Knowledge Gained from F/A-22/F119 Propulsion System Ground and Flight Test Analysis

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ABSTRACT

This paper describes the teaming strategy between the Air Force's two major propulsion test centers, the Arnold Engineering Development Center (AEDC), and the Air Force Flight Test Center (AFFTC) to evolve new paradigms and approaches for cost sharing and sharing knowledge for risk management in the development of new aero-propulsion systems. The AEDC is responsible for the ground-based altitude development of current and future propulsion systems, and the AFFTC is responsible for in-flight development testing of installed propulsion systems. I'm Allan Webb, Chief of the Propulsion Integration Branch at the Air Force Flight Test Center at Edwards Air Force Base, CA and I will be presenting the introductory and summary slides addressing knowledge gained from F/A-22/F119 propulsion system ground and flight test analysis. Dr. Donald Malloy from the Arnold Engineering Development Center in Tennessee will discuss propulsion system ground and flight test analysis procedures for the F119 powered F/A-22 aircraft.

1.0 OUTLINE

- **Introduction**
- **Propulsion System Ground and Flight Test Analysis**
  - –**Technical Approach**
  - –**Results**
- **Lessons Learned**
- **Summary**

The initial introductory charts will provide an overview of typical aeropropulsion ground and flight tests performed and common ground and flight test capabilities and needs. Then, propulsion system ground and flight test analysis approaches, model-to-data comparisons, and model-based fault detection and analysis results from F/A-22/F119 propulsion ground and flight tests will be presented. Lessons learned will be presented and then key points will be summarized.

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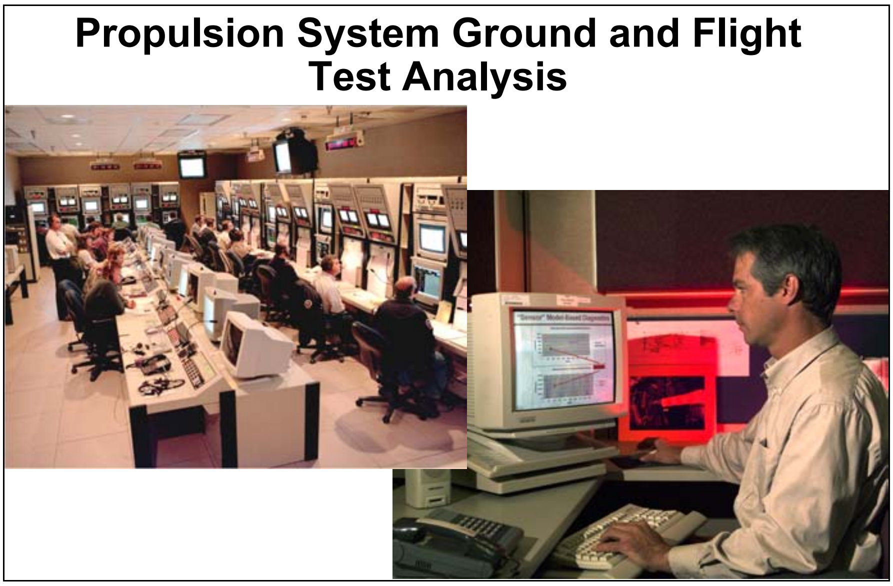
2.0 INTRODUCTION

The need to reduce analysis costs and time, and to enhance propulsion system real-time and postflight analysis capabilities, is shared by both ground and flight test centers due to significant reductions in test allocations. The need to reduce time includes the time required for both data analysis and reporting, and is required because senior decisions makers, who need the results of data analysis to make programmatic decisions on weapons systems, are on very tight schedules in today's environment, as you well know.

Developmental testing of advanced aeropropulsion systems for the F119 powered F/A-22 shown is a demanding task requiring accurate, detailed measurements and analysis at various flight conditions. Specific test requirements for the development of new aeropropulsion systems include performance testing, verifying integration of airframe and propulsion functions, determining engine and inlet compatibility, verifying engine operability and stability, determining engine structural characteristics, developing the engine control system, developing fault detection/accommodation capabilities, and accelerated mission testing.

