NDIA Physics-Based Modeling In Design & Development for U.S. Defense Conference Panel Discussion
11/6/2012

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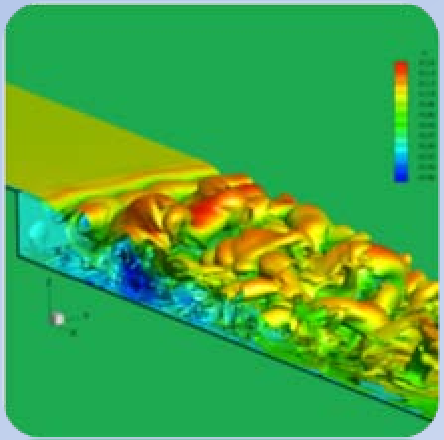
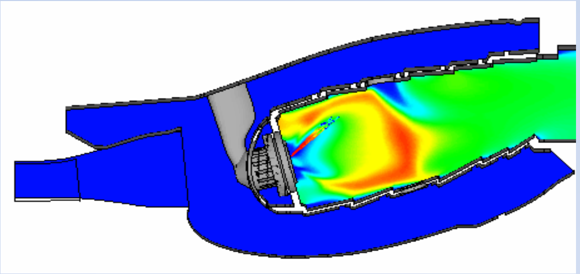
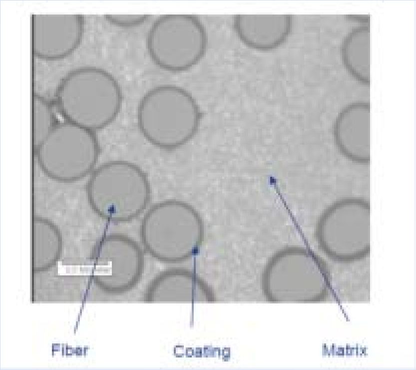
NASA Fundamental Aeronautics Program







Outline

- NASA’s Aeronautical Sciences Project Overview
- Project Structure / Disciplines
- Technical Challenges / Milestones
- High-Fidelity & MDAO / Systems Analysis
- Discipline Overviews
- Summary

Aeronautical Sciences Project

Enable efficient and accurate design and analysis of advanced air vehicles and propulsion systems by developing validated physics-based tools and exploratory cross-cutting technologies for advanced fluid mechanics, combustion, structures & materials, measurement and controls disciplines, while developing improved MDAO and systems analysis tools to enable multi-disciplinary integration.

NASA Aeronautics Programs

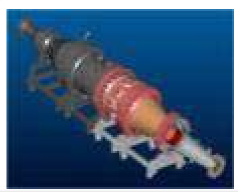



Fundamental Aeronautics Program

Conduct fundamental research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

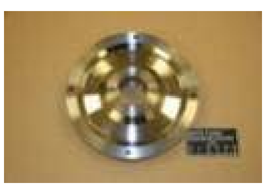
Integrated Systems Research Program

Conduct research at an integrated system-level on promising concepts and technologies and explore/assess/demonstrate the benefits in a relevant environment



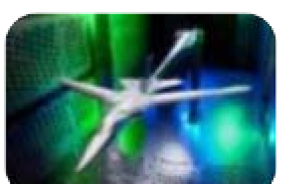
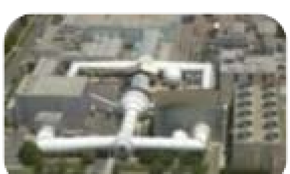
Airspace Systems Program

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.




Aviation Safety Program

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.

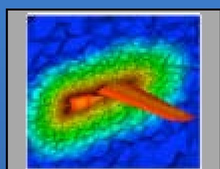
Aeronautics Test Program

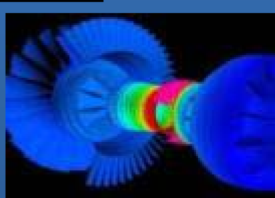
Preserve and promote the testing capabilities of one of the United States' largest, most versatile and comprehensive set of flight and ground-based research facilities.


New FA Program Organization Structure

Fundamental Aeronautics Program Office

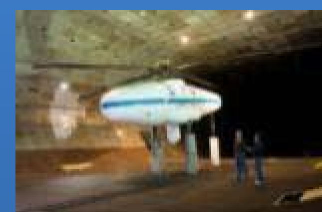
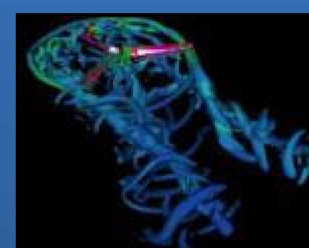
Aeronautical Sciences Project



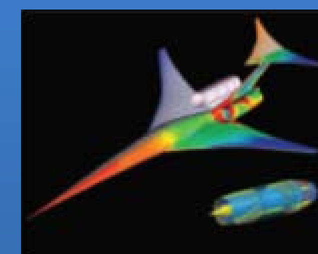


Fixed Wing Project


Rotary Wing Project

High Speed Project




Aeronautical Sciences (AS)
Enable fast, efficient design & analysis of advanced aviation systems through physics-based tools, methods, & cross-cutting technologies.

Fixed Wing (FW)
Explore & develop technologies and concepts for improved energy efficiency & environmental compatibility of fixed wing, subsonic transports

Rotary Wing (RW)
Develop and Validate Tools, Technologies and Concepts to Overcome Key Barriers to Practical, Large Rotary Wing Vehicles for the Future Air Transportation System

High Speed (HS)
Enable tools &technologies and validation capabilities necessary to overcome environmental & performance barriers to practical civil supersonic airliners.

