Aerostructures Research at NASA Armstrong Flight Research Center

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Outline

- NASA Overview
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    - Armstrong Overview
    - Aerostructures Branch
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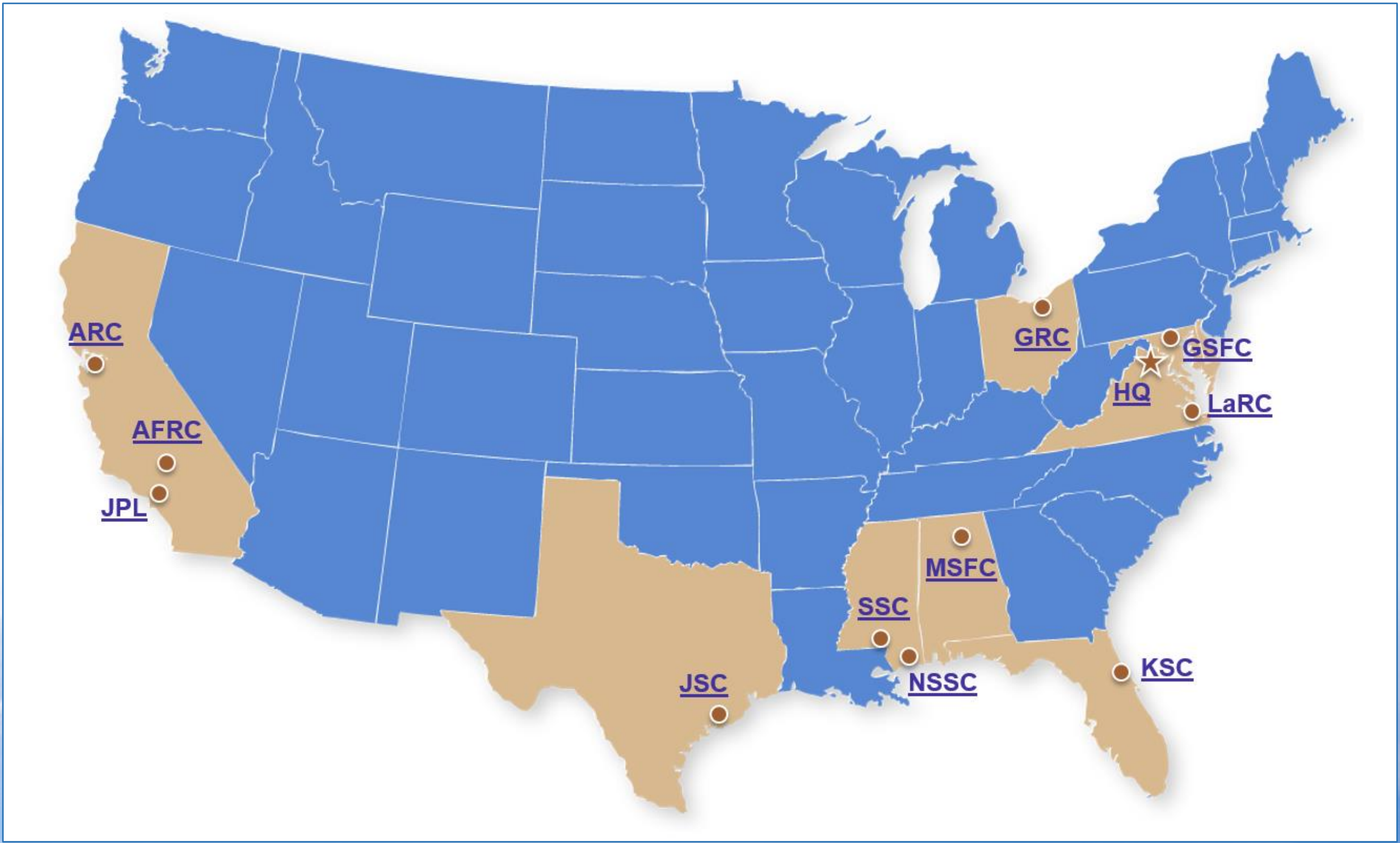
    - Space
- Research Interests
    - Innovative Structures and Sensors
    - Loads Monitoring
    - Shape Sensing
- Finite Element Methods for Shape Sensing
- Conclusions

NACA to NASA 1915-2015

NASA Centers



Mystery creates wonder and wonder is the basis of man's desire to understand.

Neil A. Armstrong

The purpose of
flight research is

> **"… to separate the real from the imagined and to make known the overlooked and the unexpected."**

— Dr. Hugh L. Dryden

Administrator of NACA (1949-1958)
First Deputy Administrator of NASA (1958-1965)

Vision: To separate the real from the imagined through flight


X-1


Space Shuttle Approach and Landing Tests

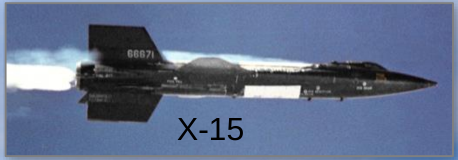

Lunar Landing Research Vehicle


F-8


X-43


M2-F1


X-29

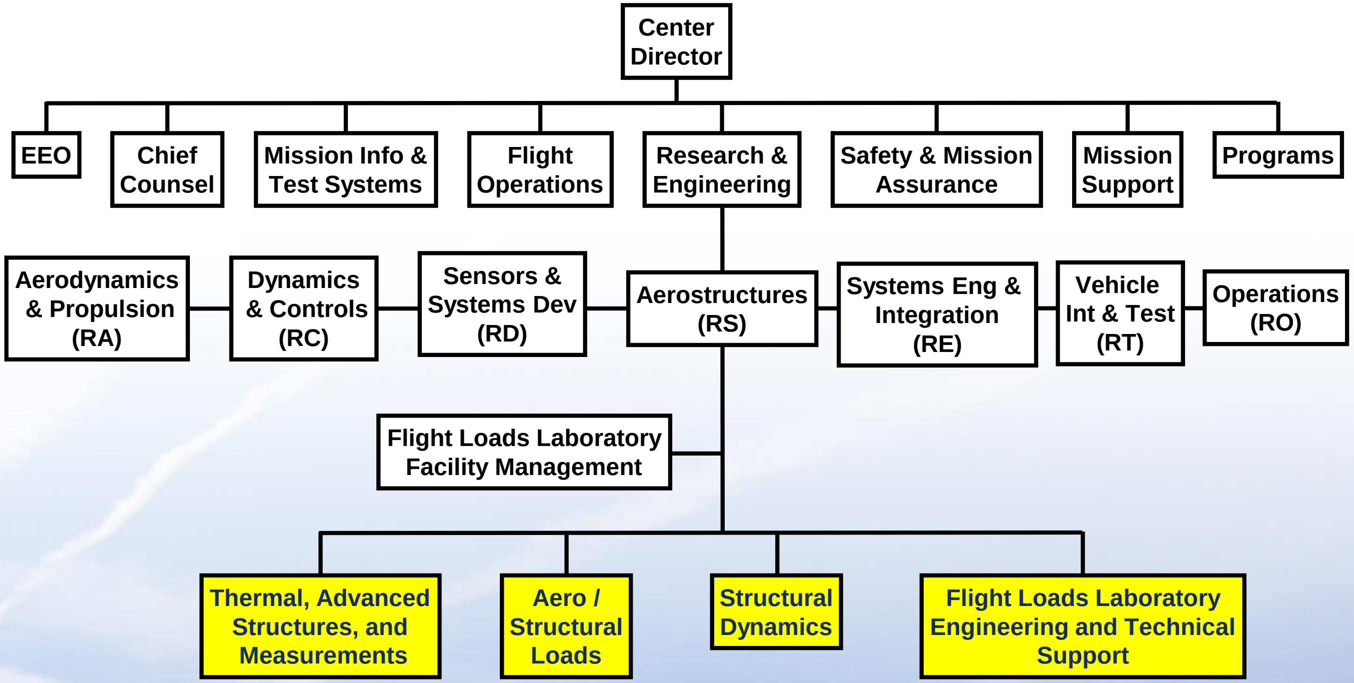

X-15


Helios

Armstrong Flight Research Center (AFRC)

- Edwards AFB
  - Remote location
  - Varied topography
  - 350 testable days per year
  - Extensive range airspace
  - 29,000 feet of concrete runways
  - 68 miles of lakebed runways
  - 301,000 acres
  - Supersonic corridor

Aerostructures Branch



Center Director

EEO

Chief Counsel

Mission Info & Test Systems

Flight Operations

Research & Engineering

Safety & Mission Assurance

Mission Support

Programs

Aerodynamics & Propulsion (RA)

