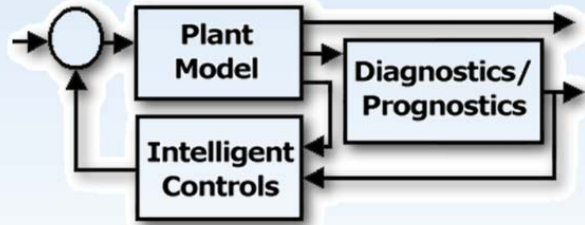Air Breathing Propulsion Controls and Diagnostics Research at NASA Glenn under NASA Aeronautics Research Mission Programs

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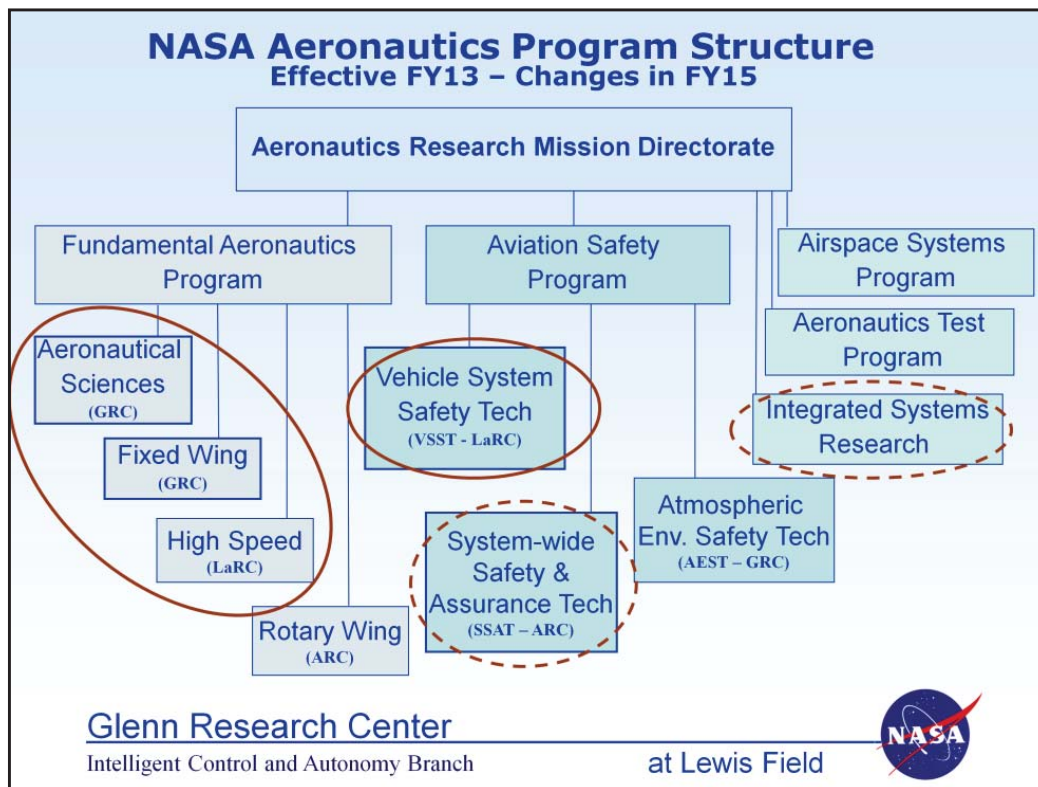http://www.grc.nasa.gov/WWW/cdtb

Glenn Research Center
Intelligent Control and Autonomy Branch
at Lewis Field

Abstract

The Intelligent Control and Autonomy Branch (ICA) at NASA (National Aeronautics and Space Administration) Glenn Research Center (GRC) in Cleveland, Ohio, is leading and participating in various projects in partnership with other organizations within GRC and across NASA, the U.S. aerospace industry, and academia to develop advanced controls and health management technologies that will help meet the goals of the NASA Aeronautics Research Mission Directorate (ARMD) Programs. These efforts are primarily under the various projects under the Fundamental Aeronautics Program (FAP) and the Aviation Safety Program (ASP). The ICA Branch is focused on advancing the state-of-the-art of aero-engine control and diagnostics technologies to help improve aviation safety, increase efficiency, and enable operation with reduced emissions. This paper describes the various ICA research efforts under the NASA Aeronautics Research Mission Programs with a summary of motivation, background, technical approach, and recent accomplishments for each of the research tasks.

NASA Aeronautics Program Structure
(Effective FY13)

The NASA Aeronautics Research Mission Directorate (ARMD) program structure consists of 5 major programs: Fundamental Aeronautics (FAP) , Aviation Safety (ASP), Airspace Systems, Aeronautics Test, and Integrated Systems Research (ISRP), with each of these programs having two or more projects. The ICA activities are primarily in the various projects under FAP and ASP, with a small participation in the Environmentally Responsive Aviation (ERA) project of ISRP.

Detailed information about the ARMD programs is available at:
http://www.aeronautics.nasa.gov/programs.htm

Note that the above ARMD program structure was established in FY13 (NASA Fiscal Year is from Oct. 1 to Sept. 30). The program structure will change in FY15 with a focus on six strategic thrusts. Most of the work described in this paper is expected to continue in the new program structure. Information on the NASA Aeronautics Research strategic vision is available at:
http://www.aeronautics.nasa.gov/pdf/armd_strategic_vision_2013.pdf

ICA Tasks Under NASA Aeronautics Research

The Intelligent Control and Autonomy Branch (ICA) tasks under the NASA Aeronautics Research Mission Directorate programs, and the program/project that support these tasks, are listed above. The tasks are briefly described below and are discussed in more detail in the rest of the paper.

Fundamental Aeronautics Program

Distributed Engine Control: This task is developing tools and methods to study and enable the engine control hardware architecture of the future which is expected to be decentralized and modular with smart components interfacing through a digital data bus.

Model Based Engine Control: This task is developing the engine control logic architecture of the future which will help increase engine operational efficiency by reducing the conservatism in control design. Active Combustion Control: This research is focused on developing the tools and methods to provide effective suppression of thermo-acoustic instabilities in future low emission combustors.

Pressure Gain Combustion: This task is looking at initial innovative concepts for unsteady combustion which provide a pressure gain across the combustor as opposed to the traditional combustors which have a small pressure loss. This work is supported with funding from Air Force Research Lab.