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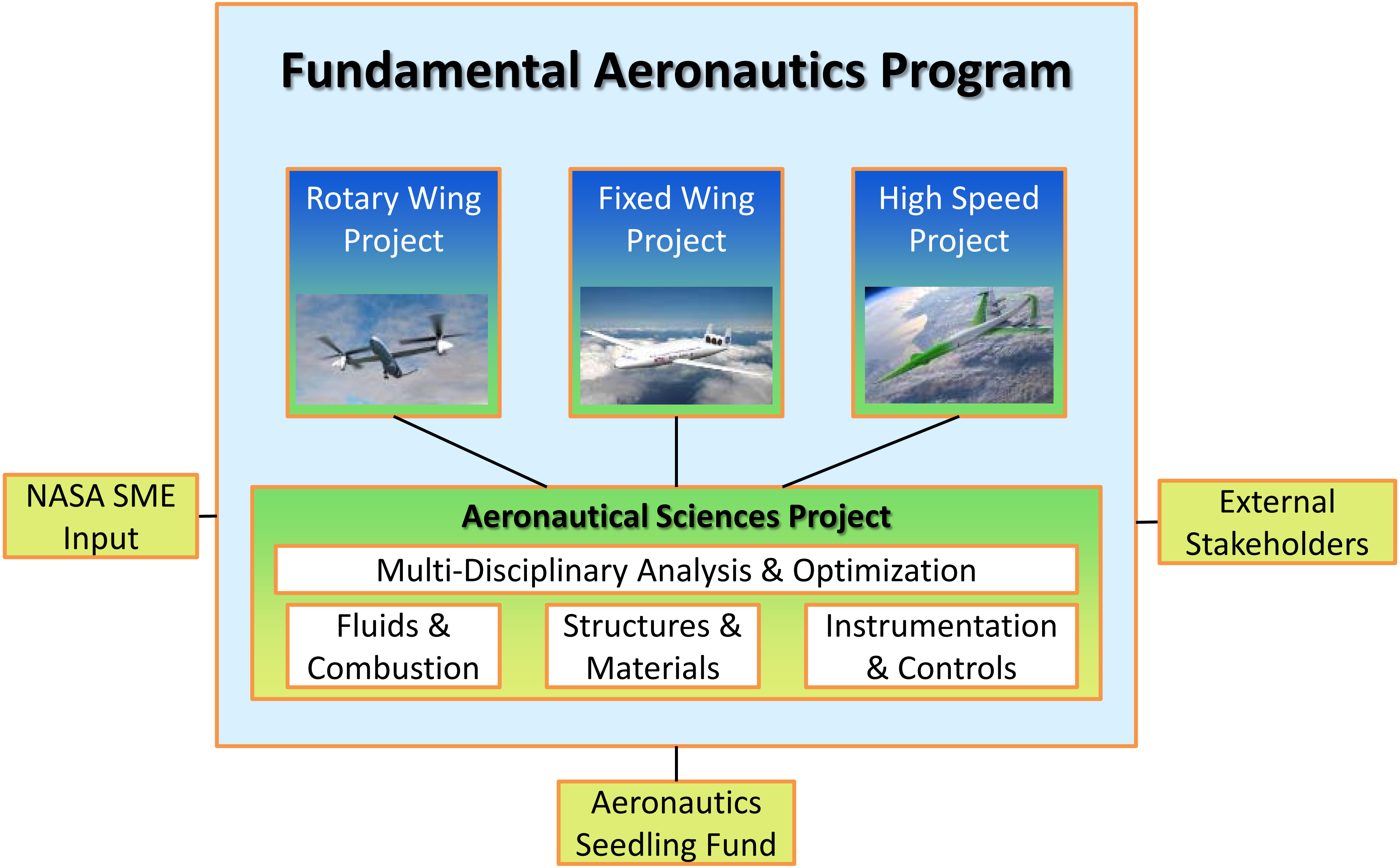
FAP Connectivities and Inputs



Aeronautical Sciences Project Organization

PROJECT LEVEL

- Organized By Technical Disciplines
- Technical Leads for Disciplines providing overall technical direction and oversight
- Center POCs providing coordination and support for all work at center

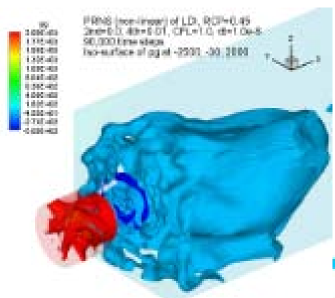
Project Manager: Jim Heidmann (GRC)
Deputy Project Manager: Stan Smeltzer (LaRC)

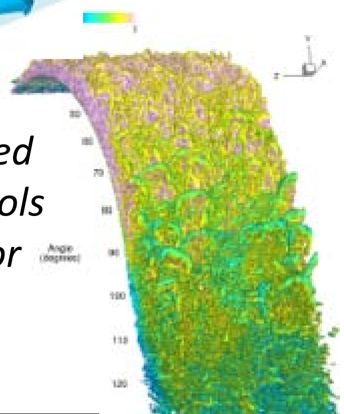
ARC POC: Mike Rogers ARC Resource Analyst: Sandra Ramirez	DFRC POC: Mark Davis DFRC Resource Analyst: Becky Miani	GRC POC: Jim Heidmann GRC Resource Analyst: Tom Halstead	LaRC POC: Stan Smeltzer LaRC Resource Analyst: Keisha Shands

TECHNICAL DISCIPLINES

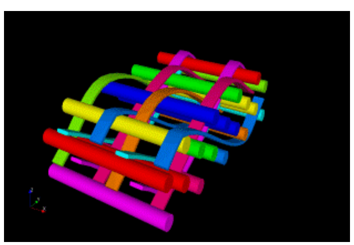
Revolutionary Computational Aerosciences: Mujeeb Malik (LaRC)	RCA		RCA	RCA
Structures and Materials: Dale Hopkins (GRC)		SAM	SAM	SAM
MDAO & Systems Analysis: Jeff Robinson (LaRC)	MDAO	MDAO	MDAO	MDAO
Combustion: Dan Bulzan (GRC)			Combustion	
Controls: Sanjay Garg (GRC)		Controls	Controls	Controls
Innovative Measurements: Tom Jones (LaRC)	Measurements	Measurements	Measurements	Measurements