Dynamics & Controls (RC)

Sensors & Systems Dev (RD)

Aerostructures (RS)

Systems Eng & Integration (RE)

Vehicle Int & Test (RT)

Operations (RO)

Flight Loads Laboratory Facility Management

Thermal, Advanced Structures, and Measurements

Aero / Structural Loads

Structural Dynamics

Flight Loads Laboratory Engineering and Technical Support

NASA Armstrong Flight Loads Lab

Flight Loads Laboratory (FLL)

- Airworthiness
- Research

Test Capabilities

- Proof loading, load calibrations, control surface proof of operations, loads flight test
- Modal test, flutter flight test, ASE test, freeplay test, MOI test
- Thermal and thermal-mechanical test, TPS development and test, pyrometry, SMAs, elastomer aerospace applications, frangible joint evaluations
- Conventional, high temperature, and advanced instrumentation (e.g. FOSS)

Aerostructures

- **Airworthiness**
  - Loads: External loads; Inertial loads; Store loads; Structural deflections; FEA; Stress analysis; Airframe modification evaluation; Structural design; Loads calibrations; Proof load testing; Functional testing under load; Thermal/mechanical instrumentation; Flight-test support; Envelope expansion
  - Dynamics: Modal analysis; Flutter analysis; Ground Vibration Testing (GVT); FEM model tuning; Mass property testing; Structural mode Interaction (SMI) or Structural Coupling Test (SCT); Dynamics and flutter flight-test support; Envelope expansion
  - Thermal, Advanced Structures, and Measurements: Heat transfer; Thermal stress; Thermal protection systems/methods; Instrumentation application/installation
  - FLL: Ground test execution; Test design; Non-Destructive Evaluation (NDE); Instrumentation; Component calibration

Airworthiness

JPL's UAVSAR equipped C-20A (GIII)

ER-2 Science Platform

F/A-18

Ikhana MQ-9 Predator B Science/Research Platform

Stratospheric Observatory for Infrared Astronomy (SOFIA)

F-15A/D

DC-8 Science Platform

Global Hawk RQ-4 Science Platform

Aerostructures

- **Research**
  - Loads: Loads calibration techniques; Fiber Optic Strain Sensing (FOSS) applications; Testing of advanced structural concepts; Aero-tow
  - Dynamics: GVT methods; MOI methods; Improved flutter flight-test techniques; Multidisciplinary Design, Analysis, and Optimization (MDAO) tool development; Passive/active control analysis/design of flexible structures (multi-discipline); Operational Modal Analysis (OMA); Aeroservoelastic (ASE) systems modeling, analyses, and tool development; Elevated-temperature modal test and analysis
  - Thermal, Advanced Structures, and Measurements: Hot structures test techniques; Hot structures design; Thermal coatings; Thermal protection system (TPS) development; Pyrometry; Shape memory allows (SMAs) for aerospace applications; Elastomer aerospace applications; Frangible joint evaluations (NESC); Instrumentation application; FOSS applications; Non-contact strain and temperature measurement; High temperature instrumentation development; Composites M&P
  - FLL: Thermal/mechanical testing and analysis

NASA Armstrong Projects

NASA Mission Directorates

Aeronautics Research Mission Directorate (ARMD)

Human Exploration & Operations Mission Directorate (HEOMD)

Science Mission Directorate (SMD)

Rendering courtesy Whittinghill Aerospace

Space Technology Mission Directorate (STMD)

Aeronautics

X-56 MUTT

GIII SCRAT Testbed

F-15 Testbed

X-48

F-18

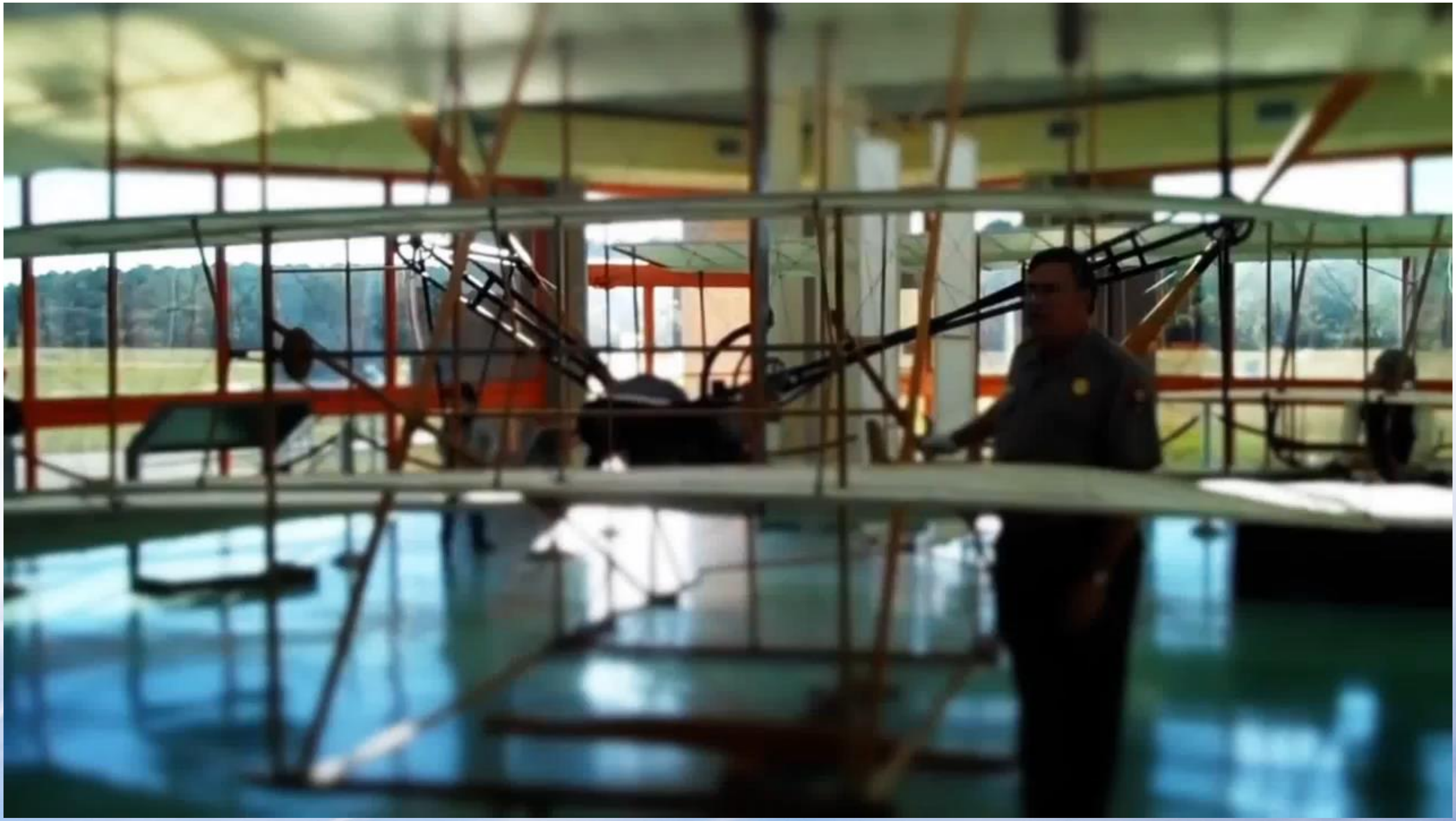
X-48C Hybrid Wing Body (HWB)

- Quiet and fuel-efficient technology demonstrator
- Evaluate the low-speed stability and control for a “low-noise” version of the HWB
- Develop control system strategies, including limiters, for robust and safe prototype control system for future commercial aircraft
- Conduct flight experiments with the HWB 8.5% dynamically scaled model
- Final flight (30 flights completed) was April 9, 2013

X-56A Multi-Utility Technology Testbed (MUTT)

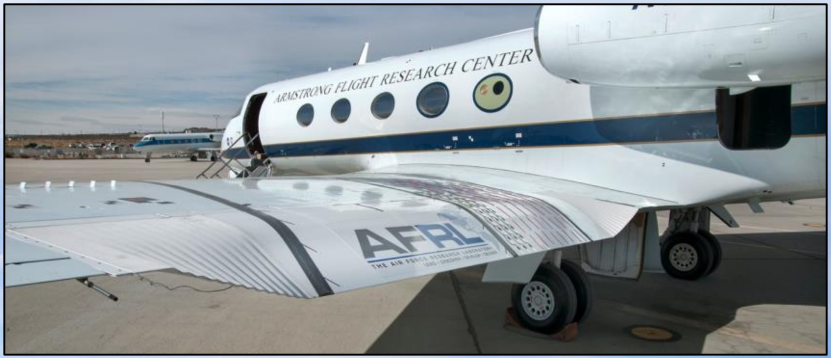
- X-56A MUTT is used to explore integrated structural control of extremely lightweight flexible aircraft
- Partnership: NASA, AFRL, and LM
- Performance Benefits: Active control of flexible wings = weight reduction = fuel savings

