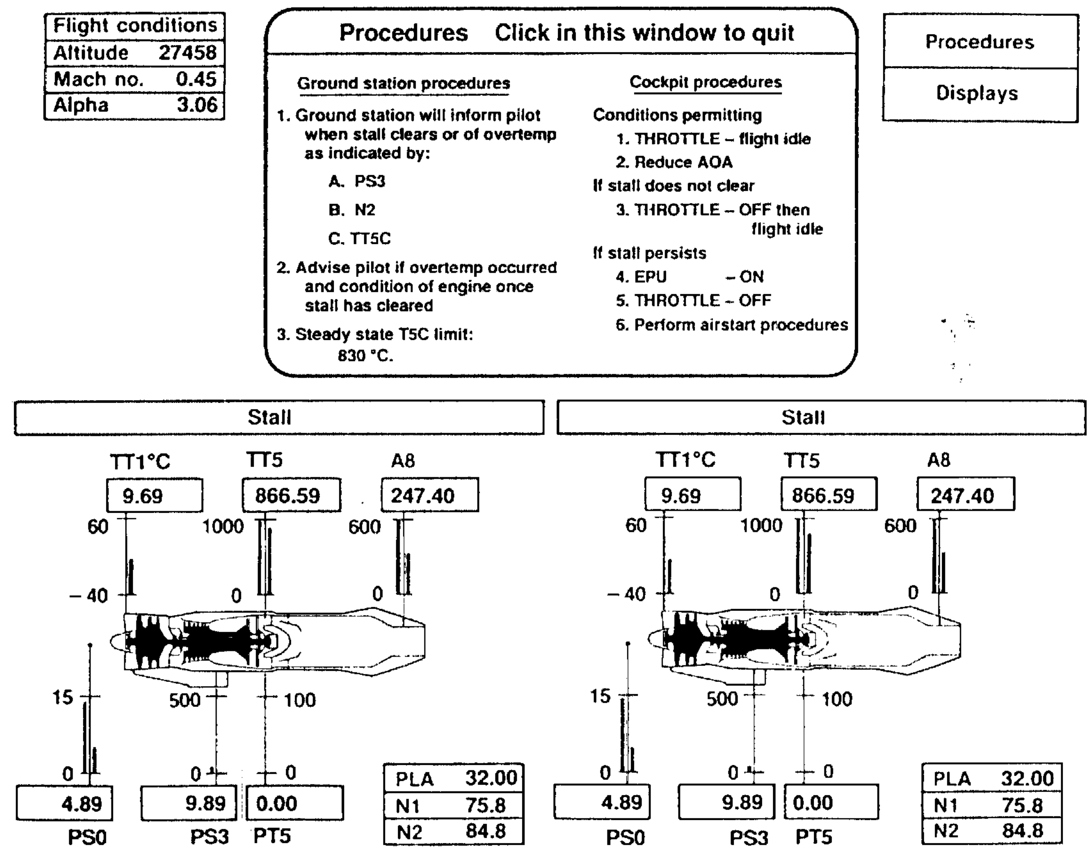


Figure 10. F-18 HARV advanced engine health monitoring system display.