Dynamic Systems Analysis: The objective of this task is to develop tools and techniques that can be used to assess, at the early design stage, the capability of new turbo-engine designs to meet dynamic performance and operational safety requirements.
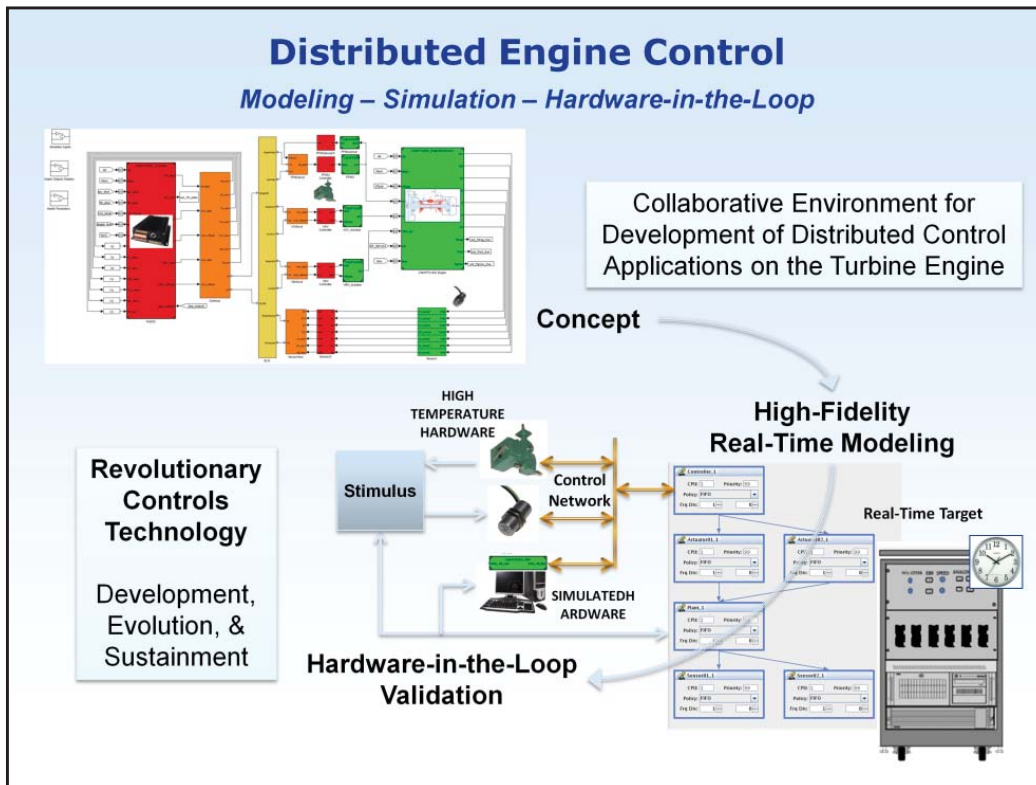
Aero-Propulso-Servo-Elasticity: This work is done in collaboration with NASA LaRC and the focus is to develop tools and techniques to be able to assess the coupling between aero-servo-elastic modes and the propulsion system for the future supersonic aircraft configurations.

Aviation Safety Program

Gas Path Health Management: The focus on this effort is developing innovative approaches for engine gas path performance estimation and fault diagnostics.

Robust and Enhanced Engine Response Propulsion Control: The focus is on developing the capability to be able to use the engines for flight control and flight path management in emergency situations.
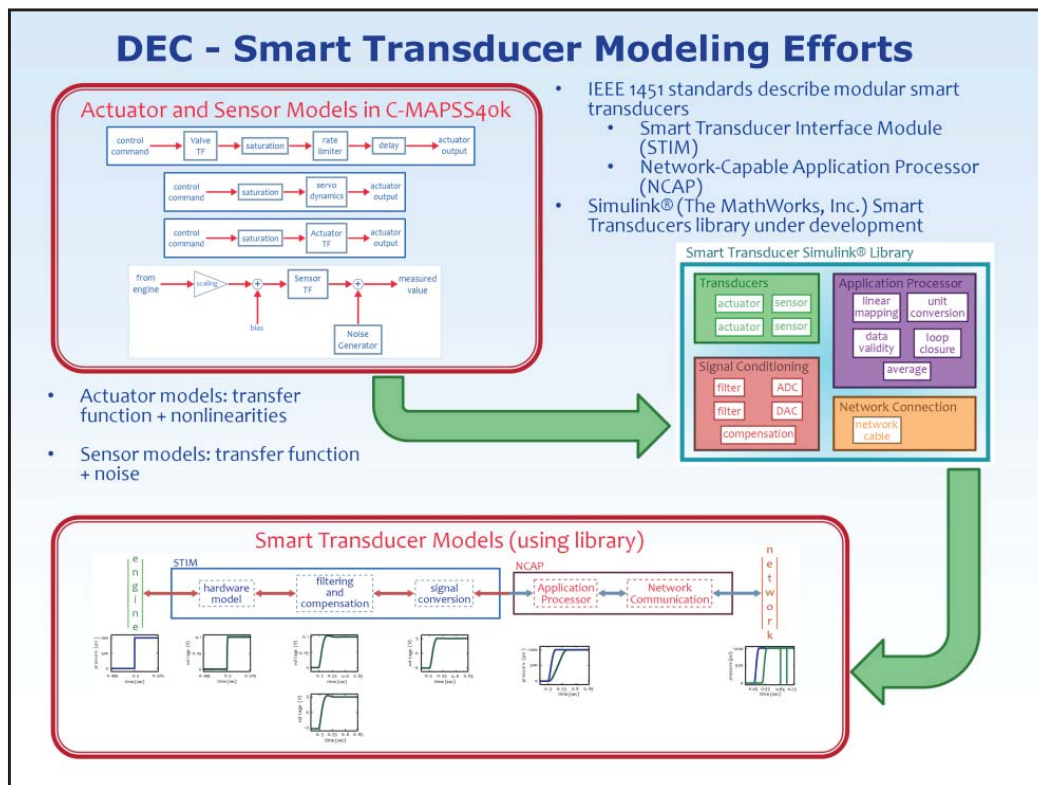
Run-time Assurance of Complex Systems: The concept of run-time assurance is to provide safe system operation with advanced complex control algorithms which might be too difficult to certify.

Distributed Engine Control
Modeling – Simulation – Hardware-in-the-Loop

Turbine engine control technology is poised to make the first revolutionary leap forward since the advent of full authority digital engine control in the mid-1980's. This change aims squarely at overcoming the physical constraints that have historically limited control system hardware on aero-engines to a federated architecture. A distributed control architecture, enabled by high temperature electronics, allows the complex analog interfaces between system elements and the control unit to be replaced by standardized interfaces with signals that have been digitized at the source. These effects additionally include embedded processing, and common network interfaces that modularize the system at a hardware level. While this scheme simplifies the physical integration of the system, its complexity appears in other ways. In fact, integration now becomes a shared responsibility among suppliers and system integrators. While these are the most obvious changes, there are additional concerns about performance, reliability, and failure modes due to distributed architecture that warrant detailed study. NASA Glenn Research Center is in the process of developing a new facility intended to address the many challenges of the underlying technologies of distributed control. The facility is capable of performing both simulation and hardware studies ranging from component to system level complexity. Its modular and hierarchical structure allows the users to focus their interaction on specific areas of interest.

Ref.: Culley, D.E., Zinnecker, A..M., Aretskin-Hariton, E.D., and Kratz, J.L., "Developing an Integration Infrastructure for Distributed Engine Control Technologies," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland, OH.

DEC – Smart Transducer Modeling Efforts

Progress toward the implementation of distributed engine control (DEC) in an aerospace application may be accelerated through the development of a hardware-in-the-loop (HIL) system for testing new control architectures and hardware outside of a physical test cell environment. One component required in an HIL simulation system is a high-fidelity model of the control platform: sensors, actuators, and the control law. The control system developed for the Commercial Modular Aero-Propulsion System Simulation 40k (C-MAPSS40k) provides a baseline for development of a model for simulating a distributed control architecture with a high degree of accuracy. This distributed controller model will contain enhanced hardware models, capturing the dynamics of the transducer and the effects of data processing, and a model of the controller network.

A multilevel framework has been developed that establishes three sets of interfaces in the control platform: communication with the engine (through sensors and actuators), communication between hardware and controller (over a network), and the physical connections within individual pieces of hardware. This introduces modularity at each level of the model, encouraging collaboration in the development and testing of various control schemes or hardware designs. At the hardware level, this modularity is leveraged through the creation of a Simulink library containing blocks for constructing smart transducer models complying with the IEEE 1451 specification. The complexity added to the control platform model when such hardware models are incorporated introduces realistic effects, related to quantization of feedback measurements, in the controller response while still allowing simulation in real-time, as required for HIL simulation.