Adaptive Compliant Trailing Edge (ACTE)



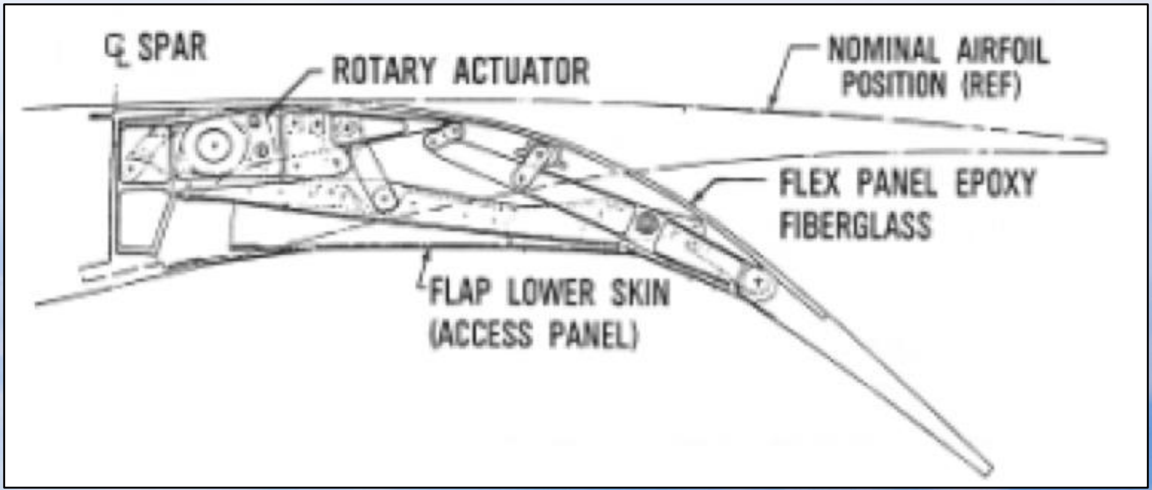
ACTE Project Overview

- Project objective: Flight demonstrate a compliant structure that replaces a large control surface
- Partnership between: NASA, AFRL, and FlexSys Inc.
- ACTE potential performance benefits:
  - Cruise drag reduction, wing weight reduction through structural load alleviation, and noise reduction during approach & landing
- Status:
  - Phase 1 complete: -2 to 30 deg deflection; flight envelope to 0.75, 40kft, 340 KCAS, 2g load factor
  - Phase 2 test planning: Mach expansion to 0.85; Flap twist for load/cruise performance tailoring; Drag characterization; Noise characterization



Historical Perspective: Mission Adaptive Wing

- Mission Adaptive Wing was a joint USAF/NASA/Boeing demonstration program
- Variable camber leading and trailing edge surfaces were installed on a F-111 testbed using mechanical rigid linkages
- The AFTI/F-111 MAW system had 59 flights from 1985 through 1988
- The flight test data showed a drag reduction of around 7 percent at the wing design cruise point to over 20 percent at an off-design condition
- Mechanical actuation system weight penalties and system complexity hindered the acceptance of the technology

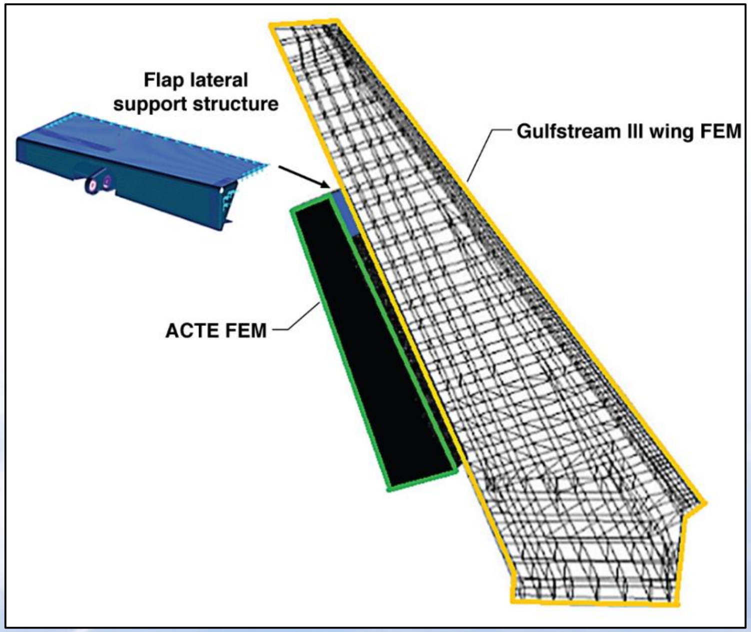


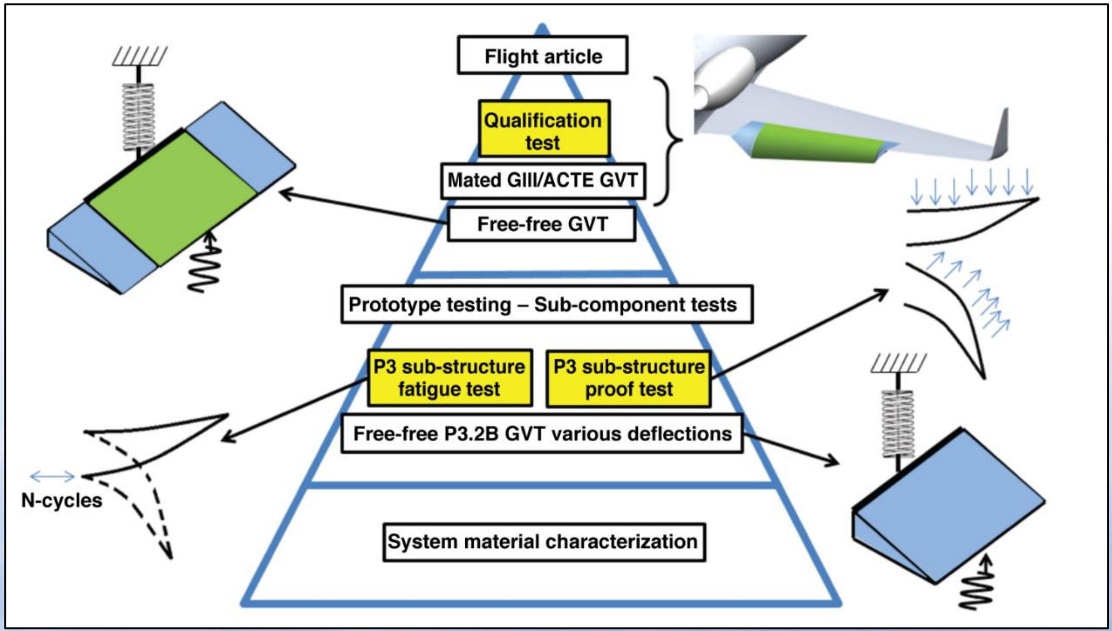
Compliant Mechanisms Overview

- Compliant design embraces elasticity, rather than avoiding it, to create one-piece kinematic machines, or joint-less mechanisms, that are strong and flexible (for shape adaptation)
- Large deformations can be achieved by subjecting every section of the material to contribute equally to the (shape morphing) objective while all components share the loads
- Every section of the material undergoes only very small linear elastic strain with very low stress and hence the structure can undergo large deformations with high fatigue life