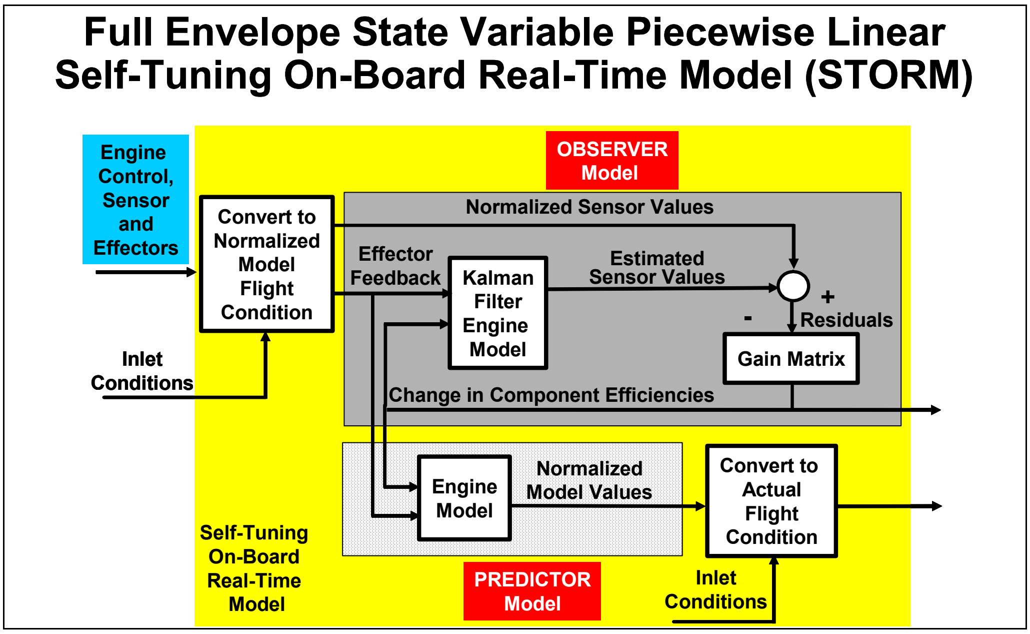


The emphasis of this paper is on the development and application of a nonlinear aerothermodynamic component-level model that serves as the basis for the model-based analysis and fault identification process and documentation of lessons learned from propulsion system ground and flight test analysis. Model-to-data comparisons and model-based fault detection and analysis results used to detect instrumentation faults and changes in flows and efficiencies of the F119's rotating components during propulsion ground and flight test of the F/A-22 are also presented.

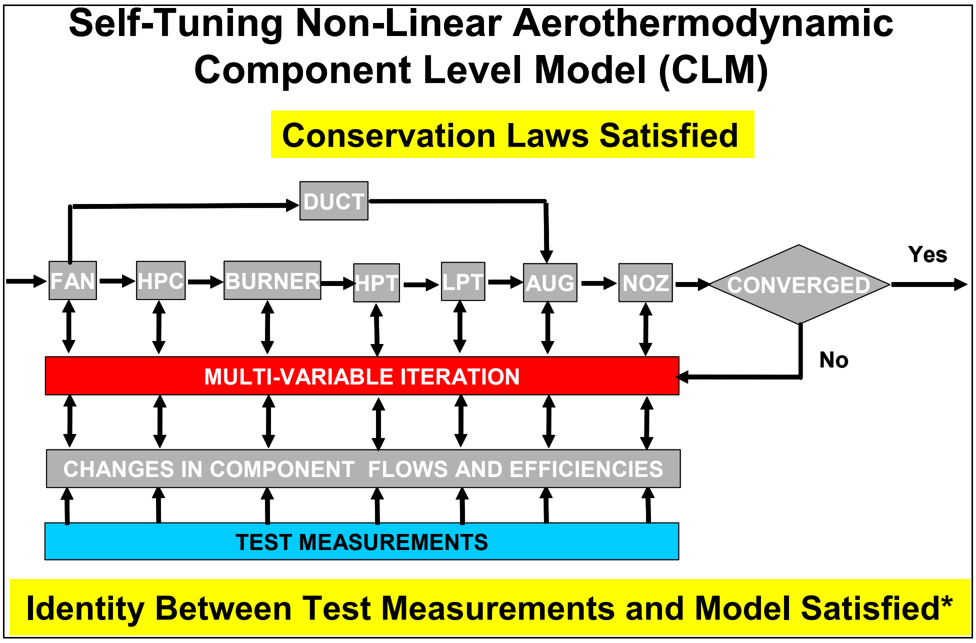
Shown on the left is the Ridley control room at Edwards Air Force Flight Test Center. On the right is our co-author Dave Kidman who could not attend this week's symposium. Dave served as the USAF lead propulsion engineer at the F/A-22 flight test squadron, where he was responsible for all aspects of the F/A-22 / F119 propulsion flight test effort. Currently, Dave is the Technical Expert for Propulsion Systems Integration Testing at Edwards Air Force Base.

3.0 PROPULSION SYSTEM GROUND AND FLIGHT TEST ANALYSIS

3.1 Technical Approach



Modeling and simulation tools are used to support propulsion ground and flight test operations. The Pratt & Whitney developed STORM calculates engine-related parameters in real time. The on-board model consists of a Kalman filter observer and a predictor. The observer compares model outputs to engine control sensor values and adjusts component efficiencies so that the model estimates match measurements. The predictor calculates engine values (such as fan airflow and engine gross thrust) on the basis of effector information and adjusted component efficiencies. The engine manufacturer, using common design practices, normalized the state-variable engine model to maintain numerical robustness in the filter design calculations. Use of a normalized flight condition also reduces memory requirements for the piecewise linear state-variable model (SVM) employed within the observer and predictor models. Observer and predictor models both employ a SVM to model the gas generator and an aerothermal model of the afterburner. The SVM models low-frequency effects that are embedded in the spool dynamics and heat-transfer characteristics of the hot sections of the engine.