Ref.: Zinnecker, A..M., Culley, D.E., and Aretskin-Hariton, E.D., "A Modular Framework for Modeling Hardware Elements in Distributed Engine Control Systems," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland, OH.
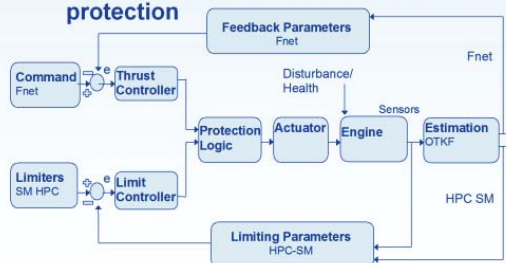
Model Based Engine Control

Goals
- Use an on-board "self-tuning" model of the engine to provide accurate estimates of unmeasured parameters for control design as the engine ages
- Allow for the engine to serve as a backup to the flight control system during emergency scenarios by improving the transient response time of the engines
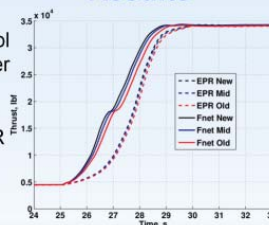
Approach
- CMAPSS40k simulation as baseline engine
- Integrate engine with Optimal Tuner Kalman Filter to get estimates of unmeasured parameters
- Replace current control architecture with a Thrust controller and Stall Margin limit protection

Results

Thrust Control response over engine life compared to baseline EPR control

Stall Margin limiter over engine life cycle compared to baseline acceleration limiter

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Model Based Engine Control

Model- based engine control (MBEC) is being developed as one of the advanced engine control system methodologies to improve turbofan engine efficiency as well as transient performance. The MBEC concept is to use an on-board engine model to generate estimates of quantities that cannot be measured or are difficult to measure, such as Thrust and Compressor Stall Margin, and use these estimates to provide direct control of the parameters of interest. Such an approach will result in consistency of engine throttle to thrust response as the engine degrades with usage.

Using an MBEC approach to directly limit the minimum stall margin during a transient, the engine can be operated closer to the stall line in steady-state operation. This expanded operating envelope can be used to improve efficiency or improve engine response time by reducing some safety margins during emergency scenarios. The latter could be critical in emergency scenarios, where the propulsion system could enhance the nominal flight control or serve as a backup control system in the case of a loss of the nominal flight control system. The challenge in MBEC is to ensure that the on-board model provides good estimates of the parameters of interest even as engine condition changes.

An MBEC architecture has been developed and is comprised of two components; an on-board model designed to provide real-time estimates of desired unmeasured parameters, and a controller with limit protection logic. Simulation studies have been conducted with MBEC designed for the Commercial Modular Aero-Propulsion System Simulation 40,000 (CMAPSS40k) engine model. Results are shown for a large thrust transient at low altitude, which could simulate a takeoff scenario or emergency operations during a landing. The plots compare the MBEC and baseline controller. The bottom plot shows that using the MBEC approach, the minimum Stall Margin reached during acceleration transients can be tightly controlled to a preset value throughout the operational life of the engine. This allows the capability to set the minimum Stall Margin limit to a lower value and hence provide a faster engine response. Current research work is focusing on how to leverage the capability provided by MBEC to design the overall engine system for higher efficiency operation.

Ref.: Connolly, J., "Model-Based Control of a Nonlinear Aircraft Engine Simulation using an Optimal Tuner Kalman Filter Approach," 49th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 2013-4002, July 15-17, 2013, San Jose, CA.

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Active Combustion Control – Fuel Modulator Development

Lean combustion concepts for aircraft engines are prone to combustion instabilities. Mitigation of these instabilities is an enabling technology for low-emissions combustors. Prior research at NASA Glenn Research Center has demonstrated active control to suppress a high-frequency combustion instability in a combustor rig designed to emulate an actual aircraft engine instability experience with a conventional, rich-front-end combustor. The current effort is structured to develop further understanding of the problem as applied to future lean-burning, very low-emissions combustors. See reference listed below for an overview of GRC accomplishments in active combustion control for low emission combustors.

Current research is focused on suppressing the thermo-acoustic instabilities related to increasing fuel flow that may prevent full-power operation of a combustor. Active combustion instability suppression using the Adaptive Sliding Phasor Average Control (ASPAC) method has been successfully demonstrated experimentally in a NASA combustion test cell operating at engine pressures, temperatures, and flows. A critical component in the control loop using the ASPAC method is a high-frequency fuel valve used to perturb the combustor fuel flow.

To meet the challenge of thermo-acoustic instability suppression using ASPAC, to further investigate applicability of the ASPAC method, and to investigate other control methods, actuators with the ability to modulate fuel flow frequencies as high as 1 kHz are required. For practical application, these modulators will be small, fast, and tolerant to high temperatures. Devices to meet these requirements require custom design since they are not off-the-shelf commercially available. To this end, NASA GRC is partnering with various small businesses to develop actuators that can be used for active combustion control in the GRC combustion research facilities. The concepts shown in the chart are at various stages of development.

Ref: DeLaat, J.C., Kopasakis, G., Saus J. R. et al., "Active Combustion Control for a Low Emissions Aircraft Engine Combustor Prototype: Experimental Results," AIAA *Journal of Propulsion and Power*, July-August, 2013.
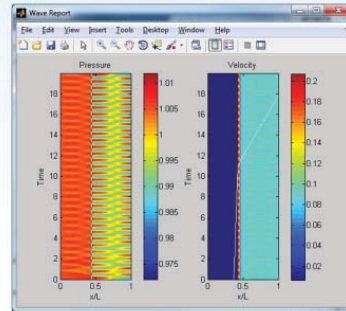
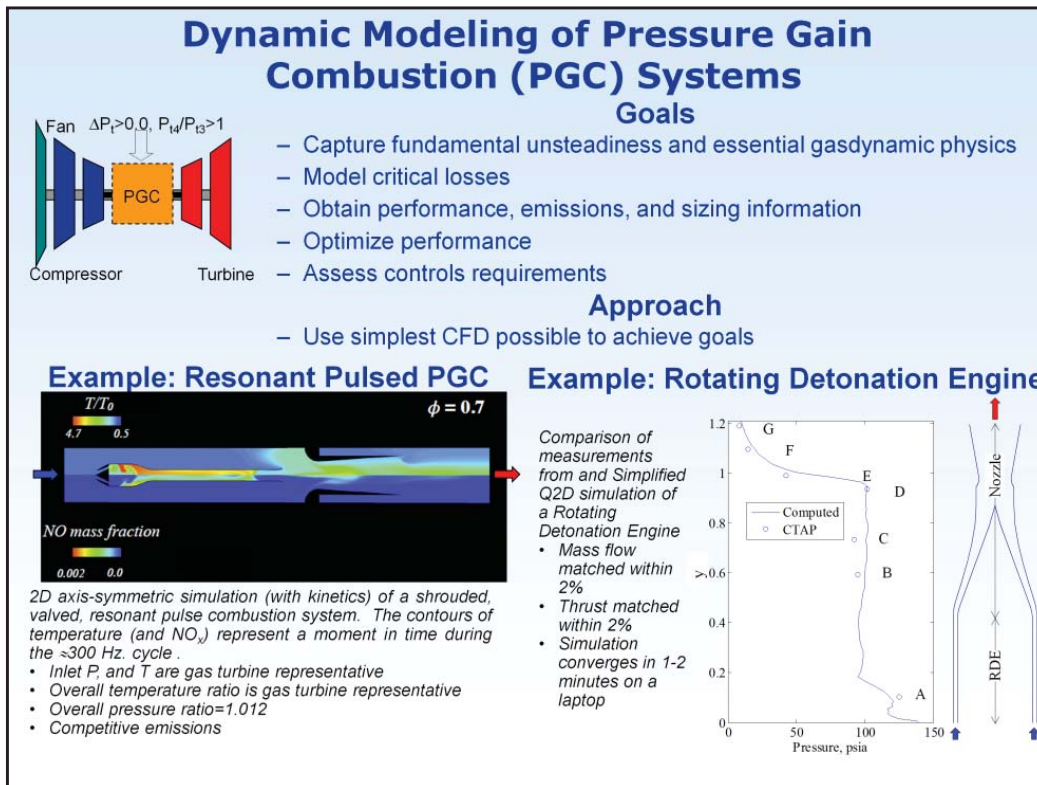**Active Combustion Control – Combustor Dynamic Simulation Development**

As discussed previously, NASA Active Combustion Control (ACC) research considers modulating the fuel flow into the combustor to assert pressure oscillations out-of-phase with the thermo-acoustic instability; thus, suppressing the thermo-acoustic instability. Such a control approach employs a dynamic pressure sensor for feedback, an actuator to provide high bandwidth fuel flow modulation, and a control algorithm to command the actuator with feedback signals from the sensor. To streamline development of closed-loop control algorithms, a combustor simulation, the simulated one-dimensional MATLAB-language-based (S1D_ML) code, has been developed. This is a MATLAB based version for the sectored-one-dimensional combustor simulation process, developed earlier in Fortran – see listed reference.