ACTE Airworthiness

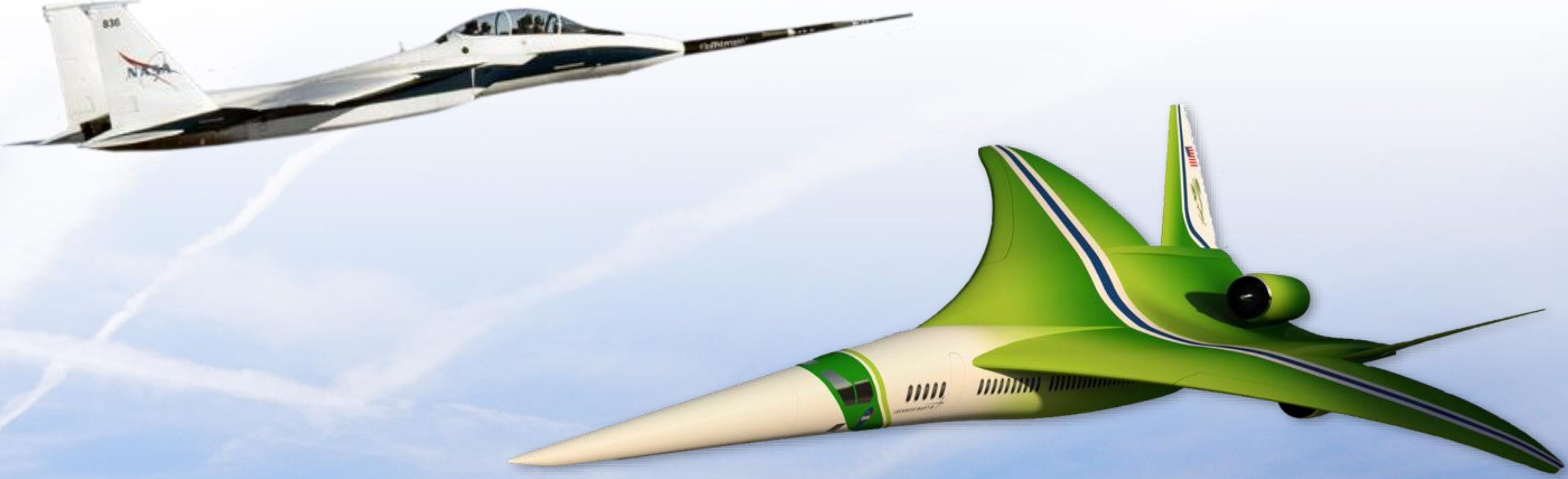
- New structure designs required tailoring center processes for clearing the structure for flight
- Analysis, ground testing, and health monitoring techniques were all utilized





Supersonics/High Speed Project

- NASA’s ongoing effort to mitigate sonic boom effects for overland supersonic cruise



Science

C-20A (G-III)

ER-2

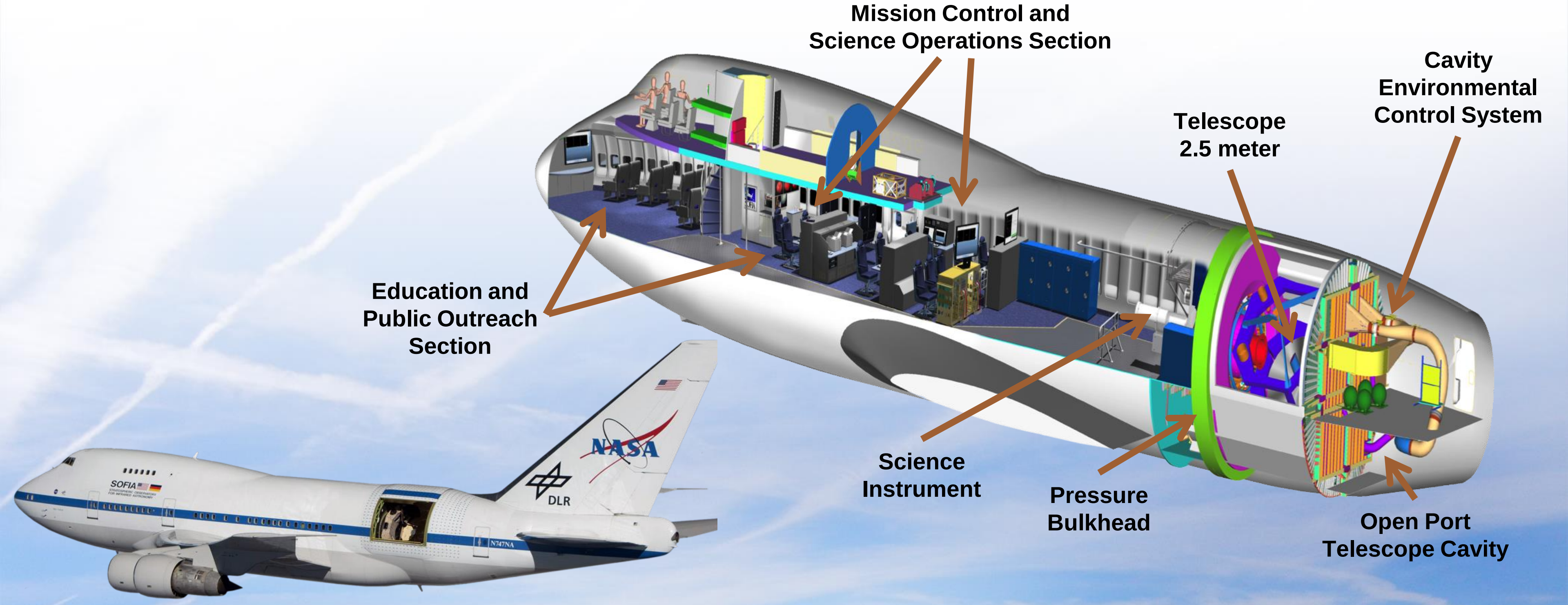
Global Hawk

DC-8

Ikhana Predator B

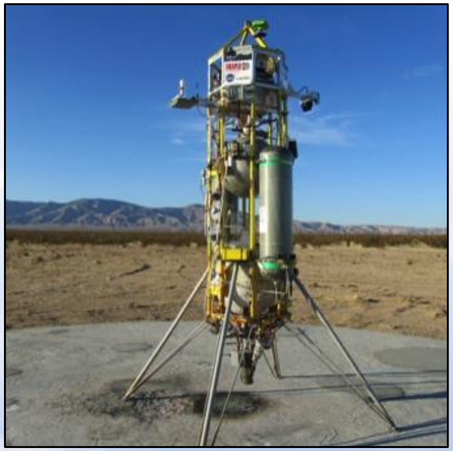
Stratospheric Observatory for Infrared Astronomy

- SOFIA's 2.5-meter primary mirror, telescope weighs 44,000 pounds
- Missions fly at 43,000 feet to get above 99% of the Earth's water vapor, which blocks much of the infrared radiation from reaching the ground
- SOFIA can deploy around the world to observe transient events or gain better astronomical visibility.



Space Technology

- Armstrong partners with private industry, NASA Centers, and other government organizations to advance space technology
- Utilizes aircraft platforms to prove technologies
- Develops unique systems to lower the cost to access space

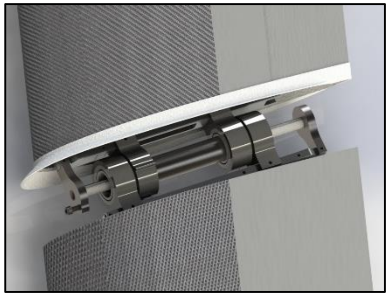


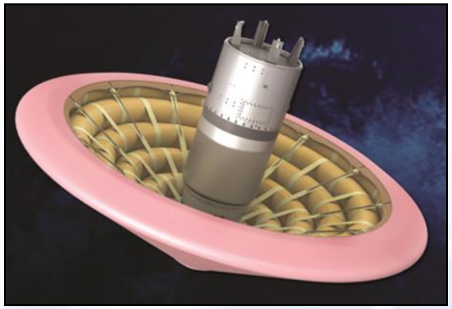
Aerostructures Research

Innovative Structures and Sensors

- Compliant mechanisms
- Materials capable of large deformations
- Shape memory alloys