Aeronautical Sciences Project





Develop validated physics-based tools and methods for cross-cutting technologies



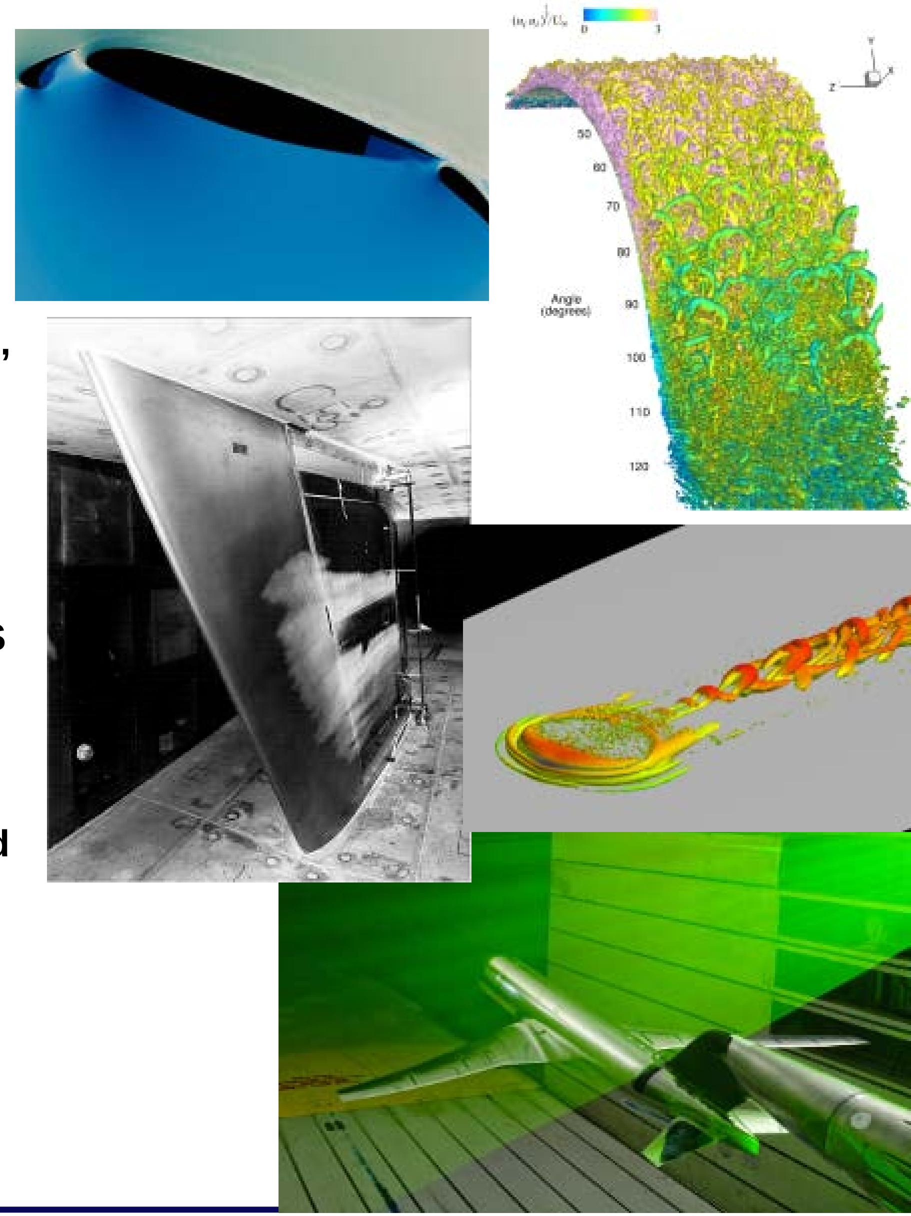
Technical Challenge	Milestones
Develop physics-based turbulence models and simulations that can more accurately predict flow separation onset and progression, the evolution of free shear flows, and shock-turbulence and shock-boundary layer interactions.	FY14: Implement and evaluate second-order full Reynolds Stress Model for prediction of flow separation.
	FY15: Demonstrate wall-modeled Large-Eddy Simulation (LES) for high Reynolds number flows involving flow separation.
Develop high-temperature materials for turbine engines that enable a 6% reduction in fuel burn for commercial aircraft, compared to current SOA materials.	FY14: Experimentally demonstrate 2700ºF temperature capability in ceramic matrix composite (CMC) material.
	FY15: Characterize and document mechanical properties and durability of 2700ºF-capable ceramic matrix composite (CMC) material.

Additional Technology Focus Areas:

- Combustion
- Controls
- Innovative Measurements
- MDAO & Systems Analysis

Revolutionary Computational Aerosciences

- Turbulence Modeling (and associated validation experiments)
  - 2nd (and higher order) Reynolds stress modeling, structure-based models
  - Large Eddy Simulations (LES) with wall modeling
  - Hybrid RANS/LES approaches (DDES, PANS, stochastic modeling)
  - Direct Numerical Simulation (DNS) for canonical flow configurations
- Transition Prediction and Modeling (and associated validation experiments)
  - Receptivity, PSE, supersonic transition, DNS
  - Reduced order models for transition prediction (Langtry-Menter, etc.)
- Numerical Methods
  - High-order methods with low dissipation and low dispersion errors
  - DG, Flux reconstruction, WENO, CESE, etc.
  - Adjoint-based grid adaptation
  - Convergence acceleration strategies
- Validation/Prediction Workshops
- RCA Institute



Turbulence Modeling

PROBLEM

Current models are unable to accurately predict turbulent flow separation and free shear flows across the speed regime, which limits the applicability of CFD codes for the design of innovative aircraft and propulsion systems.

OBJECTIVE

Develop new and improved turbulence models and simulation strategies that overcome the existing challenges in prediction of complex turbulent flows and significantly increase the accuracy and range of applicability of the models.

APPROACH

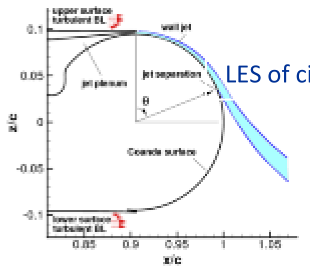
- Advanced (higher moment closures, structure-based) turbulence models.
- LES with wall modeling for high Reynolds number flows.
- Hybrid RANS/LES with improved interface to increase accuracy and confidence in separated flow predictions.
- DNS of canonical flows to provide data for development of turbulence models.
- Experiments to provide flow physics data for model development/validation.

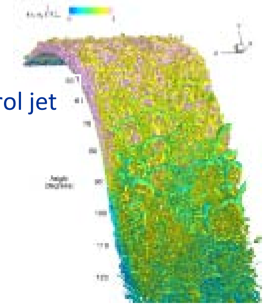
RESULTS

- RANS models fail to represent circulation control jet flow-field. LES of the jet has provided detailed data to improve RANS models.
- Analysis of the NASA Trap Wing experiment during the 1st High-Lift Prediction Workshop showed significant variability in CFD prediction of separated zones. Inadequate resolution of wing tip vortex led to poor prediction of Cp in that region.
- A hybrid RANS/LES approach has been developed, which serves to keep RANS effects in the RANS zones and LES effects in the LES zones, thus improving overall physical fidelity. Results obtained for channel flow are very encouraging.
- A new lag turbulence model predicts separated flow regions in FAITH experiment.

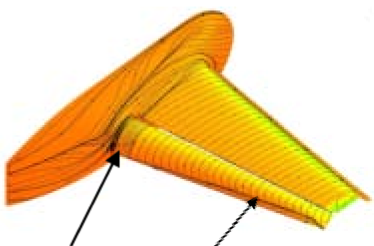
SIGNIFICANCE

Research will result in accurate and validated models required for improved design of future air vehicles, especially those with new concepts with much reduced reliance on physical testing.





LES of circulation control jet



Near body separation

Flap separation

MILESTONES

- Implement and evaluate improved RANS Explicit Algebraic Stress Model for aero and propulsion applications, 9/30/2013.
- Complete Reynolds stress measurements in the circulation control jet, 9/30/2013.
- Implement and evaluate second-order full Reynolds Stress Model for prediction of flow separation, 9/30/2014.
- Assessment of improved hybrid RNAS/LES methods for aerodynamic and propulsion applications, 9/30/2014.
- LES of mixing layers with significant compressibility, 9/30/2014.

Transition Prediction and Modeling

PROBLEM

Current physics-based transition prediction methods do no account for environmental effects such as surface roughness, free stream turbulence level and acoustic disturbances. In addition, CFD codes do not have reliable transition prediction capability.

OBJECTIVE

Develop amplitude-based transition prediction methods for laminar flow wing design and develop reduced order transition prediction models for routine use in CFD codes.