Source code modification can be made to the S1D_ML simulation using MATLAB programming tools. This code can be compiled to an executable that reads an input setup file to define combustor geometry and boundary conditions. This alleviates the need to own a copy of MATLAB to make changes to the process-defining source code and for running the S1D_ML simulation.

The process is designed to periodically save information for post processing report generation. The data saved can be reduced to create the following two types of graphical reports: Power Spectral Density (PSD) and a Wave pattern analysis (Wave). Illustrated in the lower right corner of the chart above is an example of a wave pattern analysis report. The Wave illustrates pressure and velocity on contour plots with respect to location and time. The Wave report enables recognition of resonance patterns in the data set.

Ref: DeLaat, J.C., Paxson, D.E., "Characterization and Simulation of the Thermoacoustic Instability Behavior of an Advanced, Low Emissions Combustor Prototype", AIAA-2008-4878, NASA/TM—2008-215291, 44th Joint Propulsion Conference and Exhibit, July 2008.

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Dynamic Modeling of Pressure Gain Combustion (PGC) Systems

Pressure gain combustion (PGC) is under investigation for the full range of air breathing flight applications. Of particular interest is the potential application to gas turbines. Here, the pressure rise (as opposed to a conventional combustor loss) yields higher engine thermal efficiency and specific power.

All PGC systems are fundamentally unsteady. They achieve limit cycle, not steady-state operation. Furthermore, they are fluidically (though not mechanically) complex. As such, there is a certain level of fidelity that models require in order to capture the physics and provide utility as design and optimization tools. The current PGC modeling effort is focused on providing such fidelity, but not more than is necessary. This effort has led to the use of simplified CFD approaches, two of which are illustrated above.

The left side shows output from a 2D axis-symmetric simulation of a so-called resonant pulse combustor. These are among the simplest of the PGC systems. They provide the least amount of pressure gain, but their simplicity, robust operation, and low emissions potential are attractive. They have also been successfully integrated and operated in gas turbine systems.
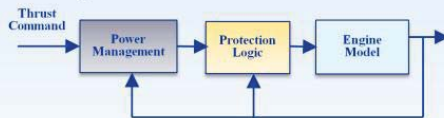
The right side compares computed and measured (CTAP) results from a rotating detonation engine (RDE). These PGC devices produce some of the highest pressure gains, but also produce high heat loads, substantial flow non-uniformities, and valving challenges. The flow in an RDE is nominally axial; however, the detonation travels circumferentially and continuously.

Ref: Paxson, D. E., "Numerical Analysis of a Rotating Detonation Engine in the Relative Reference", 2014 AIAA Aerospace Sciences Meeting, January 13-17, 2014, National Harbor, MD.

Dynamic Systems Analysis

Systems Analysis is typically done with steady state performance in mind. However, for complex systems such as aircraft engines, the capability to meet transient performance requirements over a wide operating envelope and a long operating life is critical. The steady-state performance based system analysis approaches do not capture the capability of a system to meet such requirements. When assessing technologies for system performance improvement, it is quite possible that a configuration that looks good from a steady-state performance perspective might be more challenging to control to meet transient and safety requirements. The objective of the Dynamic Systems Analysis (DSA) task is to develop tools and techniques that can be used to evaluate competing configurations and technologies from the perspective of being able to meet transient performance, operational life and safety requirements. The initial focus of this work is to develop the tools for DSA of traditional turbine engine configurations, with a goal to extend these tools to alternative innovative propulsion concepts.

The Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) was developed as an initial step for DSA of turbofan engines. It is a semi-automated control design tool for subsonic aircraft engine simulations. The purpose of this tool is to provide the user a preliminary estimate of the transient performance of an engine model without the need to design a full nonlinear controller. TTECTrA has been developed in the MATLAB®/Simulink® environment, which allows users to access a standard library of functions and to add on toolboxes such as the Control System Toolbox®, which can be used to simplify the control design process (and is required to use TTECTrA). The user's guide referenced below provides additional information and the software is expected to be publicly available in July 2014.

Industry members who face challenges in developing systems analysis tools for their applications which can consider dynamic performance requirements in early stages of assessing various competing technologies, can partner with us to leverage our experience in developing such tools for turbomachinery systems.

Ref.: Csank, J.T., and Zinnecker, A.M., "Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) Users' Guide," NASA TM-2014-216663, June 2014

Supersonic Propulsion System Modeling and Control

For the NASA High Speed Project, the overall objective is to perform the research to advance the technology so that the industry will be in a position to develop supersonic cruise civil transport aircraft. There are many technical challenges remaining for supersonic vehicle technology development, such as sonic boom reduction for overland flight, emissions (NOx) reduction, fuel efficiency, materials, control and handling qualities, etc.

The objective of the Aero-Servo-Elasticity (ASE) task and specifically the Aero-Propulso-Servo-Elasticity (APSE) task is to develop dynamic models for integrated propulsion and airframe systems and associated control designs to study overall vehicle performance, such as vehicle stability and vehicle ride quality as well as aerodynamic efficiency. The future supersonic transport vehicles are expected to be slender body with a highly flexible structure. Initial studies have shown that there is a potential for significant coupling between the vehicle flexible mo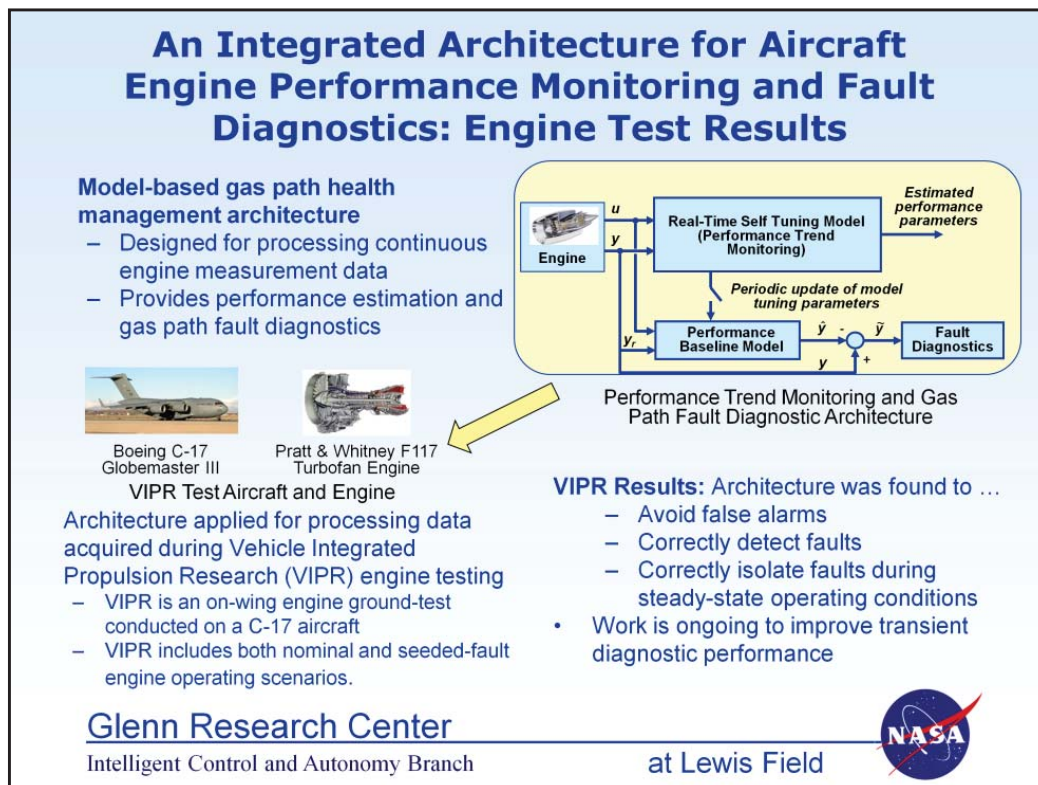des and the propulsion dynamics under atmospheric turbulence, which can result in unacceptable ride qualities. Therefore the objective of the overall APSE effort is to develop higher fidelity propulsion system dynamic models, understand the coupling issues with vehicle flexible modes, and design conceptual control logic to mitigate the effects of such coupling. The types of modeling employed are volume gas dynamics with component performance characteristics - lumped and stage-by-stage, Computational Fluid Dynamics (CFD), and parallel flow path modeling. Control designs involve feedback controls loop shaping, and engine schedules for compressor Inlet Guide Vanes, fan bypass, and exit nozzle area.