An AEDC developed, Component Level Model (CLM), capable of simulating steady-state and transient engine operation, serves as the basis for the fault identification process. The CLM, which includes both observer and predictor components, combines the physical relationships that govern engine operation with empirical relationships that describe individual component performance. The result is a self-tuning, nonlinear aerothermodynamic model in which the effects of changes to engine attributes are incorporated by making corresponding changes to the model attributes. Additionally, the component-matching approach quantifies the changes to engine parameter interrelationships, which provide a prediction capability for the fault identification process.

Model Comparison

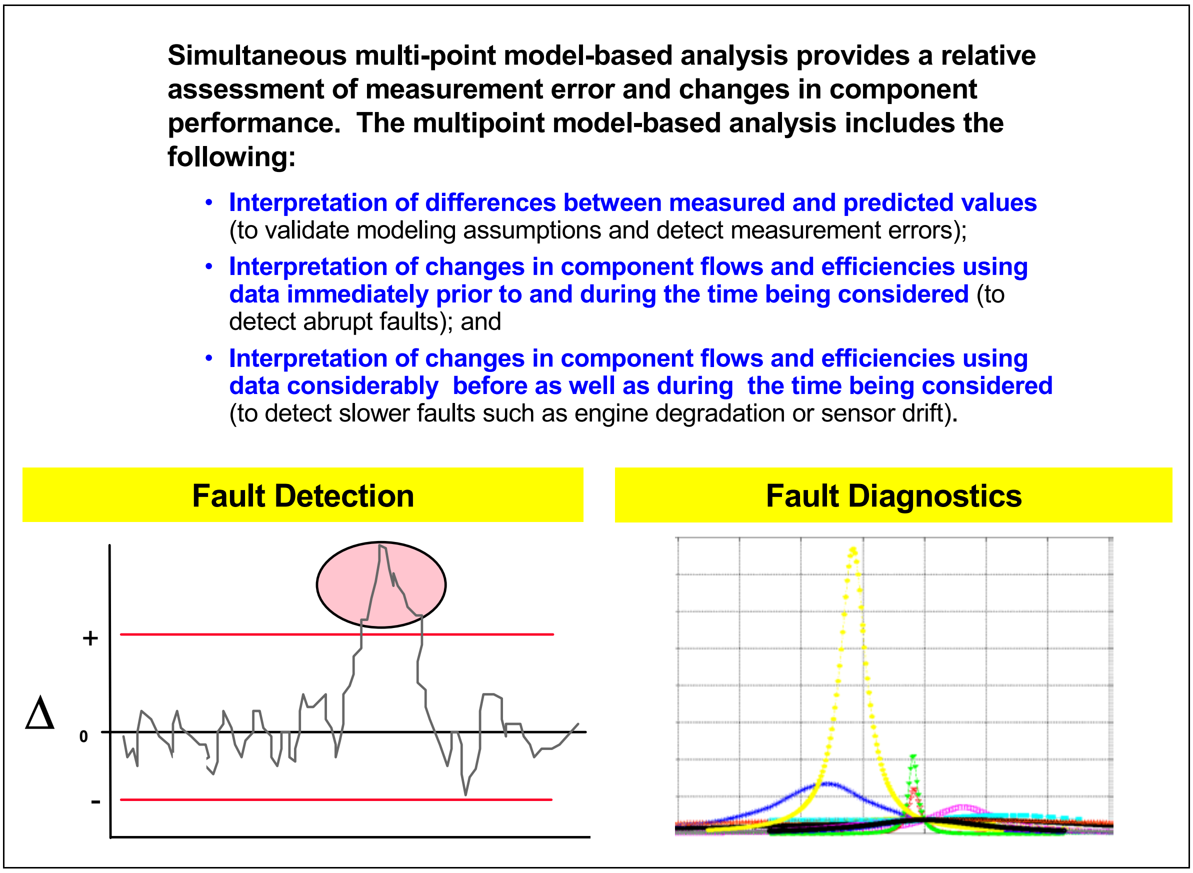
Self-Tuning On-Board Real-Time Model (STORM)	Non-Linear Aerothermo Component Level Engine Model (CLM)
• Self-Tuning • Reasonable Fidelity • Real-Time Calculations • Cost Effective Predictions/Checkout • On-line Performance Monitoring • ***In-Flight Thrust Calculation*** . . . • On-Board Control Sensor Validation • On-Board Model-Based Control • On-Board Performance Optimization	• Self-Tuning • High Fidelity • Real Time Calculations • Pre-Flight Predictions/Analysis • Post-Flight Analysis • On-line Performance Monitoring • ***In-Flight Thrust Calculation*** • ***On-Line Sensor Validation*** . . . • Problem Resolution

Model calibration techniques depend heavily on the level of model development and the available measurements. A key similarity between the models is that the accuracy of both the STORM and the CLM are improved through self-tuning to account for engine-to-engine variation and engine degradation.

It is well known that state-variable models (such as STORM) can be executed in real time. Through the use of advanced computing technologies and high-speed computing platforms, the nonlinear CLM can also be executed in real time. Furthermore, state-of-the-art parallel computing technologies permit faster than real-time execution of the nonlinear CLM for postflight processing of recorded data.