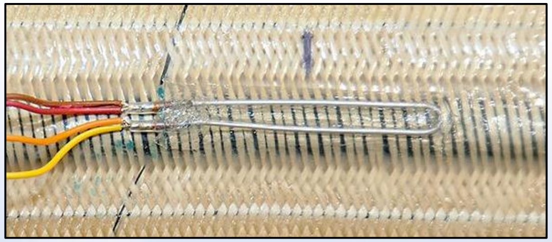
SMA Actuator

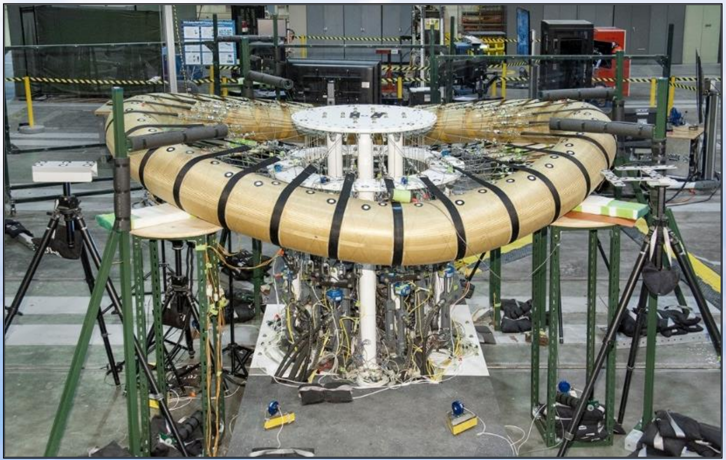




HIAD
Hypersonic
Aerodynamic
Inflatable
Decelerator

Liquid Metal Strain Gage

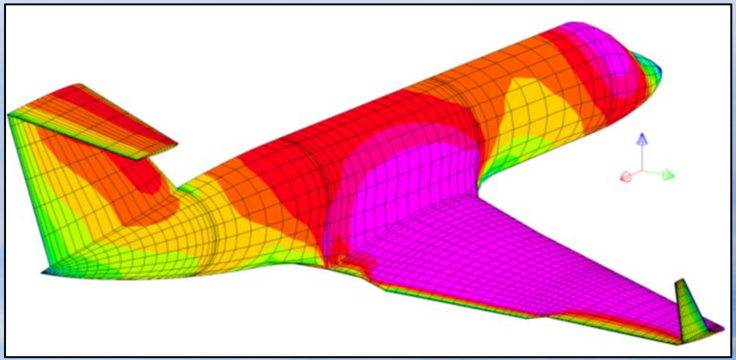




ACTE
Compliant
Mechanisms

Loads Monitoring

- Wing load monitoring and analysis
- Force balance load measurement



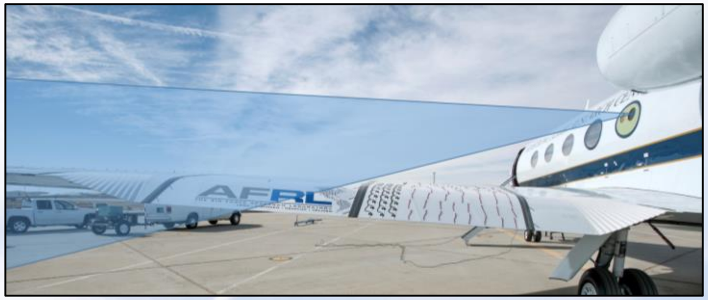
Structural Shape Sensing

Need: to monitor inflight deformation

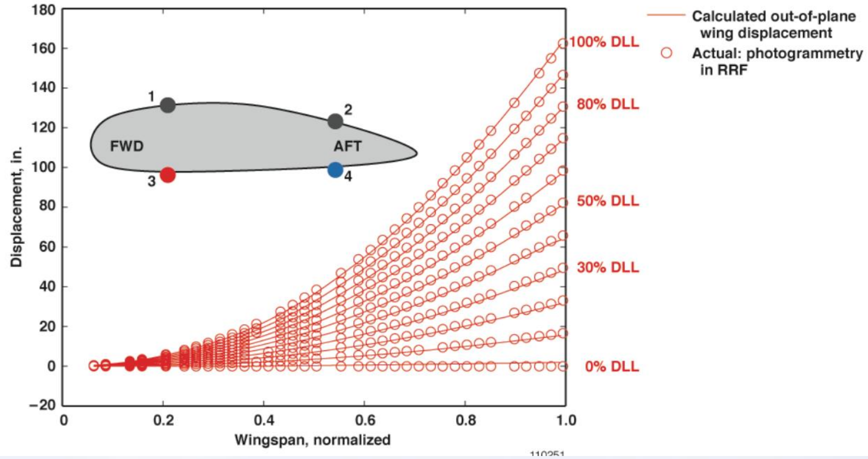
Helios Wing

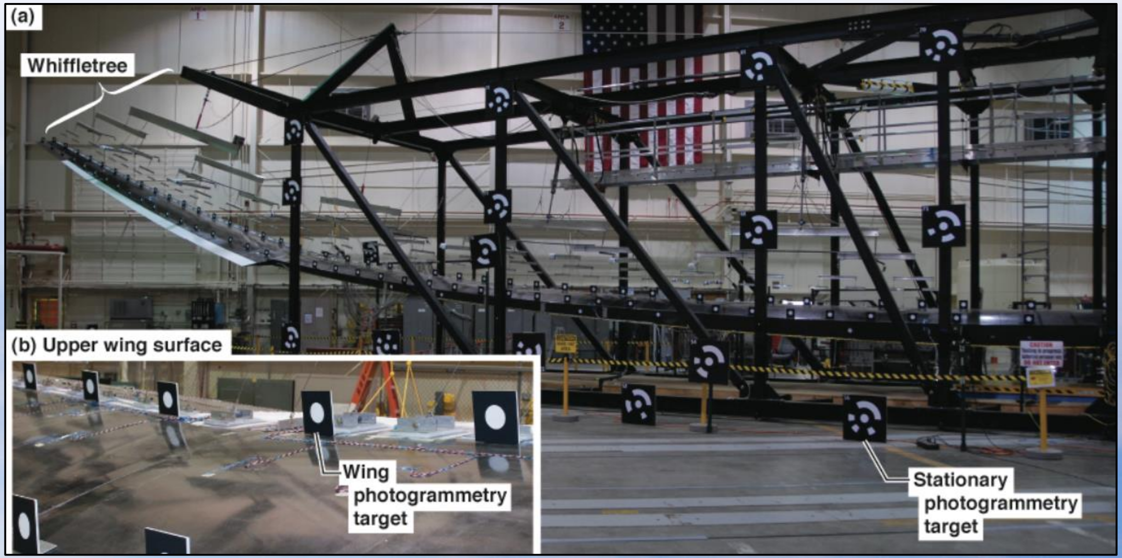
In-flight breakup

Solution: vision systems



Solution: sensors for measuring deflection





Finite Element Methods for Shape Sensing

Background

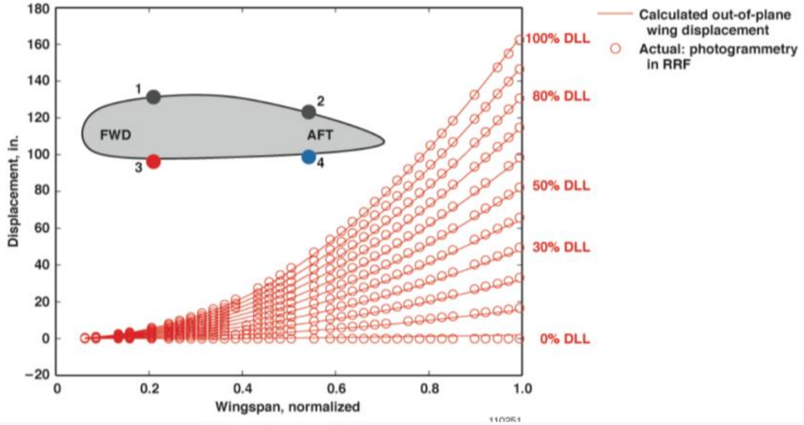
- Shape sensing is an active area of research at NASA AFRC
- Multiple shape sensing methods are available such as beam bending approximations and finite element methods
- Alex Tessler has developed the Inverse Finite Element Method (iFEM) for plate and shell three node elements at NASA Langley over the past 10 years
- Eric Miller and Melissa Barnett (summer student) in 2012 implemented a 1-D element in Matlab to investigate the usefulness of this method for upcoming AFRC flight test projects

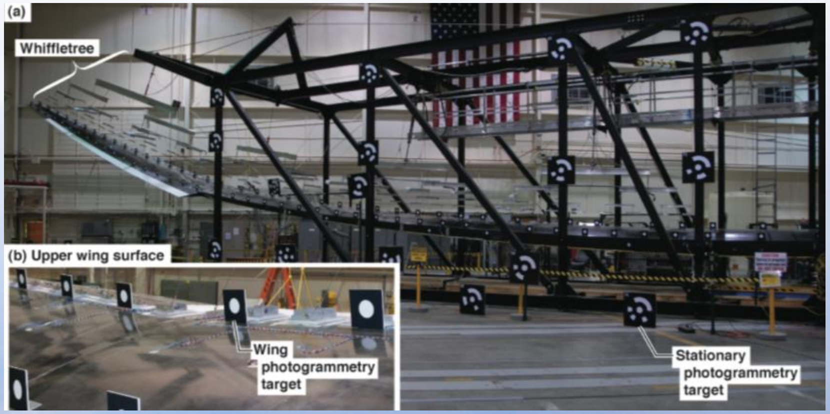
Beam Approximation Shape-Sensing Analysis