Shown in the chart above are: simulated thrust responses for various Mach numbers; a frequency domain response of the nozzle; 2D flow field for a CFD model developed for the inlet dynamics; the steady state static pressure distribution across the inlet; and the first preliminary APSE model developed with associated wing displacements response - with and without the propulsion system.

Ref.: Kopasakis, G., Connolly, J.W., Seidel, J. A., and Christhilf, D.M., "Propulsion System Dynamic Modeling of the NASA Supersonic Concept Vehicle for AeroPropulsoServoElasticity," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland, OH.

Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)
Public Benchmarking Results

Recent technology reviews have identified the need for objective assessments of aircraft engine health management (EHM) technologies. To help address this issue, a gas path diagnostic benchmark problem was created and made publicly available through the NASA Software Catalog. This software tool, referred to as the Propulsion Diagnostic Method Evaluation Strategy (ProDiMES), has been constructed based on feedback provided by the aircraft EHM community. It provides a standard benchmark problem enabling users to develop, evaluate and compare gas path diagnostic methods.

The availability of ProDiMES was publicized to the aircraft engine health management community. Interested participants were invited to apply their diagnostic methods to the provided benchmark problem, and participate in a follow-on workshop to share results and lessons learned. At this workshop, four diagnostic methods that had been applied to the ProDiMES blind-test-case data set were presented. These methods, which were developed by NASA, the University of Liege, and Wright State University, included: Weighted Least Squares Single Fault Isolation; Probabilistic Neural Network Single Fault Isolation; Performance Analysis Tool; and Generalized Observer/Estimator for Single Fault Isolation

The blind test comparison results highlighted the relative strengths of the four diagnostic methods. The study revealed that the applied detection strategy had a significant impact on overall diagnostic performance, and pairing the best fault detection and fault isolation approaches gave the best overall diagnostic results. Also, it was found that analytical (model-based) and empirical (data-driven) diagnostic approaches gave similar results when applied to ProDiMES. Overall participant feedback on the ProDIMES benchmarking tool and process was generally positive. ProDiMES was found to provide a suitably challenging problem and an effective means for conducting an initial evaluation of gas path diagnostic methods.

Ref: Simon, D.L., Borguet, S., Léonard, O., Zhang, X., "Aircraft Engine Gas Path Diagnostic Methods: Public Benchmarking Results," ASME Journal of Engineering for Gas Turbines and Power, Vol. 136, pgs.. 041201/1-10, April, 2014.

An Integrated Architecture for Aircraft Engine Performance Monitoring and Fault Diagnostics: Engine Test Results

Conventional aircraft engine gas path diagnostic approaches are designed for ground-based post-flight processing of "snapshot" measurement data collected at a limited quantity of operating points each flight. However, advances in onboard processing and flight data acquisition capabilities are providing access to increased quantities of flight data and enabling new diagnostic approaches. Analyzing full-flight streaming measurement data, either onboard in real-time or post-flight, can help reduce diagnostic latency and improve overall engine safety and reliability. In response to this need, NASA has developed a model-based performance trend monitoring and gas path diagnostic architecture designed to process streaming full-flight aircraft engine measurement data.

Recently, this architecture has been applied for the processing of data collected during the NASA Vehicle Integrated Propulsion Research (VIPR) engine tests. The VIPR program is a series of ground-based engine tests conducted to mature aircraft engine health management technologies. These tests are ongoing at the NASA Armstrong Flight Research Center/Edwards Air Force Base on a C-17 aircraft equipped with Pratt & Whitney F117 turbofan engines. The VIPR tests include "baseline" runs, where the test engine is operating normally without faults, as well as non-damaging fault cases consisting of mis-scheduled actuators in two bleed valves.

Analysis of the VIPR engine test data marks the first time the model-based performance trend monitoring and gas path fault diagnostic architecture was applied for processing real engine data. Overall, the results are encouraging. The technique was shown to avoid false alarms when presented nominal data, and to correctly detect anomalies when presented faulty data. Furthermore, the technique was found to correctly isolate the correct fault type during steady-state engine operating conditions although it did experience fault misclassifications during engine transients. Future work will focus on improving the model's dynamic accuracy.

Ref : Simon, D.L., Rinehart, A.W., "A Model-Based Anomaly Detection Approach for Analyzing Streaming Aircraft Engine Measurement Data," ASME-GT2014-27172, ASME Turbo Expo Conference, June 16-20, 2014, Düsseldorf, Germany.

Model Predictive Automatic Recovery System (MPARS)

The Model-Predictive Automatic Recovery System (MPARS) is a proof-of-concept algorithm that monitors an aircraft's flight condition during the approach to landing phase. It continually estimates the minimum altitude that would be reached if the pilot were to initiate a go-around maneuver at any point during the landing approach. When it determines that the expected minimum altitude reached during a go-around is getting close to a safe threshold, then it initiates an immediate go-around maneuver by increasing thrust and pitching up the aircraft. The concept relies on a simplified on-board model of the flight dynamics that determines when the aircraft operation is unsafe as defined by its inability to perform a go-around without coming dangerously close to the ground when not above the runway. If it would result in a minimum altitude threshold violation when the aircraft is not over the runway, the go-around is initiated. If not, normal operation continues. MPARS shuts off once the runway is reached. MPARS was developed and tested in NASA Glenn's flight simulator using the NASA-developed Transport Class Model (TCM), an aircraft simulation, integrated with two copies of the NASA-developed C-MAPSS40k model, a turbofan engine simulation. Piloted simulations using MPARS showed that it was able to intervene safely whenever the pilot was in an unstable approach mode, but did not interfere when the pilot was maintaining a safe approach for landing. MPARS research is motivated by the multiple reports of pilot errors during the landing phase which have resulted in ground collisions.

Ref: Litt, J. S., Liu, Y., Sowers, T. S., Owen, A. K. and Guo, T. H., "Piloted Simulation Evaluation of a Model-Predictive Automatic Recovery System to Prevent Vehicle Loss of Control on Approach," AIAA 2014-0036, AIAA Atmospheric Flight Mechanics Conference, January 13-17, 2014, National Harbor, MD.