On-board, real-time models can be used for on-board control sensor verification, model-based control, and performance optimization. Both the STORM and the CLM can be used for online performance monitoring. A key difference between these modeling approaches is that the CLM-based approach allows engineers to 1) automatically interpret measured and predicted responses and interrelationships throughout the propulsion system quantified by the CLM and 2) effectively utilize additional test measurements available during developmental ground and flight testing. The CLM also provides a capability to detect and accurately diagnose faults -- a capability which is independent of the experience level of the analysis engineer.

The automated data validation and fault identification approach that uses aerothermal engine cycle matching techniques will now be described. Then, model-to-data comparisons and model-based fault detection and analysis results for F/A-22/F119 propulsion ground and flight test are presented for a middle of the envelope test condition.



The model-based fault detection approach relies on a real-time interpretation of measured and predicted responses and interrelationships throughout the propulsion system quantified by the CLM. A simultaneous multipoint analysis is used to provide a relative assessment of measurement error and changes in component performance. The multipoint analysis includes the following:

- Interpretation of differences between predicted and measured aerothermodynamic measurements over the time being considered (to validate modeling assumptions and detect measurement errors);

- Interpretation of changes in component flows and efficiencies using data obtained immediately before and during the time being considered (to detect abrupt faults); and
- Interpretation of changes in component flows and efficiencies using data obtained considerably before and during the time being considered (to detect slower faults such as engine degradation or sensor drift).

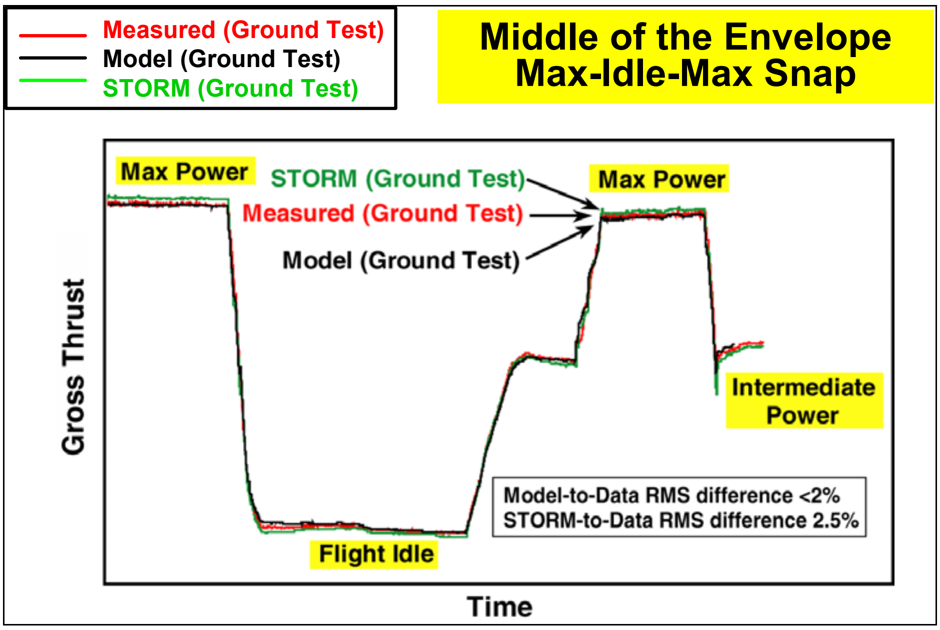
3.2 Results

- **Model to Data Comparisons**
  - **Middle of the Envelope Max-Idle-Max Throttle Snap**
- **Model-Based Fault Detection and Analysis**
  - **Augmentor Inlet Temperature Measurement Anomaly During Throttle Snap**
  - **Augmentor Inlet Pressure Measurement Anomalies During Nozzle Vectoring**

Model-to-data comparisons and model-based fault detection and analysis results for F/A-22/F119 propulsion ground and flight test are presented for a middle of the envelope throttle snap. Unless otherwise noted, the "model" referred to in the model-to-data comparisons and in the model-based fault detection and analysis results is the CLM.

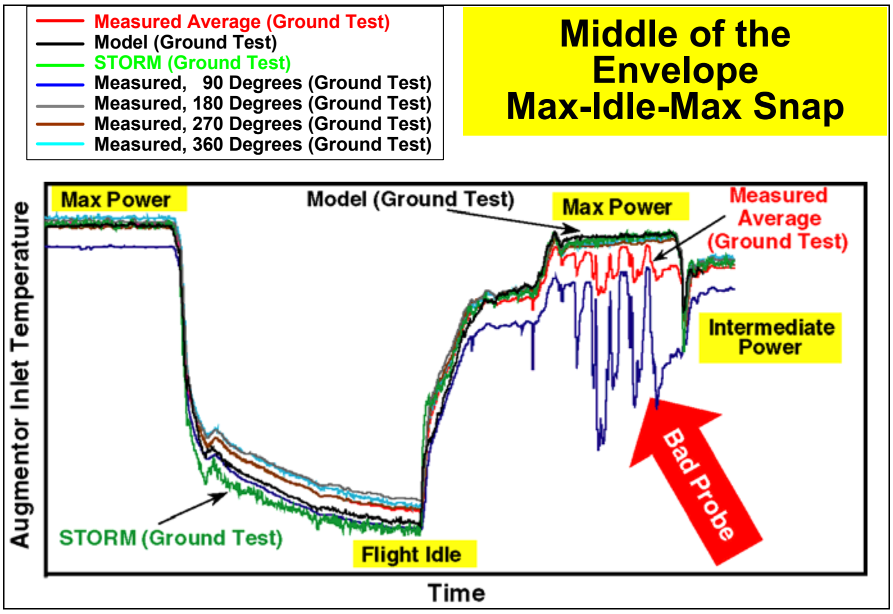
Two examples of model-based fault detection and analysis are presented for ground tests in which the faults could be independently verified using redundant test measurements. The first is an augmentor temperature measurement anomaly that occurred during an engine power lever snap. The second is an augmentor pressure measurement anomaly that occurred during rapid, sinusoidally varying, pitch axis vectoring of the two-dimensional, convergent-divergent nozzle.