APPROACH

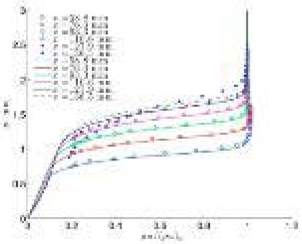
- Physics-based prediction of transition in 2D and 3D subsonic and supersonic boundary layers, including effect of roughness.
- DNS of transition to provide validation of lower fidelity prediction.
- Validation experiments to provide confidence in prediction methods.
- Reduced-order models implemented in CFD codes for transition prediction.

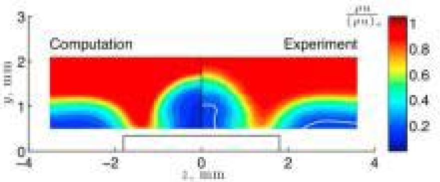
RESULTS

- Experiments on transition induced by an isolated roughness performed in Mach 3.5 quite tunnel. Results indicate that the instability of the streak downstream of the roughness element constitute the dominant transition mechanism. Very good agreement between experimental and computational results. Paper #29 in RTO-AVT-200/RSM-030
- Hybrid Laminar Flow Control (HLFC) experiment analyzed by using Langley Stability and Transition Analysis Code (LASTRAC) and found good comparison between computed and measured disturbance mode shapes. Resonant triad interaction of traveling crossflow modes was identified as a potent laminar-turbulent breakdown mechanism. AIAA 2012-2820.

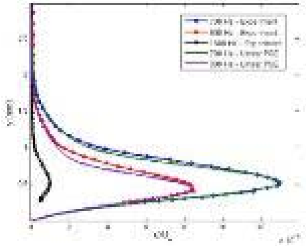
SIGNIFICANCE

Research will result in physics-based computational tools for laminar flow wing design to reduce aircraft drag. In addition, CFD codes with simplified transition prediction modules will yield more accurate prediction of aircraft drag.





Computed and measured mass flux contours and profiles (left) behind a roughness element in Mach 3.5 flow.



Computed and measured disturbance mode shapes in HLFC model boundary layer

HLFC swept wing model

MILESTONES

- Physics based transition prediction for isolated 3D roughness validated against measurements and/or DNS in supersonic flow, 9/30/2013.
- Implement and evaluate fast transition prediction capability in a NASA CFD code, 9/30/2013.
- Experimental study of supersonic boundary layer transition due to distributed roughness, 6/30/2014.
- Demonstrate holistic transition prediction for swept wing boundary layer transition, 9/30,2014.

Numerical Methods

PROBLEM

Current CFD codes are not well suited for simulation of unsteady turbulent flows since the embedded numerical schemes have high dissipative and dispersive errors, and the time to solution is too long.

OBJECTIVE

Develop numerical methods that significantly increase accuracy, efficiency, and robustness of turbulent flow computations for aerodynamic and propulsion applications.

APPROACH

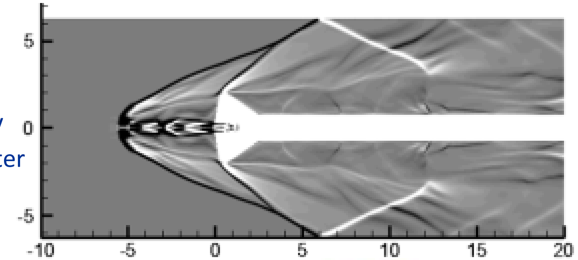
- Structured and un-structured grid high-order methods [e.g., flux reconstruction (FR), discontinuous Galerkin (DG), discontinuous collocation, CE/SE, …] with low numerical dissipation and dispersion.
- Convergence acceleration strategies (e.g., grid adaptation, enhanced linear/nonlinear solvers and temporal integration) for efficient solution of Navier-Stokes equations.
- Error estimation and uncertainty quantification to increase solution credibility.

RESULTS

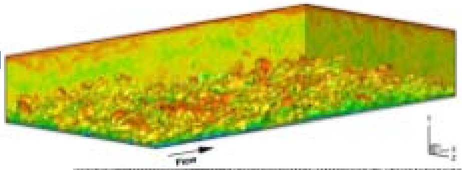
- Simulation of the CEV model with a counter flowing jet using the genuinely multi-dimensional CE/SE scheme demonstrate its excellent shock-capturing capability. Results agreed well with the experimental data. AIAA 2011-4030.
- A low dissipation, summation by part hybrid scheme was developed and tested for LES of canonical flows (e.g., channel flow) at subsonic and supersonic Mach numbers. AIAA-2012-4263.
- In a path finding activity, in partnership with ORNL, it was demonstrated that FUN3D code can efficiently utilize “leadership-class” systems at the DOE lab.

SIGNIFICANCE

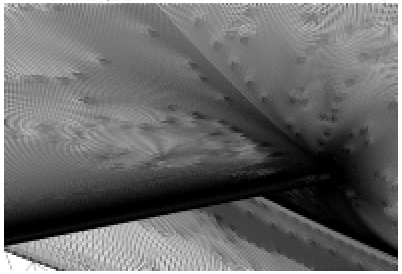
Improved speed and numerical accuracy of turbulent flow computations resulting in efficient and validated CFD codes, enabling fast generation of aero and propulsion databases and reducing design cycle time.



Simulation of CEV model with counter flowing jet using CE/SE scheme.



LES of fully developed Channel flow



Close-up of an adapted DPW grid (5.5 billion tets), looking upstream at the intersection with fuselage.

MILESTONES

- Demonstrate implicit time-advancement capability for high-order temporal and spatial discretization, 9/30/2013.
- Implement and evaluate an uncertainty quantification method in a NASA CFD code, 9/30/2013.
- Demonstrate entropy-stable discontinuous collocation for 3D unsteady Navier-Stokes equations, 6/30/2014.
- Demonstrate 4th-order CE/SE scheme for multi-scale simulations, 9/30/2014.

RCA NRAs

PROBLEM

Research in turbulence modeling, numerical methods and CFD code development requires expertise available at universities and industry to make progress.

OBJECTIVE

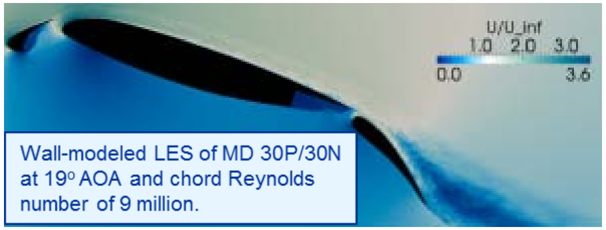
Use NASA Research Announcement (NRA) to solicit required research from academia and industry.

