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Aeroelastic Tailoring of High Aspect Ratio Wings: Design, Fabrication and Testing Challenges and How We Overcame Them

Karen M. B. Taming

Structural Efficiency Tech Lead, Advanced Air Transport Technology Project
NASA Langley Research Center
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Background: NASA Subsonic Transport Technology Focus



- Subsonic commercial transport (passenger) fixed-wing aircraft
- Performance – fuel burn, emissions and noise reduction
- Common design elements – high aspect ratio wings, non-circular fuselages
- Technology development applicable to new aircraft 2-3 generations out

Future wings will be of higher aspect ratio, lighter, more flexible, and have varying degrees of laminar flow to reduce drag and improve performance

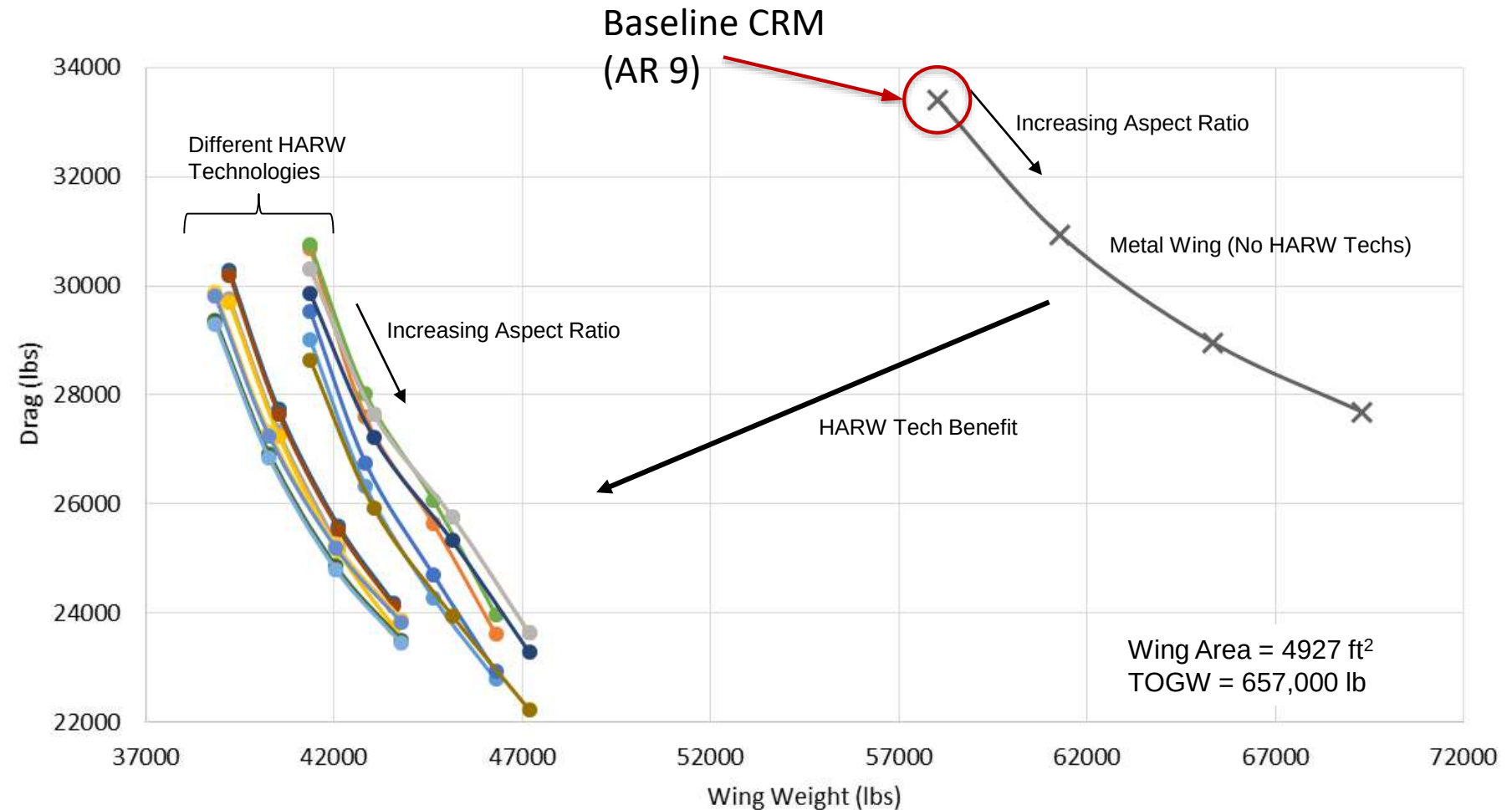


NASA N+3: conceptual depictions of future subsonic commercial transport configurations