3.2.1 Model to Data Comparisons



It should be clear that the engine model-based diagnostic concept requires accurate modeling of the physics of the engine. As would be expected, the fidelity of the model and the uncertainty in the test data are strongly influenced by the engine cycle and the engine operating conditions, including altitude, Mach number, and power setting. A comparison of measured and predicted gross thrust for a middle of the envelope throttle snap from maximum afterburner power to idle power and then back to maximum power is shown. The root-mean-square (RMS) error between the measured transient ground test data and the CLM prediction is less than two percent. Similarly, the RMS error between the transient test data and the STORM prediction of gross thrust is approximately two-and- one-half percent. Model-to-data comparisons, including those for the engine operating conditions shown, illustrate the high fidelity of the engine model.

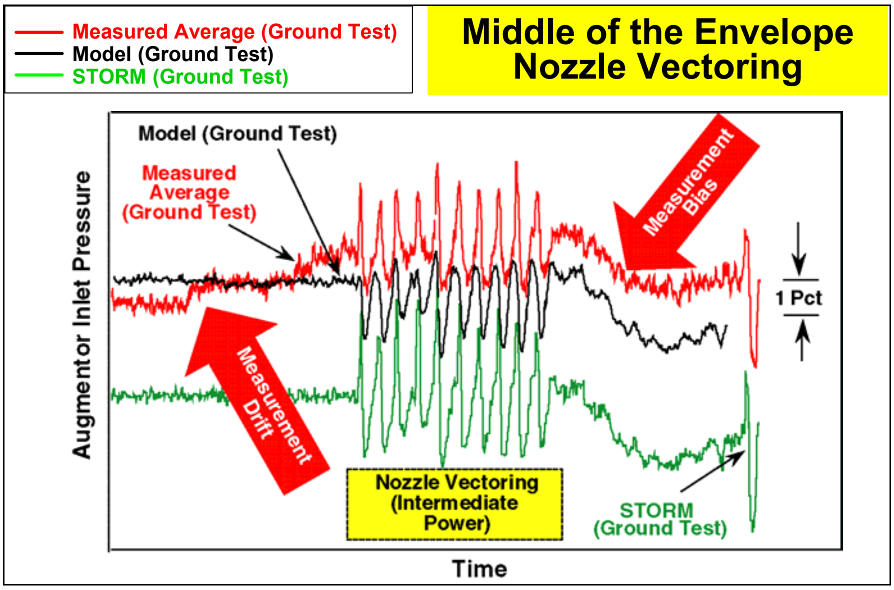
3.2.2 Model-Based Fault Detection and Analysis



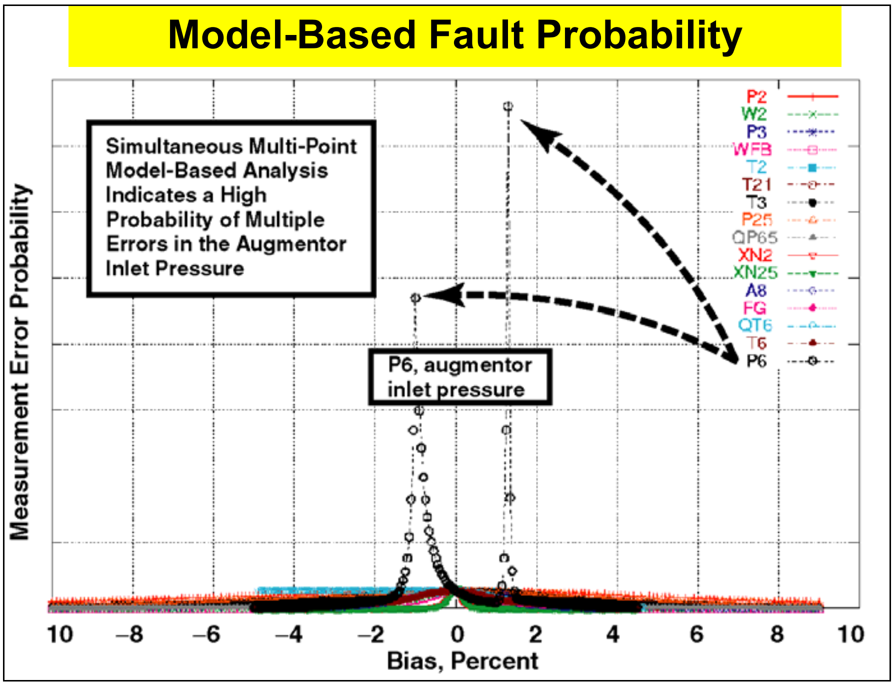
While the measured and predicted gross thrust levels shown in the previous slide are in good agreement, significant deviations between measured and predicted augmentor inlet temperature can be seen in the figure shown. The measured augmentor inlet temperature was low and erratic during and after engine acceleration to maximum augmented power.