APPROACH

- Development of Turbulence/Transitional Model and Assessment of Complex Aerodynamic Flows; Hassan/NC State.
- Large Eddy Simulation with Near-Wall Modeling of Multi-Component Airfoils at Flight Reynolds Numbers;Moin/Stanford
- Structure Based Modeling of 3D Separated Flows; Iaccarino/Stanford
- High-Fidelity Multi-Resolution Turbulence Computations of Highly Separated Aerodynamic Flows, Girimaji/Texas A&M
- Turbulence Structure Preserving Unified and Dynamic Large Eddy Simulation of Separated Flows; Heinz/Wyoming.
- Fourth-Order RANS-Based Model: Rational Approach to Turbulence Modeling for Aerodynamic Applications; Poroseva/New Mexico.
- Hybrid and Pure Turbulence Modeling for Separation and Detached Flow; Durbin/ISU.
- Higher-Order Space-Time Adaptive Methods for Complex Turbulent Flows;Darmofal/MIT.
- Active Flux CFD Code; PI: P. Roe/Michigan.
- Scalable Adaptive High-Order Methods for Turbulent Flow Simulations; Wang/Kansas.
- Dynamic, Adaptive, and Robust High-Order Numerical Methods for the Prediction and Optimization of High Reynolds Number Turbulent Flows; Pantano-Rubino/Illinois.
- High Order Discontinuous Galerkin and Weighted Essentially Non-Oscillatory Algorithms for Compressible Turbulence Simulations; Shu/Brown.
- Revolutionary Computational Aerosciences 2030 CFD Code Vision; Khodadoust/Boeing

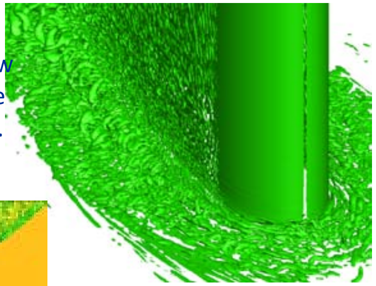
SIGNIFICANCE

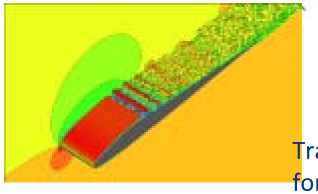
Research will provide improved turbulence models, numerical schemes and knowledge that will help improve turbulent flow prediction capability of NASA CFD codes.



Wall-modeled LES of MD 30P/30N at 19° AOA and chord Reynolds number of 9 million.

LES of juncture flow to build turbulence statistics database.





Transitional flow simulation for an airfoil using the flux reconstruction scheme.

MILESTONES

- Demonstrate three-dimensional grid adaptation for complex geometry flows, 9/30/2014.
- Demonstrate wall-modeled Large-Eddy Simulation (LES) for high Reynolds number flows involving flow separation, 9/30/2015.

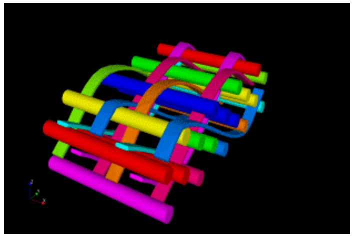
Structures & Materials

- Demonstrate **multi-functional structures & materials** that reduce weight by simultaneously meeting multiple airframe or engine requirements

- Develop **high temperature engine materials** and associated design tools and life prediction methodology to reduce or eliminate the need for turbine cooling

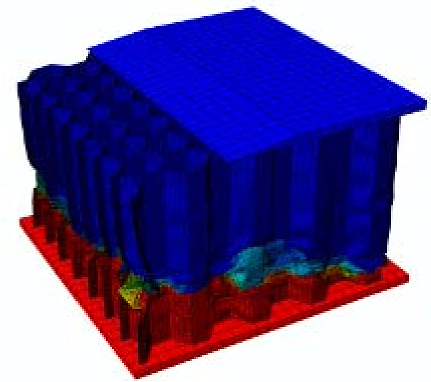
- Develop a **computational materials design and optimization** capability for airframe & engine materials

Exhaust-Washed Structures



Advanced 3D fiber architecture

EBC-coated CMC vane

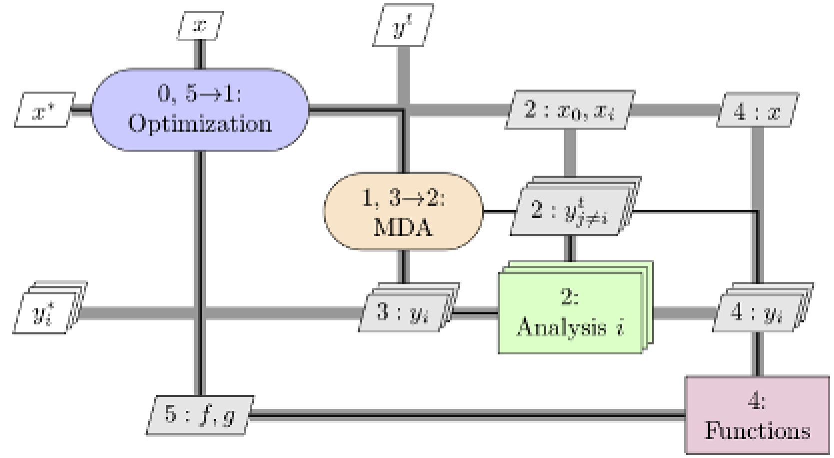


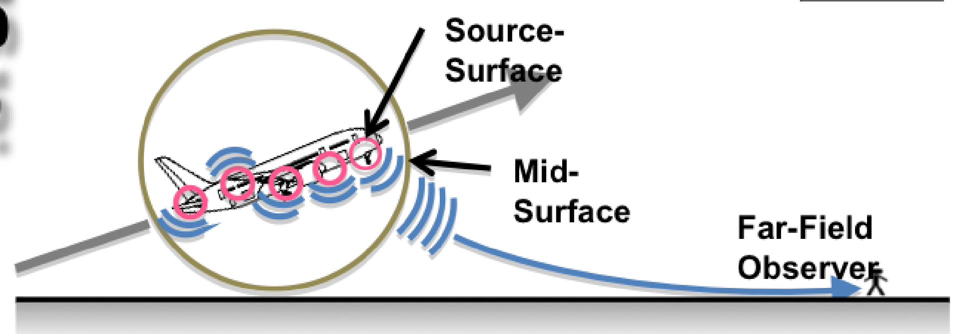
Analysis tools simulate failure process

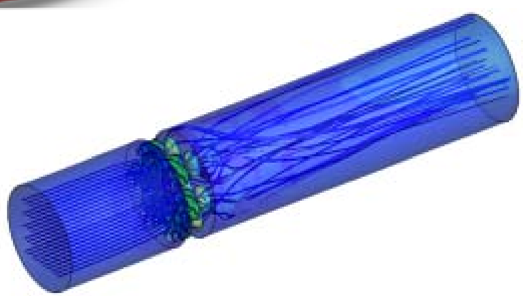
MDAO & Systems Analysis

Goals:

- Develop new methods for multi-disciplinary and multifidelity analysis of unconventional aerospace concepts
- Integration of multidisciplinary analyses with a common geometry model
- Reduce the upfront cost of applying MDAO to aerospace design problems