Enhanced Engine Response Control

In this risk-based approach to enhanced engine performance, modification of controller limits enables improved responsiveness and thrust. However, these limits are in place to protect the engine against stalling, or to achieve a minimum time between overhauls by protecting component life. These standard controller limits result in very safe, very reliable engine operation.
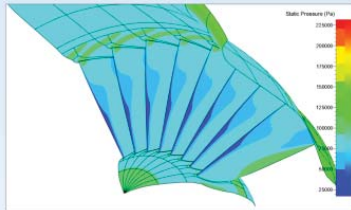
The FAA requires a risk of engine failure of 10^{-5}/flight hour or below, but in an emergency, the chance of saving the aircraft might increase through improved engine performance, outweighing a higher risk of engine failure. Enhanced operation provides faster response to throttle changes and higher maximum thrust. The improvement that is achievable depends on how much additional risk is acceptable. In this case, a risk of engine failure of 10^{-3}/flight hour was chosen. Since use of the enhanced modes is restricted to emergency situations only, the duration of their use is short, presumably justifying the higher risk.

These enhanced control features were evaluated in a piloted flight simulator using the NASA-developed Transport Class Model (TCM), an aircraft simulation, integrated with two copies of the NASA-developed C-MAPSS40k model, a turbofan engine simulation. The testing demonstrated potential safety improvements enabled by the enhanced control modes. For example, using an aircraft that has lost its flight control system, but with the pilot commands mapped into the throttles in an arrangement similar to Propulsion Controlled Aircraft (PCA), the pilot attempted to fly an altitude profile while maintaining airspeed. With the baseline engine control, the pilot over-controlled, causing large oscillations. However, with the enhanced control, the pilot was able to maintain precise control of speed and flight path. It took several tries before the pilot learned how to perform the task successfully.
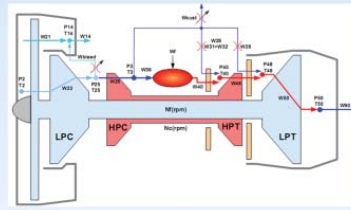
Ref: Liu, Y., Litt, J. S., Sowers, T. S., Owen, A. K., and Guo, T. H. "Application and Evaluation of Control Modes for Risk-Based Engine Performance Enhancements," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland, OH.

High Angle of Attack Propulsion System Modeling

Commercial engines are designed to operate over a limited range of angles of attack (AOA). As AOA gets larger, the airflow into the engine is reduced, resulting in reduced thrust and stability. The thrust depends on the controlled variable (fan speed or engine pressure ratio (EPR)). NASA Aviation Safety Program is interested in developing aircraft simulations that can provide realistic training for pilots in handling Loss of Control (LoC) situations where the aircraft has reached an abnormal flight state. Part of this effort involves developing realistic engine performance simulations in high AOA situations.

The high AOA engine modeling was performed using CFD (Computational Fluid Dynamics) by sectoring the inlet and fan into four equal quadrants. The C-MAPSS40k engine simulation was sectored into four corresponding parallel streams using Parallel Compressor Theory. This is a well-established technique for modeling the effects of inlet distortion on compressor performance. The CFD provided performance map adjustments at various AOAs for each of four parallel versions of C-MAPSS40k. Running the parallel version of C-MAPSS40k provided thrust and stall margin reduction information, which was subsequently converted to tabular form to serve as an adjustment to the output of the baseline single stream C-MAPSS40k. This allows much faster execution of the simulation while producing results similar to those of the parallel compressor approach. Currently, full annulus CFD modeling at high AOA is being pursued to validate these results.

Ref: Liu, Y., Claus, R., Litt, J. S., Guo, T. H. "Simulating Effects of High Angle of Attack on Turbofan Engine Performance," AIAA 2013-1075, 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, January 7-10, 2013, Grapevine, TX.

T-MATS

The Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) is a Simulink toolbox for modeling and simulation of thermodynamic systems and their controls. The package contains generic thermodynamic and controls components that may be combined with a variable input iterative solver and optimization algorithm to create complex systems to meet the needs of a developer.

The T-MATS software contains a simulation framework, multi-loop solver techniques, and modular thermodynamic simulation blocks. While much of the capability in T-MATS is in transient thermodynamic simulation, the developer's main interests are in aero-thermal applications; as such, one highlight of the T-MATS software package is the turbomachinery block set. This set of Simulink blocks gives a developer the tools required to create virtually any steady-state or dynamic turbomachinery simulation, e.g., a gas turbine simulation. In systems where the control or other related systems are modeled in Simulink, the T-MATS user has the ability to create the complete system in a single tool.

T-MATS turbomachinery blocks were created using a philosophy that combines the understandability and logic of physics-based models with the accuracy and tunability of empirically-developed models. The user's guide referenced below is written with the assumption that the user is familiar with modeling thermodynamic systems. T-MATS is written in MATLAB/Simulink v2012b (The Mathworks, Inc.). It is open source, which enables collaboration without limitation between industry, government, and academia. The T-MATS software comes with an example application for modeling a turbojet engine, data for which is available in published literature.

T-MATS has been used to recreate the NASA developed C-MAPSS (Commercial Modular Aero Propulsion System Simulation) model of a 90,000lb thrust class engine, and also a turbofan engine developed earlier in the NPSS (Numerical Propulsion System Simulator) format.

Ref: Chapman, J.W., Lavelle, T.M., May, R.D., Litt, J.S., and Guo, T.H., "Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) User's Guide," NASA/TM—2014-216638, January 2014
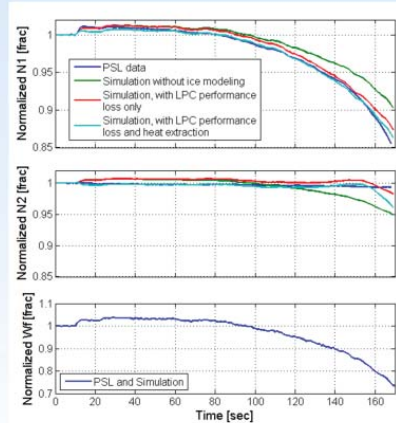
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Engine Ice Crystal Accretion Effect: Simulation, Detection and Mitigation

Engine Ice Crystal Accretion Effect: Simulation, Detection and Mitigation

Over the past twenty years, there have been over 150 reported cases of aircraft engine power loss due to the accretion of ice crystal particles in the compression system of commercial turbofan engines. The majority of the work in response to this aviation safety concern has focused on understanding the mechanism by which particles in high ice-water content (HIWC) conditions can accrete on compressor stator blades, understanding the environmental conditions in which accretion can occur, and related regulatory guidance. While avoidance of HIWC conditions and compressor redesigns are the ideal long-term solutions, a systems level analysis highlights some near-term solutions.
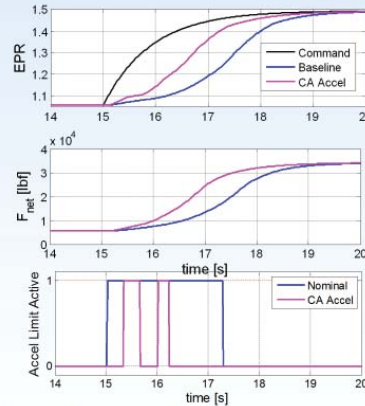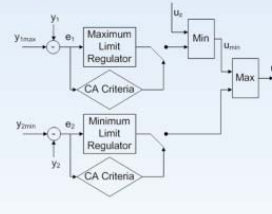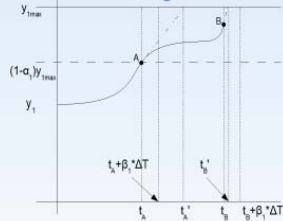
To this end, Low Pressure Compressor (LPC) maps gave been generated that include the effect of blockage due to ice accretion. These compressor maps have been integrated into the C-MAPSS40k engine simulation to model the change in engine performance during ice accretion to be simulated. Using this capability in conjunction with the realistic engine controller of C-MAPSS40k, previous research has shown that the engine rollback phenomenon is caused by the normal behavior of the engine controller responding to operational limits being encountered. It was then shown that the change in engine performance associated with ice accretion can be detected using the shaft speed sensors during steady-throttle flight.