A time-dependent indication of the overall fault probability based on differences between measured and predicted values and changes in component flows and efficiencies is available to the test engineer. In addition, automated model-based fault detection and diagnosis results depicting the relative measurement error probability at the instant in time when the fault was initially detected are provided to the test engineer.

Model-based analysis confirmed that the deviation between measured and predicted augmentor inlet temperature was the result of a faulty measurement used to determine the average augmentor inlet temperature using measured values at four circumferential locations.



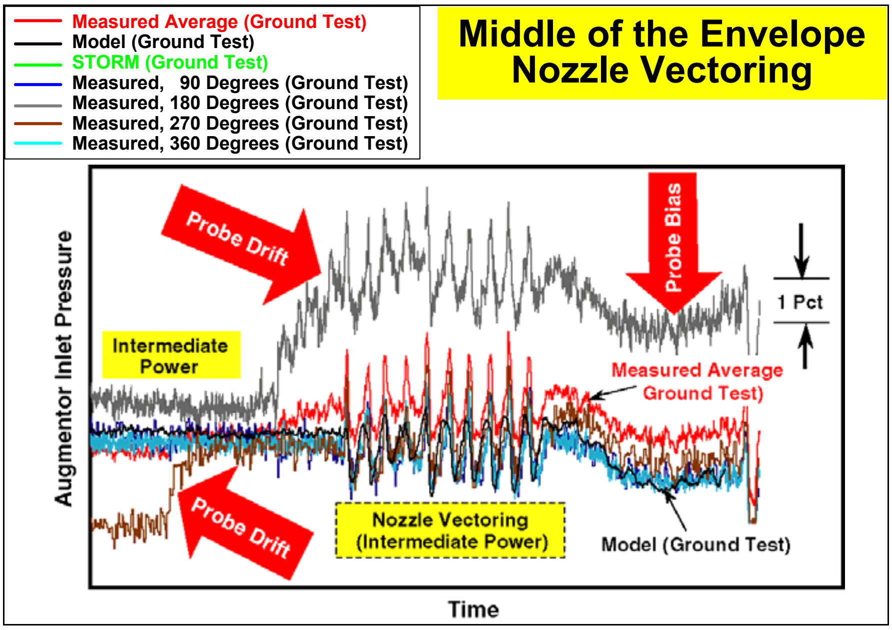
The figure shown indicates a possible drift and/or bias in the augmentor inlet pressure during rapid, sinusoidally varying pitch axis vectoring of the two-dimensional, convergent-divergent nozzle. The measured augmentor inlet pressure is approximately one-half percent low at the beginning of the time slice and one percent high at the end. In the next slide, the results of the simultaneous multi-point, model-based analysis will clearly indicate a high probability of multiple errors in the augmentor inlet pressure.



As previously stated, the simultaneous multi-point, model-based analysis indicate a high probability of multiple errors (biases) in the augmentor inlet pressure. Once a fault is detected, the fault diagnostic system concentrates on identifying individual sensor faults and tries to identify the erroneous measurement and the magnitude of the error. The calibrated CLM is used to assess the probability of measurement errors. Each measurement is sequentially perturbed, measurements being varied to determine the most probable cause of the fault (e.g., fuel flow is perturbed ± 5 percent in 0.5-percent increments; then rotor speed is perturbed, etc.).

For brevity, results from the performance degradation search are not presented. In gas turbine transient testing, the data validation process can be complex and generally includes pretest, test, and posttest validation of the data. The model- based fault detection and diagnosis system is part of an integrated fault detection and diagnostic system which also includes a comparison of redundant measurements.

The deviation between measured and predicted augmentor inlet pressure shown in the next slide was the result of measurement errors in two of the four probes used to determine the average augmentor inlet pressure.

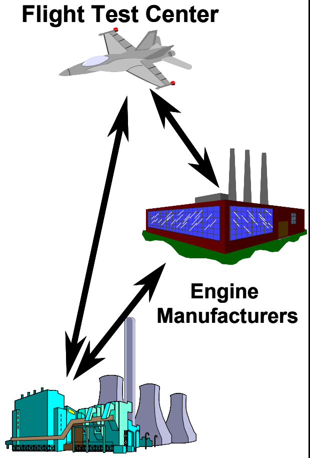


The deviation between measured and predicted augmentor inlet pressure was the result of measurement errors in two of the four probes (at 180 and 270 degrees) used to determine the average augmentor inlet pressure. The probes at 270 degrees (shown in brown) and 180 degrees (shown in gray) are both drifting prior to initiation of nozzle vectoring. A bias in the pressure measurement at 180 degrees is seen at the end of the data point.