Approach:

- Tool development at multiple levels of fidelity
- Use of an open source framework as a common engineering platform
- Use of geometry tools that can serve multiple analysis tools and provide analytic derivatives for efficient optimization
- Use of challenge problems to demonstrate capabilities

OpenMDAO Development

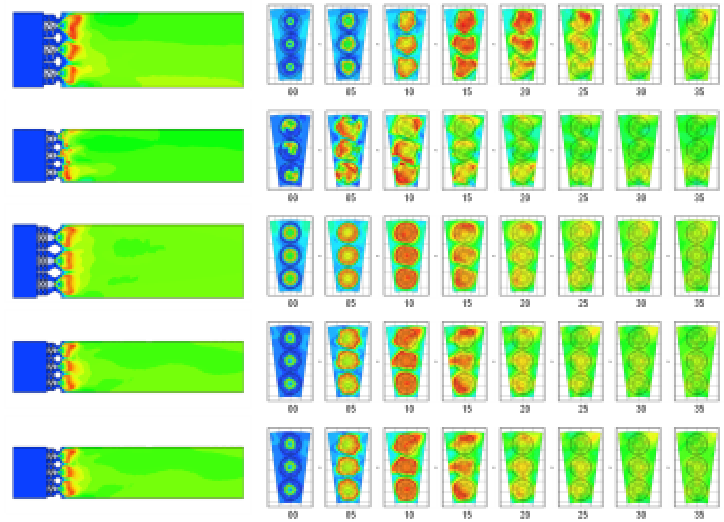
PROBLEM
Research into MDAO suffers a challenging route to adoption by the wider engineering community. Innovative new techniques are often accompanied by complex and problem specific implementations that do not allow for general use.

OBJECTIVE
Develop a MDAO Framework that provides a common platform for both MDAO research and application of MDAO to real work engineering problems. The framework will provide support for complex MDAO algorithms, integrated parametric geometry, and advanced optimization routines.

APPROACH
-- Develop OpenMDAO with open source licensing to encourage wide spread adoption and develop a community of users.
-- Provide a flexible interface for working with geometry engines tightly integrated into the framework.
-- Provide plugin development tools for easy addition of new tools and analysis wrappers
-- Develop connectivity to other COTS frameworks ensure compatibility with exiting modeling tools

RESULTS
-- OpenMDAO V 0.3.1 Released October 2012, Includes browser based GUI and complete documentation
-- First runner up in the 2012 NASA Software of the Year competition
-- Being used by AIAA MDO Technical Committee to develop a standardized MDO test problem platform

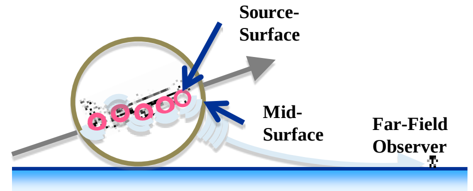
SIGNIFICANCE
OpenMDAO will provide a platform to tie together research going on in the MDAO sub-project. It will enable the integration of advanced analysis tools being researched within the sub-project with the new geometry tools being developed under NRA efforts. In addition, it provides a valuable tool for cooperation with numerous research efforts into MDAO in industry and academia.

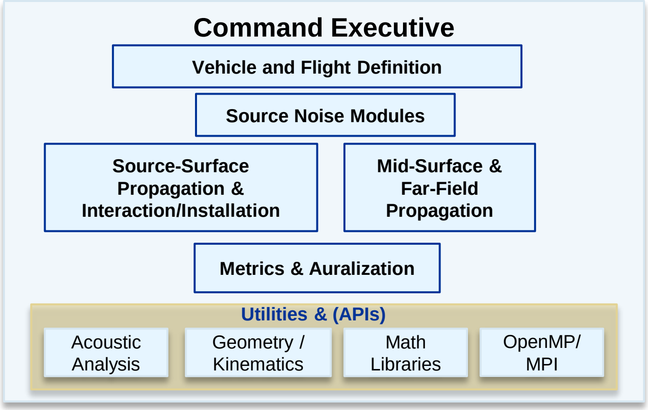


MILESTONES
-- MDAO Geometry Tools Integration Demonstration, 6/30/2013
-- Conceptual Aircraft Design Demonstration, 8/30/2013
-- OpenMDAO V1.0 Release, 9/30/2013

National Aeronautics and Space Administration

ANOPP2





PROBLEM

Aircraft noise needs to be reduced to improve the quality of life of those living near airports and to increase the productivity of airports. System noise prediction capability allows tradeoffs between noise reduction, safe flight procedures, viable designs for cost and emissions for current and future aircraft.

OBJECTIVE

Provide software framework that allows noise prediction for arbitrary aircraft designs (conventional to unconventional), of full-scale and model-scale size by accommodating multi-fidelity analyses from semi-empirical predictions for design to high-fidelity, physics-based predictions to study noise generation, propagation, human annoyance (auralization), and reduction and interface with system level frameworks such as OpenMDAO.

APPROACH

- Establish a framework where a combination of acoustic prediction methods of varied fidelity can communicate in a unified system.
- Create a system of Application Programming Interfaces (APIs) to enable building block approach to noise prediction.
- APIs provide users and developers with tools to implement preexisting and future predictions modules within ANOPP2.
- Use of self testing, documenting and verification software to enable automated builds and distribution.
- Mixed fidelity noise prediction through the use of nested Ffowcs Williams and Hawkings (FW-H) surfaces.
- Data Structures & Command Executive designed to enable varied fidelity noise predictions via object-oriented programming.
- Concurrent aircraft noise assessment of capabilities throughout development, customer as part of development team.

RESULTS

- Release of ANOPP2-Beta (November, 2012)
- Key APIs: Executive, Observer, Propulsion, Kinematics, Acoustic Analysis.
- Framework verification: through component and system level assessments.
- Collaboration/support for module implementation from HS, RW and ERA.
- ANOPP2 analysis to be reported in at least four 2013 conference papers.

SIGNIFICANCE

Provide NASA and other government agencies (FAA, DoD, etc) with tools to independently assess aircraft noise and its effects on the community. ANOPP2/ANOPP is the noise tool for the FAA EDS which is part of the Next Gen analyses capabilities.

MILESTONES

APG-9/2013: SFW.08.19.001 Develop, Improve, and Validate Next Generation Mixed-Fidelity Component and Aircraft Noise Prediction Capability: ANOPP2

Combustion

What are we trying to do ?

- Improve Combustion CFD Modeling Tools and Develop New Laser Diagnostics Techniques to Improve understanding of Combustion

Why ?

- Improved Modeling tools and understanding are needed to develop combustion concepts that will meet the NASA N+3 Emissions goals for future aircraft engines for both Subsonic and Supersonic Engine Applications

What is done today and what are the limits of current practice ?