High Aspect Ratio Wing (HARW) Technology Assessment



- From 2016 systems analysis of HARW technologies:
- Cantilever wing, Common Research Model (aspect ratio 9) baseline
- HARW technologies not only shift the curve, but also change the slope, i.e., drag can be reduced via aspect ratio increase with less weight penalty
- Fuel burn is reduced due to reduced drag, despite modest increase in weight with increasing aspect ratio



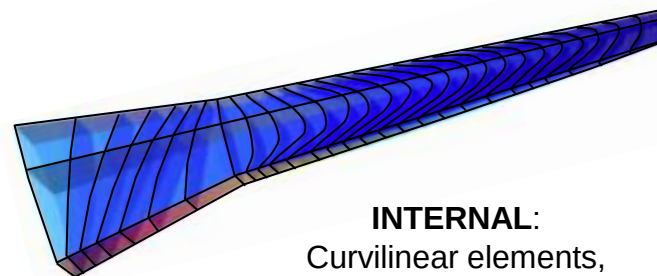
NASA – Aeroelastic Tailoring Research Thrusts



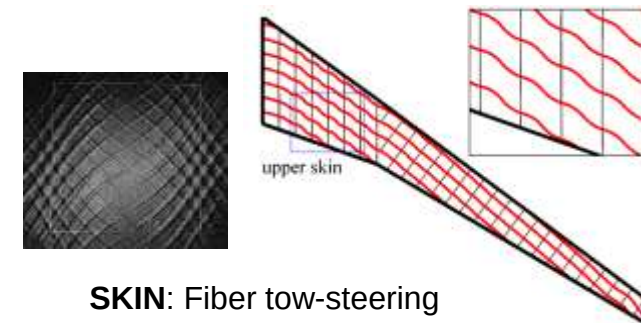
Objective: Explore and develop aerodynamic, structural, and control technologies to expand the optimal wing system drag vs. weight design trade space for reduced energy consumption. Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe structures and flight control.

Passive aeroelastic tailoring

- Curvilinear stiffened internal structure
- Topology optimized internal structure
- Tow-steered composite skins



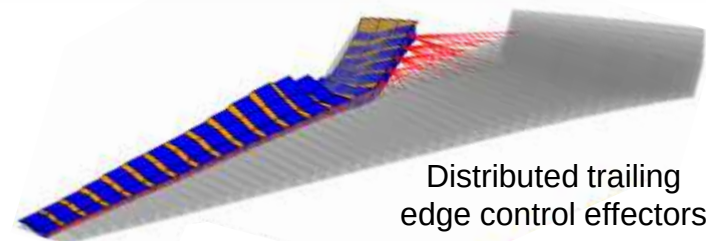
INTERNAL:
Curvilinear elements,
Topology optimization



SKIN: Fiber tow-steering

Active aeroelastic tailoring

- Novel control effectors, integrated sensors, and control laws
- Control of flexible wings demonstrating active maneuver load alleviation, gust load alleviation, off-design cruise drag reduction, and flutter suppression
- Flight and wind tunnel testing