- 1-D integration of classical beam Eqs for cantilevered, non-uniform cross-section beam (no shear deformation)

$$w_{,xx} = \frac{\varepsilon_x^+}{-c(x)} \qquad (u_x(x,z) = -z\,w_{,x})$$

$$z \in [c,-c]$$



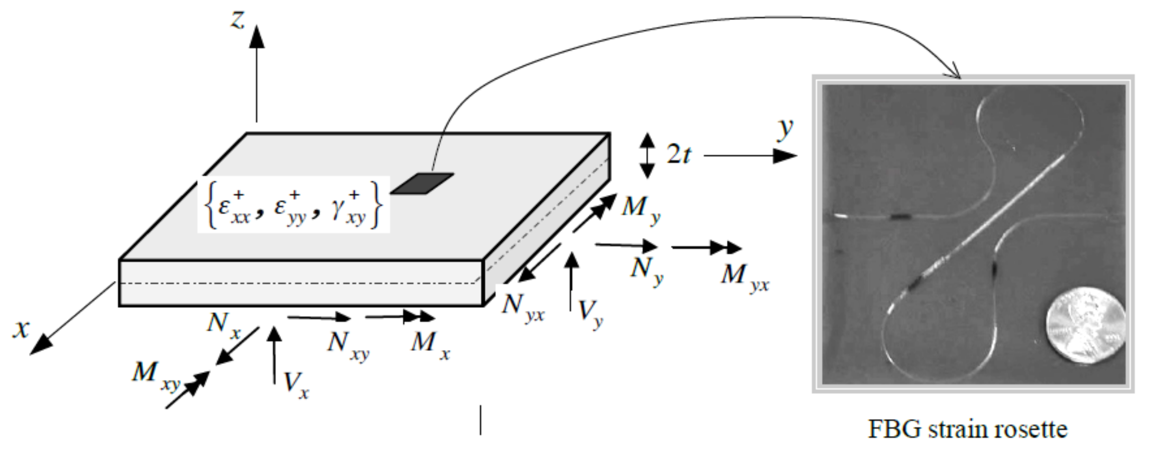


- Piecewise linear approximation of strain and taper between regularly spaced “nodes” where strains are measured
- Neutral axis is computed from detailed FEM (SPAR code) or upper and lower strain measurements
- Incorporates cross-sectional geometry of a wing in a beam-type approximation
- Shown to work well for high aspect ratio wings

Method for Real-Time Structure Shape-Sensing, U.S. Patent No. 7,520,176, issued April 21, 2009.

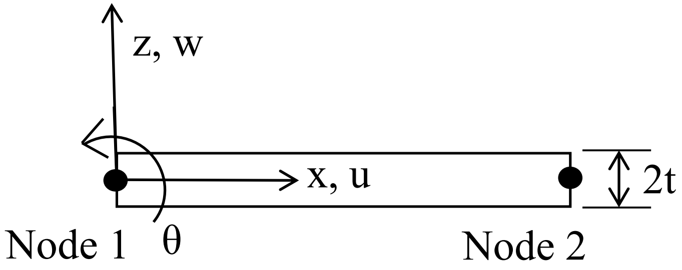
iFEM Formulation Framework

- Structure is discretized with iFEM elements, ie. beam, plate, and solid elements
- Elements defined by a continuous displacement field
- Strain-displacement relations: define element strain measures and experimental strain gage data
- Element matrices are derived from a least squares smoothing functional
- Apply boundary conditions
- Solve for the nodal displacements
- Using the nodal displacements the full field stresses and strains can be derived



inverseFEM Formulation (1-D Beam)

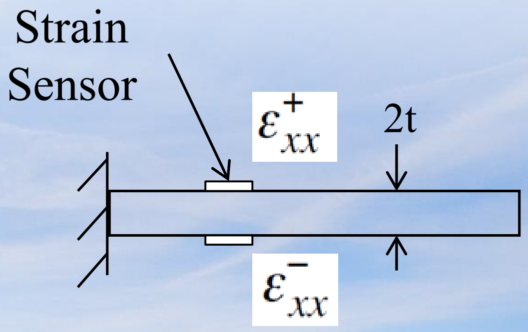
- 1-D linear Timoshenko beam implementation
  - Includes transverse shear effects



- Nodal Displacement Vector:

$$\mathbf{u}_{dof}^{T} = \{u, w, \theta\}$$

- Measured Strains:
  - Fiber Bragg Grating fiber or axial metallic foil strain gage



Strain Displacement Relation (1-D Beam)

- Nodal Displacement Vector:

$$\mathbf{u}_{dof}^{T} = \{u, w, \theta\}$$

- Strain Displacement Relation:

$$\varepsilon_{xx} = \varepsilon_x + z\,\kappa_x$$

Where z denotes the total beam thickness (2t)

- Beam Strain Measures:
  - Normal Strains

$$\varepsilon_x = \left\{ \frac{\partial}{\partial x}, \mathbf{0}, \mathbf{0} \right\} \begin{Bmatrix} u \\ w \\ \theta \end{Bmatrix} = \mathbf{B}^N \mathbf{u}_{dof}$$

  - Curvature (Bending) Strains

$$\kappa_x = \left\{ \mathbf{0}, \mathbf{0}, \frac{\partial}{\partial x} \right\} \begin{Bmatrix} u \\ w \\ \theta \end{Bmatrix} = \mathbf{B}^B \mathbf{u}_{dof}$$

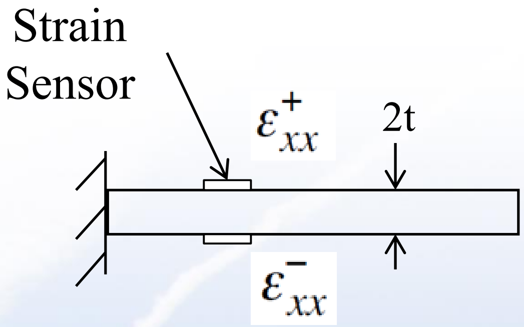
  - Transverse Shear Strain

$$\gamma_x = \left\{ \mathbf{0}, \frac{\partial}{\partial x}, \mathbf{1} \right\} \begin{Bmatrix} u \\ w \\ \theta \end{Bmatrix} = \mathbf{B}^S \mathbf{u}_{dof}$$

Experimental Strains (1-D Beam)

- Strain displacement relation in terms of experimentally measured strains

$$\varepsilon_{xx}^{\exp} = \varepsilon_{x}^{\exp} + z\,\kappa_{x}^{\exp}$$



where:
z=±t, total beam thickness of 2t
exp denotes experimental strains

$$\varepsilon_{x}^{\exp} = \frac{1}{2}(\varepsilon_{xx}^{+} + \varepsilon_{xx}^{-})$$

$$\kappa_{x}^{\exp} = \frac{1}{2t}(\varepsilon_{xx}^{+} - \varepsilon_{xx}^{-})$$

$\gamma_{x}^{\exp}$ Cannot be obtained from surface strains

Weighted Least Squares Functional

A weighted least-squares smoothing functional in terms of the unknown nodal displacement degrees of freedom

$$\Phi_e(\mathbf{u}^h) = w_e \left\| \varepsilon_x(\mathbf{u}^h) - \varepsilon_x^{\exp} \right\|^2 + w_k \left\| \kappa_x(\mathbf{u}^h) - \kappa_x^{\exp} \right\|^2 + w_g \left\| \gamma_x(\mathbf{u}^h) - \gamma_x^{\exp} \right\|^2$$

where the squared norms are

$$\left\| \varepsilon_x(\mathbf{u}^h) - \varepsilon_x^{\exp} \right\|^2 \equiv \frac{1}{n} \int_L \sum_{i=1}^{n} \left[\varepsilon_x(\mathbf{u}^h)_i - \varepsilon_{xi}^{\exp} \right]^2 dx$$

$$\left\| \kappa_x(\mathbf{u}^h) - \kappa_x^{\exp} \right\|^2 \equiv \frac{(2t)^2}{n} \int_L \sum_{i=1}^{n} \left[\kappa_x(\mathbf{u}^h)_i - \kappa_{xi}^{\exp} \right]^2 dx$$

$$\left\| \gamma_x(\mathbf{u}^h) - \gamma_x^{\exp} \right\|^2 \equiv \frac{1}{n} \int_L \sum_{i=1}^{n} \left[\gamma_x(\mathbf{u}^h)_i - \gamma_{xi}^{\exp} \right]^2 dx$$

n	number of strain sensors located within an element
w_e w_k w_g	weighting constants or penalty parameters associated with individual strain parameters

inverseFEM Formulation

- Minimize the functional with respect to nodal degrees of freedom

$$\frac{\partial}{\partial \mathbf{u}_{dof}} \sum_{e=\mathbf{1}}^{N} \Phi_e(\mathbf{u}^h) = \mathbf{0}$$