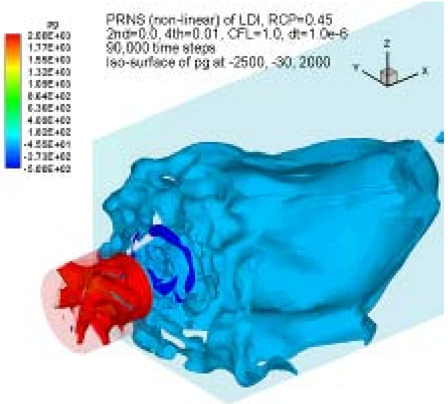
- Current Combustion CFD Modeling tools have been significantly improved but still require further development to allow accurate and reliable emissions predictions for future combustion concepts

What is new in our approach ?

- Time Filtered Navier Stokes approach for unsteady flow structure and turbulence/chemistry interaction of combustion flowfields which involve highly turbulent recirculating flows.

What is the payoff if successful ?

- Accurate, validated Combustion CFD Modeling Tools and improved understanding of combustion that can be used to develop new combustion concepts that meet NASA emissions goals for future aircraft engines.



Non Reacting Single Element LDI Flowfield Structure using TFNS

Raman Calibration Facility

Combustion Physics Based Modeling

PROBLEM

Combustion CFD Models are not sufficiently accurate to predict emissions from advanced combustion concepts. Quantitative data is not available to validate physics-based models.

OBJECTIVE

Improve capability of Combustion CFD Models to accurately predict emissions for advanced low emissions combustion concepts operating on a variety of fuels. Provide accurate quantitative data at realistic conditions to validate new physics-based models being developed. Develop non-intrusive diagnostic techniques to obtain required quantitative data.

APPROACH

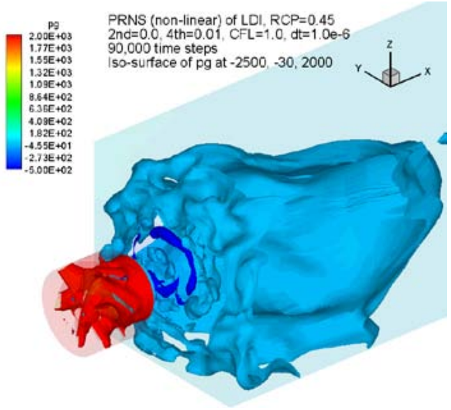
Implement advanced physics-based models for high pressure atomization/vaporization, radiation, soot, Open NCC development
Time Filtered Navier Stokes Turbulent Combustion Modeling
Single Element Lean Direct Injection Validation Experiments
Diagnostics development for high frequency species and temperature measurements, fuel vaporization rate

RESULTS

Turbulent Combustion Modeling and comparison with Single Element LDI,
  Paper at AIAA ASM Meeting, Jan, 2013
Fuel Vaporization Rate Measurement Technique proof of concept demonstrated,
  Paper submitted for ASME IGTI Turbo Expo, June, 2013
Confinement hardware completed and installed for Single Element LDI with
  Methane fuel experiments, experiments underway to define stable operating conditions for validation.

SIGNIFICANCE

Improving Combustion CFD Models is critical to the development of advanced low-emissions combustors operating at higher pressures using a variety of jet fuels.



MILESTONES

Assessment of TFNS Turbulent Combustion Models 9/30/13
Single Element LDI Validation Exp. with Methane 6/30/13
High Freq. Raman Measurement Capability demo in a Hydrogen Flat Flame Burner 9/30/13
Open NCC V1 Completed 9/30/14
Single Element LDI Validation Experiment with Single Component Liquid Fuel 6/30/14
Drop Vaporization Measurement in CE-13C 9/30/14

Combustion Fundamental Experiments

PROBLEM

Fundamental Experiments are required in order to improve our understanding of lean direct injection low emissions combustion concepts, combustion dynamics, and the potential of passive damping.

OBJECTIVE

Improve our understanding of Lean Direct Injection for low emissions capability
Improve our understanding of combustion dynamics for Lean Combustion Systems
Investigate passive damping techniques to mitigate combustion instability

APPROACH

Perform fundamental experiments in low pressure windowed flametube with optical access to study single and multi-element Gen 1 LDI configurations
Investigate combustion dynamics with well-defined inlet and exit boundary conditions
Design, fabricate, and test passive damping concepts to reduce or eliminate combustion dynamics using a 7-point LDI concept.

RESULTS

Low Pressure Flametube checkout testing continuing
Initiated passive damping design for 7-point LDI Configuration
Cold flow testing with water scheduled for early November for facility checkout.

MILESTONES

Fuel/Air Mixing and Emissions Studies completed for Single Element and 7-point Gen 1 LDI Concept 9/30/13
Passive Damping Design Completed for 7-point Gen 1 LDI Concept 9/30/13
Gen 2 LDI Design Completed 9/30/14
Passive Damping Concept Testing Completed 9/30/14

SIGNIFICANCE

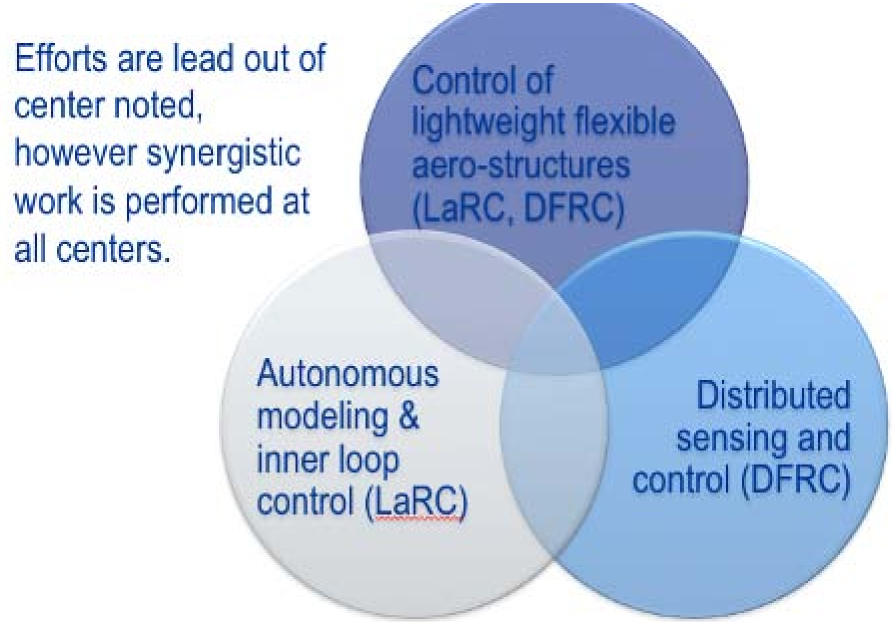
Improved understanding of Lean Direct Injection Combustor Concepts, combustion dynamics, and passive damping techniques will allow the development of low emissions combustor concepts for Subsonic and Supersonic Engine Applications that meet the stringent NASA gaseous emissions goals.