Distributed trailing
edge control effectors



6 dof control of flexible wings



Wind tunnel testing (TDT) for ASE
control of flexible wings

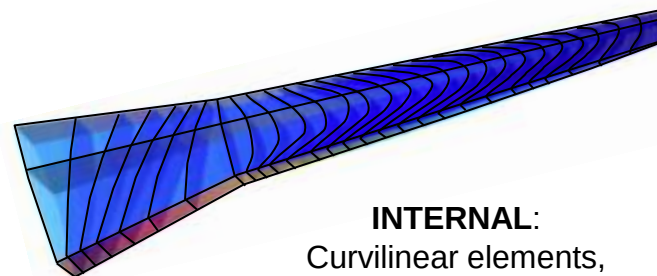
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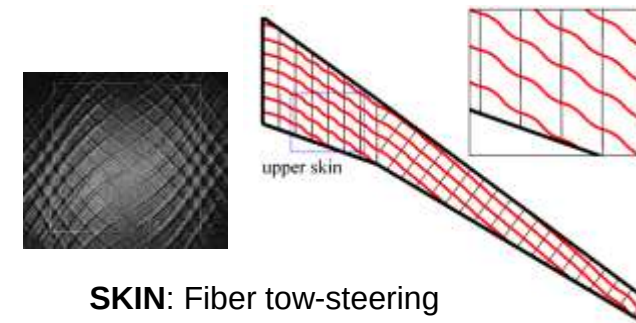
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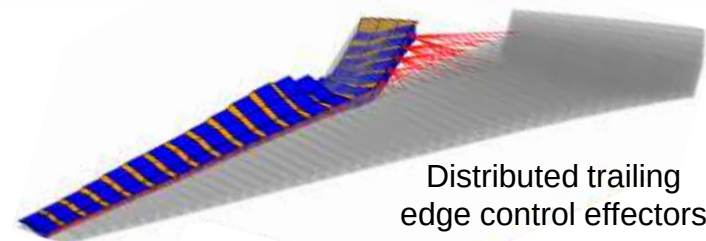
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VA Tech –Tailoring through Curvilinear Internal Wing Structure



- Series of NASA-funded activities at VA Tech (Blacksburg, VA) starting in 2004

Approach:

- Started with structural optimization of panels with curvilinear stiffeners for minimum weight
- Expanded to multidisciplinary optimization
 - Weight + acoustic damping
 - Weight + aeroelastic tailoring
- Increased from panel (EBF3PanelOpt) to entire wing (SpaRib)
- Complexity increased from isotropic (aluminum) to anisotropic (composite) stiffened structures
- Tools applied to wing, fuselage, and other aerospace structural designs

Outcomes:

- Developed robust tools for structural optimization and analysis
- Enable designs for simultaneous weight reduction and performance improvement for many configurations and applications

Design and analysis tools enable multiobjective structural optimization to improve performance

VA Tech – Key Contributors



Rakesh K. Kapania, Mitchell Professor of Aerospace and Ocean Engineering at Virginia Tech

Davide Locatelli, President and CEO of Gamma Orionis LLC

Sameer Mulani, Associate Professor at The University of Alabama

Ali Yeilaghi Tamijani, Assistant Professor at Embry-Riddle Aeronautical University

Qiang Liu, NVH CAE Engineer at FCA Fiat Chrysler Automobile

Mohamed Jrad, Computational Researcher, M4 Engineering Inc.

Wei Zhao, Post-Doc Fellow, Virginia Tech

Shuvodeep De, Post-Doc Fellow, The University of Alabama

Rikin Gupta, Karanpreet Singh and Jitish Miglani, PhD Candidates, Virginia Tech

PhD Dissertations at Virginia Tech related to SpaRibs work:

- **Ali Yeilaghi Tamijani**, “Vibration and Buckling Analysis of Unitized Structure Using Meshfree Method and Kriging Model,” 2011
- **Davide Locatelli**, “Optimization of Supersonic Aircraft Wing-Box using Curvilinear SpaRibs,” 2012
- **Qiang Liu**, “EBF3GLWingOpt: A Framework for Multidisciplinary Design Optimization of Wings Using SpaRibs,” 2014
- **Mohamed Jrad**, “Multidisciplinary Optimization and Damage Tolerance of Stiffened Structures,” 2015
- **Wei Zhao**, “Optimal Design and Analysis of Bio-Inspired, Curvilinearly Stiffened Composite Flexible Wings,” 2017
- **Shuvodeep De**, “Structural Modeling and Optimization of Aircraft Wings having Curvilinear Spars and Ribs (SpaRibs),” 2017