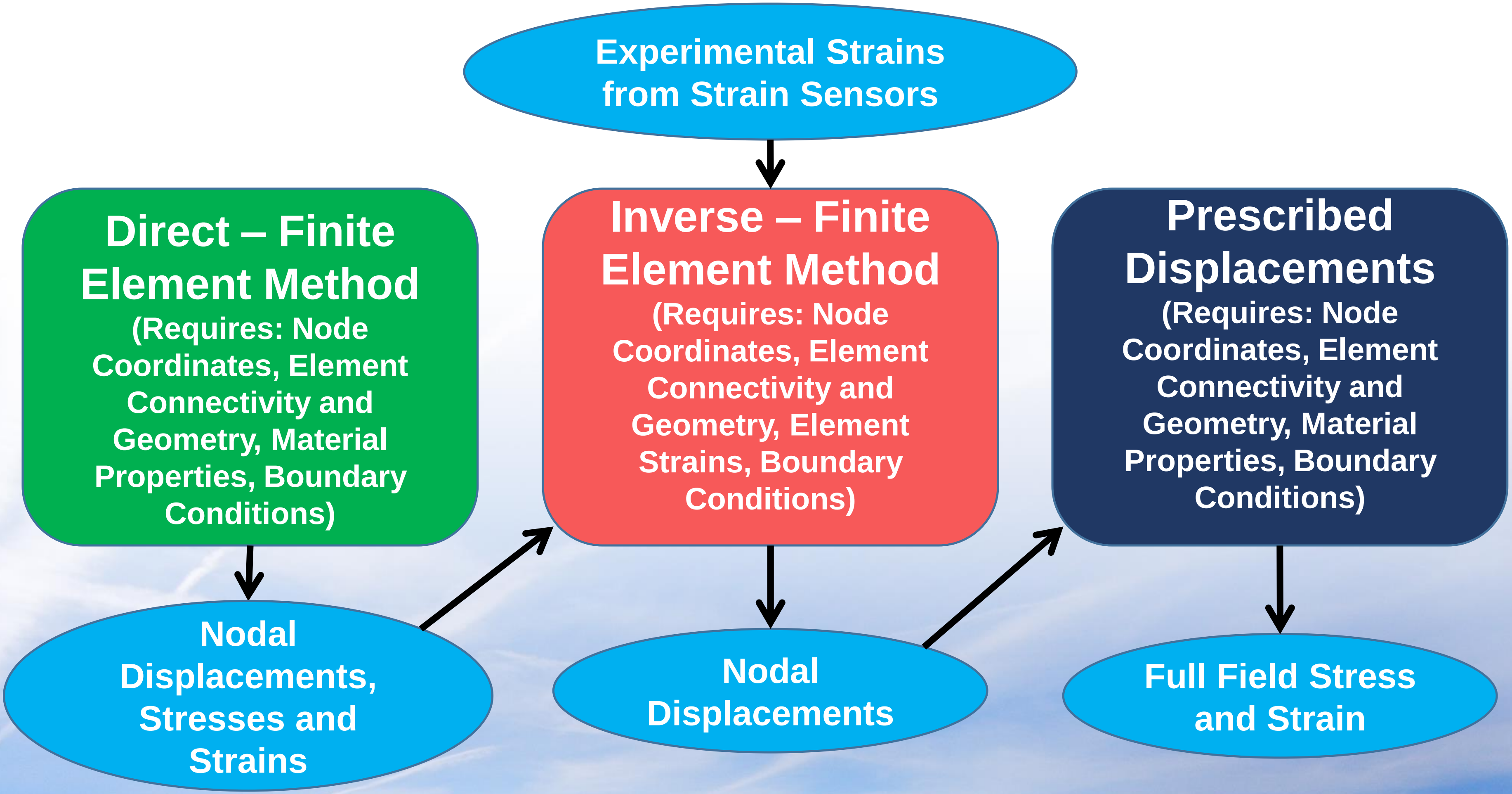
- Linear equations:
  - Nodal Coordinates
  - Element Connectivity
  - Boundary Conditions
  - Element Strains

$$\mathbf{K}\mathbf{u}_{dof} = \mathbf{f}$$

K	**Symmetric, positive definite matrix**
$\mathbf{u}_{dof}$	**Nodal Displacement Vector**
$\mathbf{f}\ (\varepsilon^{exp})$	**RHS vector in terms of experimental strain values**

- Solve for nodal displacements

iFEM Implementation Framework



Experimental Strains from Strain Sensors

Direct – Finite Element Method
(Requires: Node Coordinates, Element Connectivity and Geometry, Material Properties, Boundary Conditions)

Inverse – Finite Element Method
(Requires: Node Coordinates, Element Connectivity and Geometry, Element Strains, Boundary Conditions)

Prescribed Displacements
(Requires: Node Coordinates, Element Connectivity and Geometry, Material Properties, Boundary Conditions)

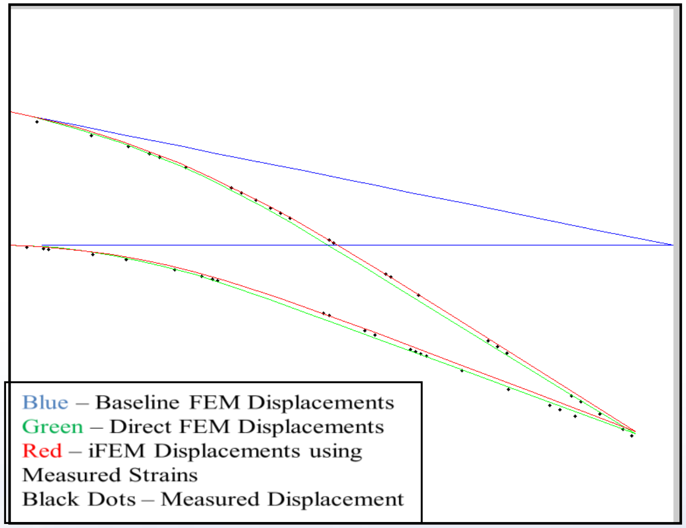
Nodal Displacements, Stresses and Strains

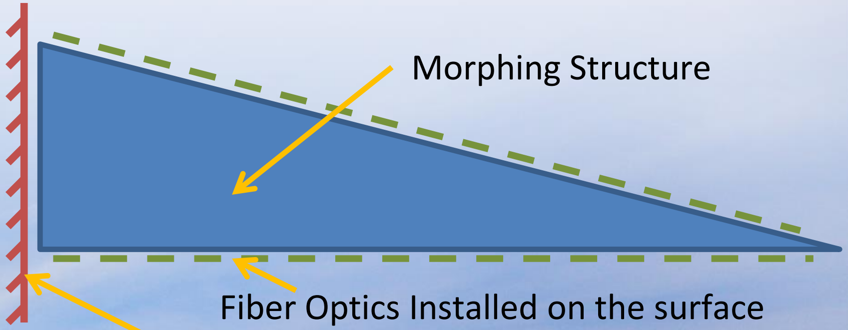
Nodal Displacements

Full Field Stress and Strain

AFRC iFEM Application

- Structural deformation results are shown for a morphing aircraft structure using direct and inverse methods
- The surface of the structure was instrumented with Fiber Bragg Gratings for measuring the chordwise strain distribution
- Structure was deformed during experimental testing and the strains and displacements were recorded
- Direct Finite Element Method (FEM) results were calculated using representative boundary conditions
- Inverse FEM results were calculated using the surface strain measurements
- Experimental displacements shown as black dots were measured using a continuous moldline measurement tool