Recently, testing of an obsolete Honeywell ALF502-R5 engine has been conducted in the NASA GRC Propulsion Systems Lab (PSL) where an ice crystal cloud is generated at the inlet to the engine. Based on data from this testing, an engine and ice accretion model has been developed using the T-MATS package. The effects of ice crystal accretion are accounted for by using "degraded" LPC maps and the effect of the ice crystal cloud is accounted for by introducing heat loss terms into the HPC to model the vaporization of the crystals. Future work will be based on this model and use the PSL data for validation/verification of both detection algorithms and mitigation strategies.

Ref: May, R.D., Guo, T-H., and Simon, D.L., "An Approach to Detect and Mitigate Ice Particle Accretion in Aircraft Engine Compression Systems," ASME-GT2013-95049, ASME TurboExpo 2013, June 3-7, 2013, San Antonio, TX.
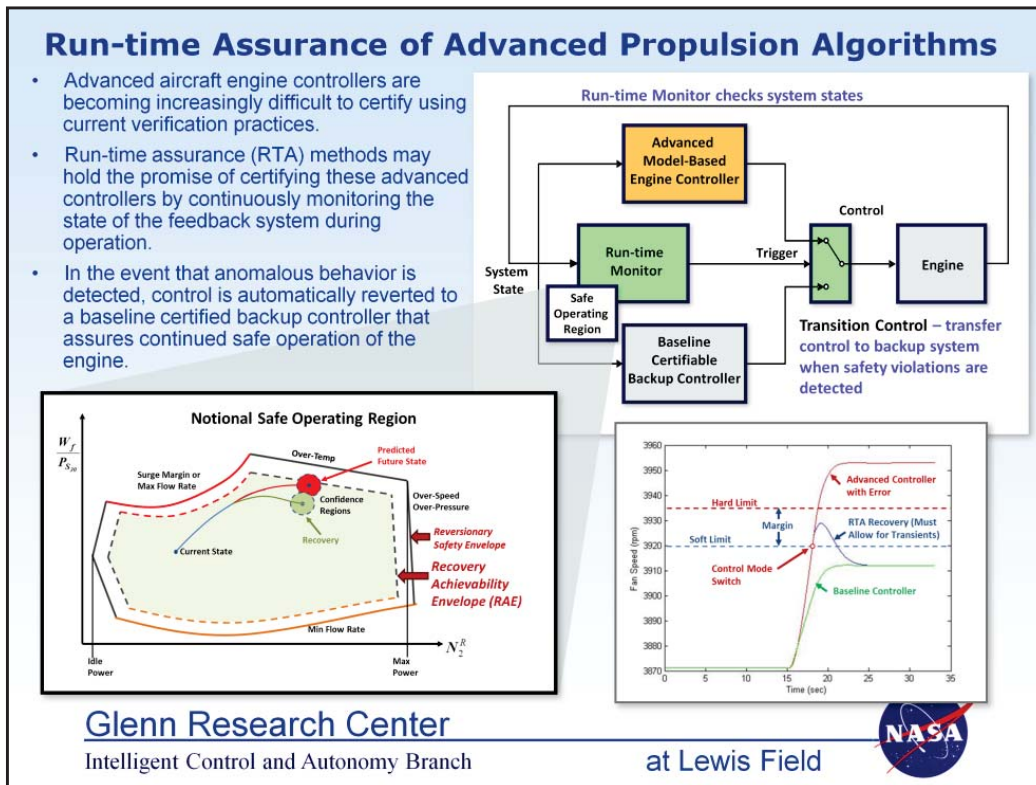
**Reducing Conservatism in Aircraft Engine Response Using
Conditionally Active Min-Max Limit Regulators**

Current aircraft engine control logic uses a Min-Max control selection structure to prevent the engine from exceeding any safety or operational limits during transients due to throttle commands. This structure is inherently conservative and produces transient responses that are slower than necessary. In order to utilize the existing safety margins more effectively, a modification to this architecture is proposed, referred to as a Conditionally Active (CA) limit regulator. This concept uses the existing Min-Max architecture with the modification that limit regulators are active only when the operating point is close to a particular limit and is approaching the limit fast enough to exceed it within a certain number of controller updates if corrective action is not taken. The CA limit regulator approach requires selection of two parameters – one defining closeness to the limit and the other defining the number of controller update steps it will take to reach the limit at the current rate of change of the variable, α and β, respectively, in the sketch shown in the chart.

The CA limit regulator approach was applied to the C-MAPSS40k engine simulation. There is no analytical approach to selecting the parameters α and β, so an empirical approach was investigated using knowledge of engine operation. The results of the application are summarized in the plots on the right in the chart. For a throttle command from idle to full, the acceleration limit regulator in the baseline engine control becomes active right when the command is issued and stays active for a long period, thus resulting in a slow engine response. With the CA limit regulator, the acceleration limit regulator is activated a little after the command is issued, and remains active only for a short period during the transient, thus resulting in a much faster response.

Ref: May, R.D., and Garg, S., "Reducing Conservatism in Aircraft Engine Response Using Conditionally Active Min-Max Limit Regulators," ASME-GT2012-70017, ASME Turbo Expo 2012, June, 2012, Copenhagen, Denmark,.
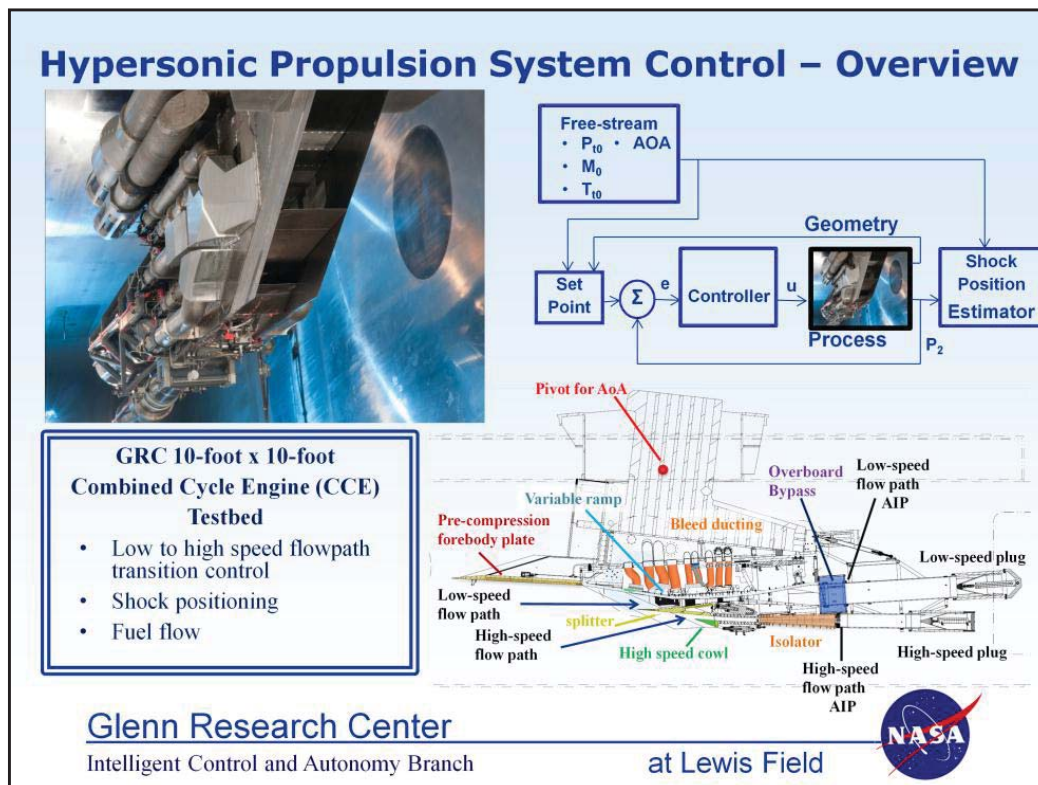
Run-time Assurance for Advanced Propulsion Algorithms