Controls

- High level objective: Autonomous, multi-functional, distributed flight control and advanced propulsion control

- Flight Controls:
  - control of lightweight, flexible structures
  - distributed sensing and control
  - autonomous modeling and inner loop control

- Advanced Propulsion Controls:
  - Distributed Engine Control
  - Model Based Engine Control



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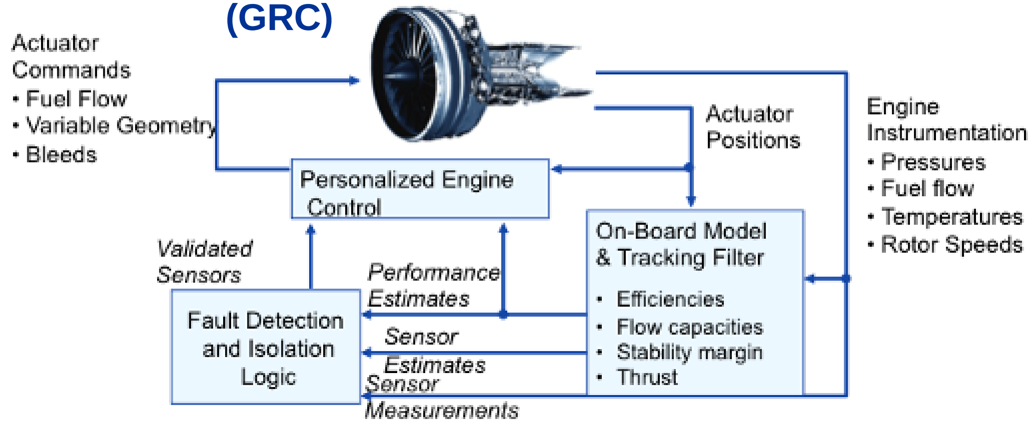
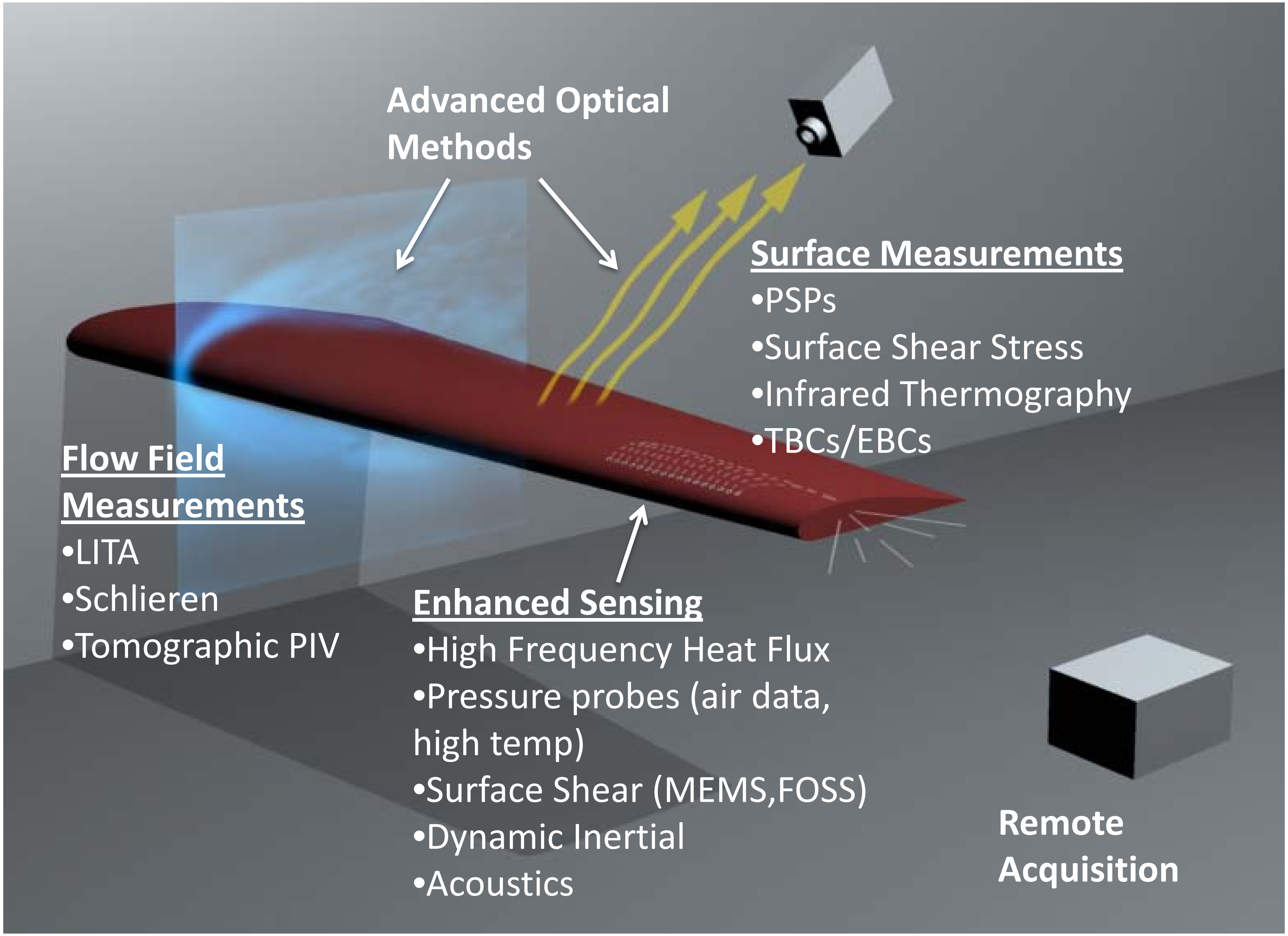


Innovative Measurements



Aeronautical Sciences NRAs

- **Revolutionary Computational Aerosciences (14)**
  - Stanford University, North Carolina State University, Stanford University, Texas A&M University, Iowa State University. Massachusetts Institute of Technology, University of Wyoming(2), University of New Mexico, University of Michigan, Iowa State University, University of Illinois at Urbana-Champaign, Brown University, The Boeing Company
- **Structures and Materials (2)**
  - University of Alabama, Michigan Technological University
- **MDAO and Systems Analysis (5)**
  - University of Michigan, MIT, Georgia Institute of Technology, California Polytechnic State, Old Dominion University
- **Combustion (2)**
  - Georgia Institute of Technology, Purdue University
- **Controls (1)**
  - Rolls-Royce North American

Total of 24 NRAs at a cost of $4.7 M

Summary

- NASA Aeronautics has a new project “Aeronautical Sciences” starting in FY2013.
- Project charter is to develop and validate cross-cutting physics-based tools and methods for air vehicles and propulsion systems.
- Current emphasis is on high-fidelity CFD using advanced physics-based methods such as LES. High performance computation capability will be exploited to dramatically reduce the cost of such simulations.
- Project aligns well with goals of CREATE – looking for partnerships with DOD and other stakeholders