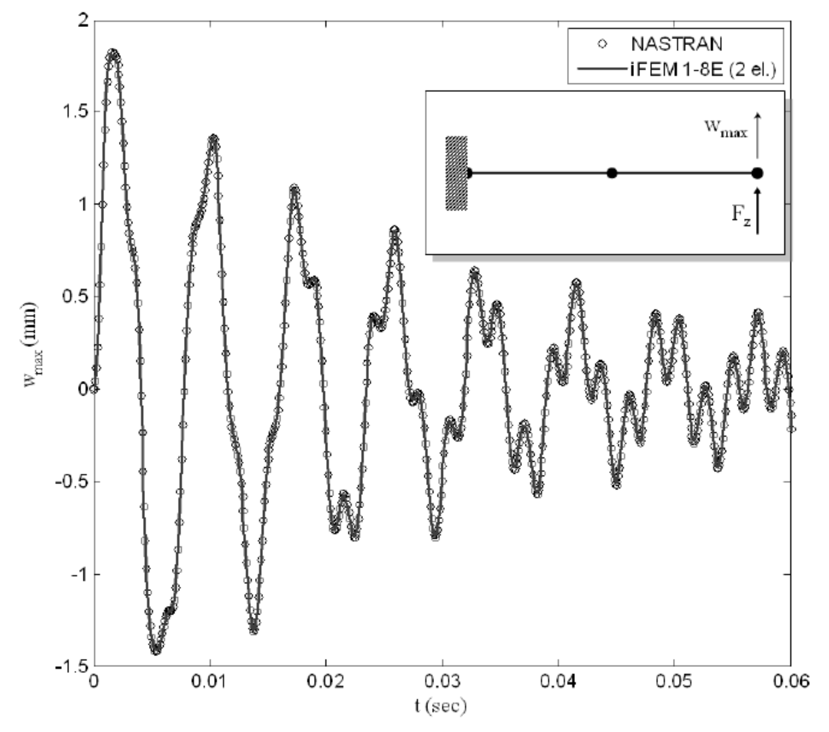
Morphing Structure

Fiber Optics Installed on the surface

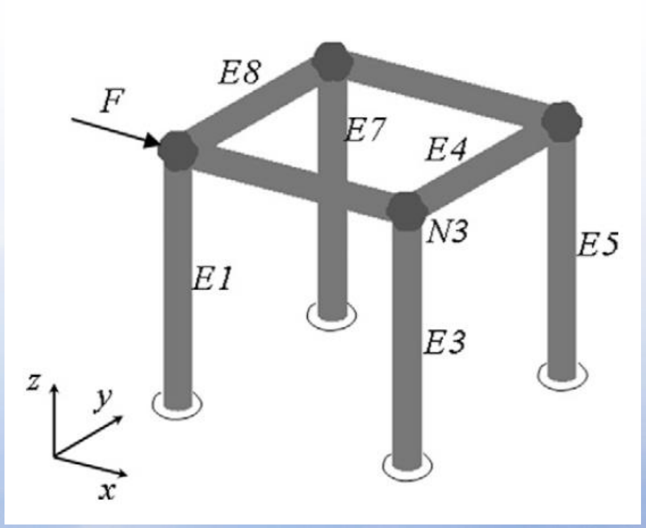
Representative Boundary Conditions Were Applied

Shape sensing of 3D frame structures

Marco Gherlone, Priscilla Cerracchio, Massimiliano Mattone, Marco Di Sciuva, Alexander Tessler



Tip deflection w_{max} of the beam loaded by a transverse concentrated force Fz at f_0=450 Hz.



Three-dimensional frame structure problem

Benefits of iFEM

- Architecture uses standard FEM
- Superior accuracy on coarse meshes (advantage of integration)
- Beam, frame, plate, shell and built-up structures
- Use of partial strain data (over part of structure, or incomplete strain tensor data)
- Strain-displacement relations fulfilled
- Least-squares compatibility with measured strain data
- Independent of material properties
- Geometrically linear and nonlinear response
- Dynamic regime
- Composite and sandwich structures

Conclusions

- Exciting time to be a structures engineer
- Innovative structures, sensors, and analysis techniques are being developed

Publications

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- Jutte, C.V., Ko, W.L., Stephens, C.A., Bakalyar, J.A., Richards, W.L., and Parker, A.R., Deformed Shape Calculation of a Full-Scale Wing Using Fiber Optic Strain Data from a Ground Loads Test. NASA/TP-2011-215975, 2011.

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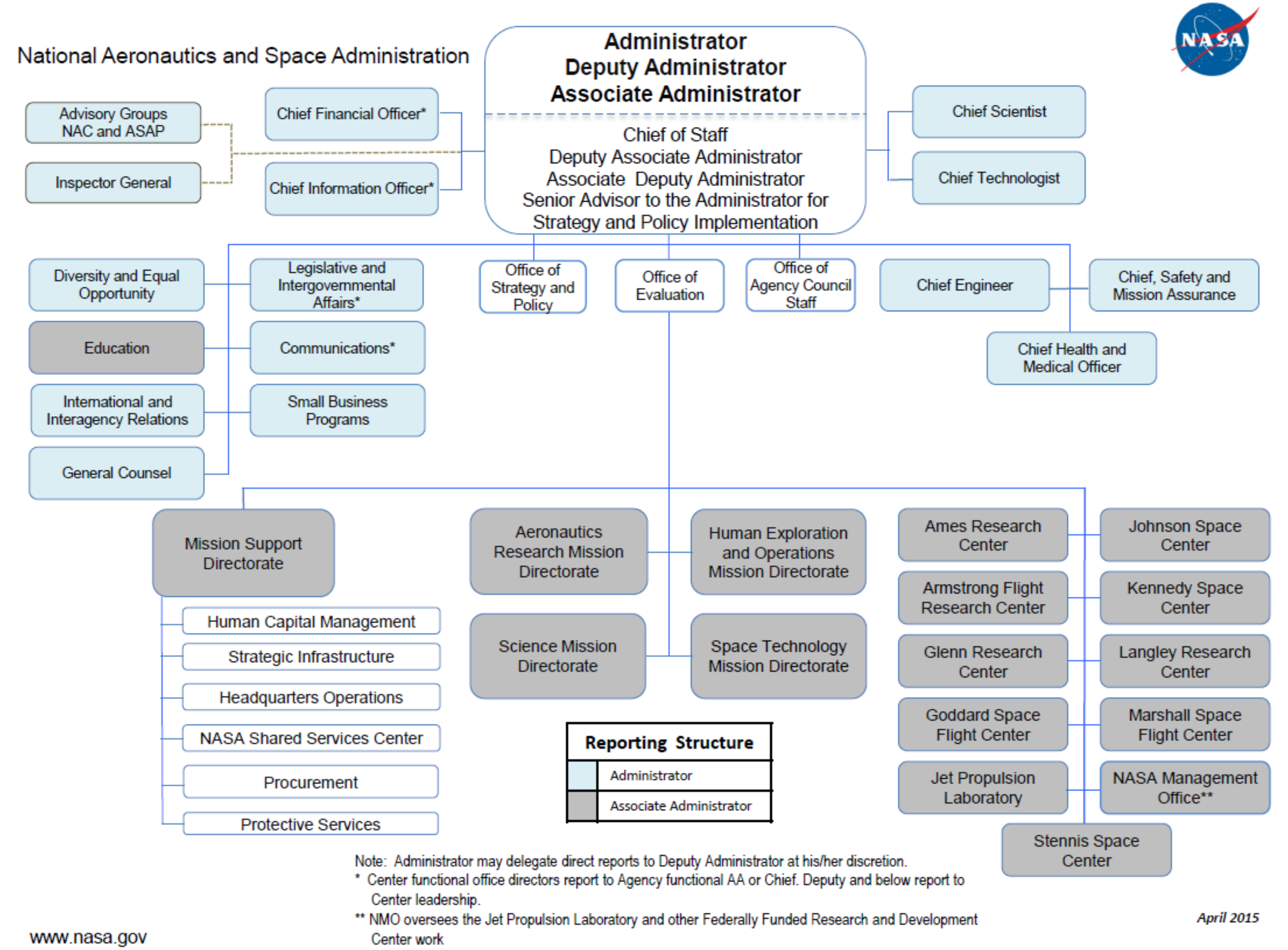

National Aeronautics and Space Administration

Administrator
Deputy Administrator
Associate Administrator

Chief of Staff
Deputy Associate Administrator
Associate Deputy Administrator
Senior Advisor to the Administrator for Strategy and Policy Implementation

Advisory Groups NAC and ASAP

Inspector General

Chief Financial Officer*

Chief Information Officer*

Chief Scientist

Chief Technologist

Diversity and Equal Opportunity

Legislative and Intergovernmental Affairs*

Education

Communications*

International and Interagency Relations

Small Business Programs

General Counsel

Office of Strategy and Policy

Office of Evaluation

Office of Agency Council Staff

Chief Engineer

Chief, Safety and Mission Assurance

Chief Health and Medical Officer

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- Human Capital Management
- Strategic Infrastructure
- Headquarters Operations
- NASA Shared Services Center
- Procurement
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Science Mission Directorate

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▨	Associate Administrator

Note: Administrator may delegate direct reports to Deputy Administrator at his/her discretion.
* Center functional office directors report to Agency functional AA or Chief. Deputy and below report to Center leadership.
** NMO oversees the Jet Propulsion Laboratory and other Federally Funded Research and Development Center work

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