Safety and operational requirements for modern aircraft systems call for increasingly advanced control capabilities. Before these advanced algorithms can be deployed, it must be assured that they never instigate instabilities that can impact the safety of the aircraft. Flight-certification of such systems will require that they undergo thorough verification and validation (V&V) to achieve high confidence in their safety. Unfortunately, rigorous certification of such systems has proven to be challenging and costly using current V&V practices. As these algorithms and systems become more complex, it is anticipated that certification will become prohibitively costly and, ultimately, infeasible. One potential approach to addressing this shortfall in V&V capability is the use of run-time assurance (RTA) methods in a complementary and enabling role. RTA methods hold the promise of certifying these advanced controllers by continuously monitoring the state of the feedback system during operation. In the event that anomalous behavior is detected, control is automatically reverted to a baseline certified controller that assures continued safe operation of the engine. The RTA framework achieves assurance by ensuring that the system state remains within predetermined safe limits.

A preliminary study was undertaken to investigate the potential ability of a RTA framework to guarantee the safe closed-loop operation of the NASA-developed model-based engine controller (MBEC). MBEC comprises of an advanced Kalman filter parameter estimator and engine controller that feeds back an estimate of thrust to control thrust directly, rather than indirectly through other sensed engine parameters. Key system variables were identified and continually monitored to ensure that the controller did not violate the safety and operational limits of the engine during simulated take-off and cruise operations. In addition, simulated sensor faults and code errors were introduced to confirm the RTA system's ability to effectively switch from the MBEC to the baseline controller. These initial experimental results illustrate the potential benefits of using RTA to safely operate the engine with advanced control systems. Research is ongoing to investigate the capability of the RTA system to safely operate the engine throughout the operating envelope.

Ref.: Wong, E., Schierman, J. D., Schlapkohl, T., and Chicatelli, A., "Towards Run-time Assurance of Advanced Propulsion Algorithms," 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 28-30, 2014, Cleveland, OH.

Hypersonic Propulsion System Control - Overview

Hypersonic air breathing propulsion is a technology of interest to NASA for more routine, safe, and affordable access to space. To enable this technology, NASA has conducted fundamental research on turbine based combined cycle (TBCC) propulsion systems. The current activity addresses the challenge of safe and efficient transition from a turbine engine to a dual-mode scramjet (DMSJ) combustor while cruising at Mach 3. This event is identified as an inlet mode transition. To experimentally investigate an inlet mode transition, a combined cycle engine (CCE) inlet system was designed, fabricated, and tested in the NASA Glenn Research Center 10- x 10-foot supersonic wind tunnel. The inlet system is called the CCE large scale inlet for mode transition experiments (CCE-LIMX). Previous activity with the CCE-LIMX in the wind tunnel included characterization testing, Phase 1, and system identification experiments for control studies, Phase 2. The Phase 1 experiments defined steady-state operating points that can be linked together to form mode transition schedules. Likewise, the Phase 2 experiments included dynamic perturbations of the inlet system to acquire data for reducing to control design models. The goal of this research effort is to conduct mode transition experiments in the wind tunnel with an operating turbine engine mounted at the aft end of the CCE-LIMX - Phase 4. To prepare for Phase 4, CCE-LIMX wind tunnel tests are needed to develop and refine bypass door control algorithms that will allow closed-loop control of the normal shock position in the turbine engine low-speed flow path - Phase 3. Current activities are focused on reinstalling the inlet into the wind-tunnel and performing controls experiments to make ready a system for testing with a turbine engine.

Ref: Stueber, T.J., "Dynamic Models for the NASA Combined Cycle Engine Large Scale Inlet," JANNAF conference, December 4, 2012, Monterey, CA.

4th GRC Propulsion Control and Diagnostics Workshop

The 4th GRC PCD (Propulsion Control and Diagnostics) Workshop was held on Dec. 11-12, 2013 at the Ohio Aerospace Institute, Cleveland, OH. The objectives of the workshop were to: Disseminate information to the research community about the propulsion control and diagnostics research being done by the Controls group in support of various projects under the NASA Aeronautics Research Mission Directorate (ARMD) programs; get feedback from peers on the value of the research and validity of the technical approach; and identify opportunities for potential collaboration and sharing of tools and methods.

The workshop consisted of: detailed presentation on ongoing research in aircraft engine control and diagnostics covering progress to date, future plans, and tools and simulations available for public use; DoD (Air Force, Army and Navy) panel and industry panel to discuss ongoing research in various organizations and future vision for engine control; poster session with demonstration of GRC developed software packages for engine simulation, control design and evaluation, and poster presentations by our partners and select research community members; and one-on-one discussions between NASA researchers and attendees to answer any questions and identify potential collaboration opportunities. There were over 60 attendees from academia, industry and government with a large portion being from the industry. The feedback from the attendees was extremely positive in terms of the workshop meeting the stated objectives and the opportunity it provides for networking within the aero-propulsion control and diagnostics research community.

The presentations from the workshop are available at the ICA Branch website as indicated in the chart above. Below is a sample of overall feedback provided by some of the attendees:
- "Well organized. Appreciate the hand out package." - Industry Participant
- "Presentations were brief and there was sufficient opportunity to interact during breaks. Providing the presentations on the CD is also very useful." - Industry Participant
- "Very worthwhile workshop both for the tech content and the interaction. The format is very convivial. I will always make every effort to attend future events; thanks for the effort and thought your team and you put into getting a quality event." - Small Business Participant
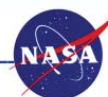
Concluding Remarks

• The Intelligent Control and Autonomy (ICA) Branch at NASA Glenn Research Center, Cleveland OH, is conducting cutting edge research in aero-propulsion control and diagnostics in support of NASA Aeronautics Research Mission Programs

• The various controls and health management technologies being developed by ICA in collaboration with industry and academia partners will help improve aviation safety and increase fuel efficiency while helping meet challenging emission reduction goals. Additionally the technologies being developed will help enable more autonomous operation of propulsion systems.

• ICA has developed many engine simulation software packages as well as other tools which are helping the research community advance the state-of-the-art for engine control and diagnostics

• Multidisciplinary cross-organizational collaboration and a system level approach are essential for successful development and transition of Intelligent Propulsion System technologies.

Glenn Research Center
Intelligent Control and Autonomy Branch   at Lewis Field

Concluding Remarks

The Intelligent Control and Autonomy Branch (ICA) at NASA GRC (Glenn Research Center) is working in strong partnership with industry, academia and other government agencies to develop the propulsion control and health management technologies that will help meet NASA's Aeronautics Research Mission goals. Research areas include: Distributed Engine Control architectures and technologies development, Model-Based Engine Control, Active Combustion Control, Supersonic Propulsion System dynamic modeling and control, and Pressure Gain Combustion dynamic modeling to help meet the objectives of the Fundamental Aeronautics Program; Gas Path Health Management, Robust and Enhanced Engine Response Control, and Run-time Assurance of complex systems to help meet the goals of the Aviation Safety Program.

Our aim is to use the public resources in a most efficient manner to make a significant contribution to the aggressive goals that have been set by the administrator in the latest strategic plan for NASA, and to ensure that our activities are aligned with the goals of the NASA Missions that we participate in. We take a systems level approach to ensure that the various components of a control or diagnostic system work together as an integrated system to achieve the desired objectives. We also actively pursue opportunities to disseminate information on our technology development efforts to the aerospace research community by presenting papers at technical conferences, holding the GRC Propulsion Control and Diagnostics Workshop on a bi-annual basis, and making available various software tools for enabling advanced research in propulsion control and diagnostics.