Lessons learned from ground and flight testing of the F119 powered F/A-22 aircraft and will now be presented by Allan. Many of the lessons learned relate to problems encountered during post-test data analysis and automation and implementation of model-based analysis techniques, including those described in detail in this paper.

4.0 LESSONS LEARNED

- **Better Characterize Installed Engine Pt/Ps Relationship**
- **Evaluate Flight Profiles During Ground Testing**
- **Develop Correlation Between Ground and Flight Test Instrumentation**
- **Share Information Between Developmental Test and Evaluation (DT&E) Phases**
- **Work Together to Develop Standardized Data Analysis Tools**
- **Modeling and Simulation (M&S) Usage During Test**



There has been much knowledge gained over the last 20 years of ground and flight testing the F/A-22 aircraft and engine. Although many of these problems may seem obvious, so much time and effort was focused on real-time test execution that post-test analysis was considered secondary. The first three lessons learned are associated with 1) better characterization of installed engine relationships during ground testing, 2) evaluation of flight profiles during ground testing, and 3) development of correlations between ground and flight test instrumentation. These three are lessons learned from flight tests that also relate to ground testing. The fourth lesson learned is associated with challenges involved in sharing information between Developmental Test & Evaluation (DT&E) phases. The fifth lesson learned highlights the need for test centers to work together to develop T&E tools for real-time and post-test analysis. The final lesson learned addresses modeling and simulation usage during test.

Better Characterize Installed Engine Pt/Ps Relationship

- Problem Description: Installation effects on engine Pt/Ps not properly identified prior to flight test necessitating revisions to engine logic
- Potential Solutions:
  - Install pressure sensors at production locations during sub-scale inlet testing
  - Engine ground test with “Portion” of A/C Inlet
  - Use Computational Fluid Dynamics (CFD) to improve Pt/Ps calibration
- Benefit: Improved Pt/Ps calibration will improve accuracy of engine scheduling and avoid schedule juggling and repeat testing due to revised engine logic

F/A-22 engine inlet pressure is sensed by the engine control using eight wall static ports in the inlet duct, manifolded together and sensed via a pressure transducer within each FADEC. A key lesson learned relates to the need for better planning to locate instrumentation sensors necessary to characterize the installed engine relationship between the sensed static pressure in the inlet duct and the total pressure at the engine face. Changes to engine control logic and repeat testing with revised engine logic were required to account for inaccurate characterization of the installed engine total-to-static pressure relationship. Potential solutions to this problem include installing the pressure sensors at the production locations during sub-scale inlet testing and using Computational Fluid Dynamics to better characterize the pressure relationship. Better characterization of the installed engine total to static pressure relationship would improve engine scheduling and avoid schedule juggling and repeat testing with revised Pt/Ps calibration within the engine logic.

Evaluate Flight Profiles During Ground Testing

Problem Description: Impacts of both throttle and altitude/Mach number profiles on performance and/or operability not fully investigated during ground testing

- Insufficient characterization of the impact of throttle profiles and stabilization times on clearances and engine performance
- Insufficient characterization of rubs/open clearances on stability margin

- Potential Solutions:
  - Use flight simulator profiles for ground tests
  - Use actual flight test profiles
  - Development and use of time-dependent engine models to better characterize impacts on performance and operability for test profiles not performed during ground test
- Benefit: Better understanding of engine performance / operability prior to flight test

Impacts of both throttle and altitude/Mach number profiles on performance and/or operability were not fully investigated during ground testing. As a result, flight testing was initiated without a thorough understanding of the impact of throttle profiles and stabilization times on clearances and engine performance. Similarly, flight testing was initiated without a thorough understanding of the effect of rubs/open clearances on stability margin (e.g., clearances associated with long descents at low power followed by an engine acceleration). Potential solutions include the use of flight simulator profiles for ground tests, use of actual flight test profiles during ground test, and the development and use of time-dependent engine models to better characterize impacts on performance and operability for test profiles not performed during ground test. Evaluation of flight profiles prior to flight test would enable a better understanding of engine performance and operability.

Develop Correlation Between Ground and Flight Test Instrumentation

- Problem Description: Incorrect conclusions can result from inaccurate correlations between flight test & ground test instrumentation
- Potential Solutions:
  - Test with similar or identical ground and flight test instrumentation
  - Create correlations between flight and developmental instrumentation during developmental ground tests
- Benefit: Better consistency between ground & flight test analysis results

Incorrect data analysis conclusions can result from inaccurate correlations between flight test and ground test instrumentation. Potential solutions include testing with similar or identical flight test and ground test instrumentation and creating correlations between flight and developmental instrumentation during developmental ground tests. These solutions would enable better consistency between ground and flight test analysis results.

Share Information Between DT&E Phases

Problem Description: Sharing information between DT&E phases is too difficult

- Potential Solutions:
  - Common data reduction and analysis procedures
  - Common accessible databases
- Benefits: Using a common approach to data analysis and using standard evaluation criteria will improve the ability to share information and combine M&S, wind tunnel, and flight testing into a single coherent evaluation

The diversity of people involved in the Test and Evaluation process, including system designers, ground testers, and flight testers, makes sharing information and combining M&S and ground and flight test results into a single coherent evaluation extremely difficult. Differences in databases, data formats, and evaluation criteria make this task even more difficult. The previous three lessons learned clearly indicate the need to provide information from system designers and ground testers to improve flight test (and vice versa). To facilitate information exchange, common data reduction and analysis procedures, and common accessible databases to allow test team interchanges during all phases of testing are essential. These databases should include all aspects of the data including sensor health, signal conditioning, raw and processed data, data processing and analysis techniques, system models, summarized evaluations, and final reports.

Work Together to Develop Standardized Data Analysis Tools

- Problem Description: Major test centers (and military service and contractor personnel) frequently develop T&E tools for real-time and post-test analysis independently, increasing development and training costs
- Potential Solutions (when possible):
  - Standardized analysis procedures
  - Common data formats, networks, computer operating systems, programming languages, and models
- Benefits: Analysis and evaluation engineers use the same analysis tools from project to project producing more consistent and efficient data analysis

Currently each major test center (and military service and contractor) independently develops T&E tools for real-time and post-flight analysis, increasing overall training and development costs. As engineers are reassigned to test different types of aircraft, they are often required to use different analysis tools developed using dissimilar computing languages and hosted on different computer platforms, significantly degrading engineer performance. Additionally, software developers must develop and maintain this software, thus requiring proficiency in multiple computing languages and platforms. The use of common, off-the-shelf software and readily available personal computers appears to be the best approach to minimize development and training costs for engineers and software developers.

Modeling and Simulation (M&S) Usage During Test

Problem Description: Model-based analysis techniques employed during test planning, test execution, and data analysis and evaluation phases of a test program to refine test plans, identify anomalous hardware and software, and focus on potential sources of unexpected results must be updated frequently and can be difficult and time consuming to use

- Potential Solutions:
  - Train analysis engineers on the benefits and use of M&S including proper data collection, instrumentation, and test progression rate
  - Develop robust data acquisition and analysis capabilities to quickly and efficiently update models during test
- Benefit: M&S cannot replace testing the actual article; however, it can be used to significantly improve test capabilities in the areas of test planning, execution, and data analysis and evaluation

The United States Air Force has a long history of using modeling and simulation (M&S) in the test and evaluation (T&E) process. While most M&S usage to date has been in the aircraft performance and flying quality areas, advancing technology and complex integration requirements are resulting in increased M&S use across a broader spectrum of technical disciplines, including all aspects of aircraft propulsion systems.

Model-based analysis techniques employed during test planning, test execution, and data analysis and evaluation phases of a test program to refine test plans, identify anomalous hardware and software, and focus on potential sources of unexpected results must be updated frequently and can be difficult and time consuming to use. Potential solutions include training analysis engineers on the benefits and use of M&S including proper data collection, instrumentation, and test progression rate and the development of robust data acquisition and analysis capabilities to quickly and efficiently update models during test.

The AFFTC and the AEDC are developing a common suite of modeling and simulation tools employing advanced predictive modeling technologies. The common set of modeling and simulation tools incorporates data validation, system identification, parameter estimation, model calibration, and automated model updating as new test results or operational data become available.

M&S cannot replace testing the actual article; however, it can be used to significantly improve test capabilities in the areas of test planning, execution, and data analysis and evaluation.

5.0 SUMMARY

- **Model-based approach enables simultaneous validation of test data and calibration of the engine model while helping the test engineer to**
  - **Interpret predicted and measured responses throughout the propulsion system quantified by the component-level model**
  - **Effectively utilize additional measurements available during developmental ground and flight testing**
- **Lessons learned enable additional reductions in analysis costs and cycle time and additional enhancements to propulsion system real-time and post-flight analysis capabilities**

In addition to summarizing lessons learned from ground and flight testing of the F/A-22 aircraft with the F119 engine, this paper described the teaming strategy between the two major U.S. Air Force propulsion test centers reduce test cost and time for the F/A-22 program.

The United States Air Force has a long history of using modeling and simulation (M&S) in the test and evaluation (T&E) process. While most M&S usage to date has been in the aircraft performance and flying quality areas, advancing technology and complex integration requirements are resulting in increased M&S use across a broader spectrum of technical disciplines, including all aspects of aircraft propulsion systems.

The M&S-based approach for simultaneous validation of propulsion ground- and flight-test data and calibration of the engine model is capable of detecting and identifying sensor anomalies as they occur, and of distinguishing these anomalies from variations in component and overall engine aerothermodynamic performance.

Even with the success of the M&S tools, there are too many unknowns to eliminate the need for ground and flight testing. However, with the M&S tools developed during this effort, engineers should be able to automatically validate propulsion ground- and flight-test data, automatically calibrate the engine model, simulate enough of the flight envelope to significantly improve test planning and conduct, and greatly enhance test safety.