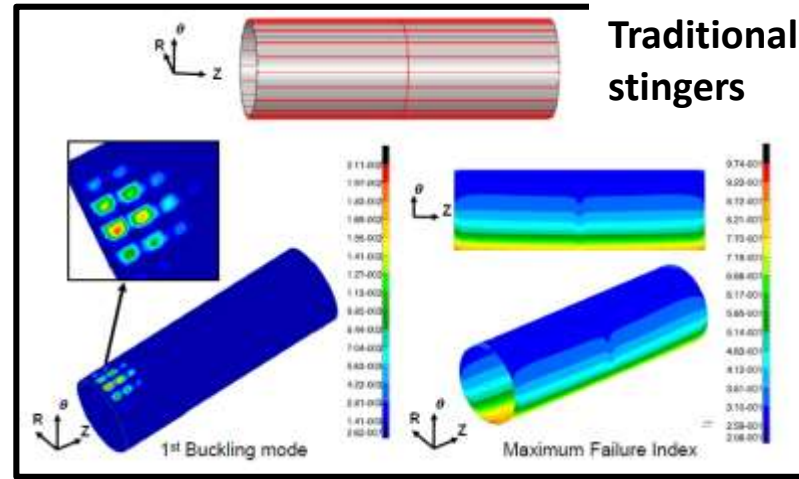
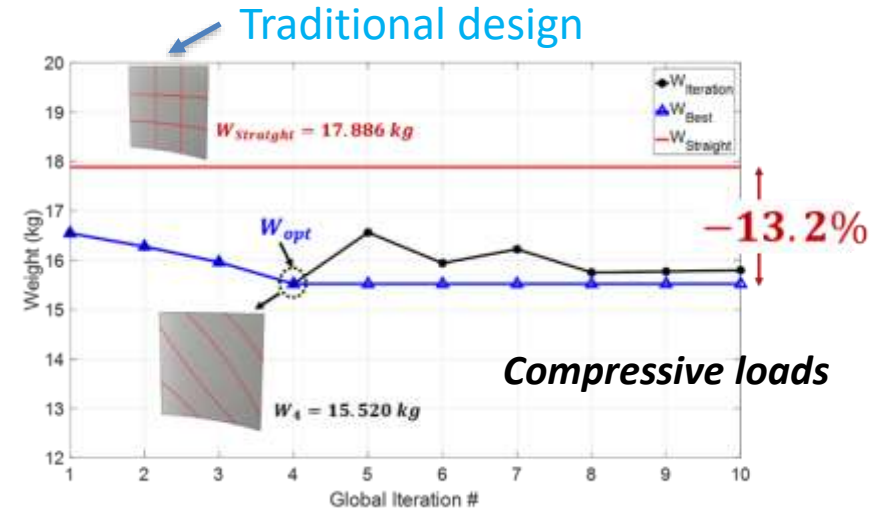
VA Tech – EBF3PanelOpt : Stiffened Panel Optimization



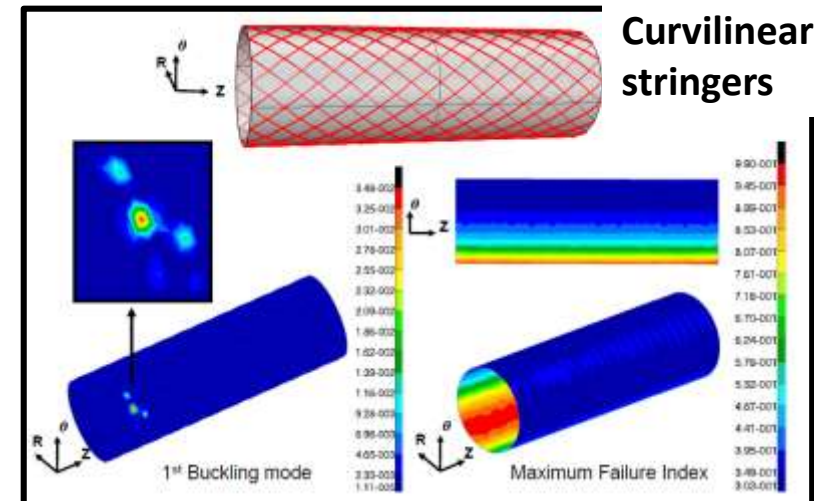
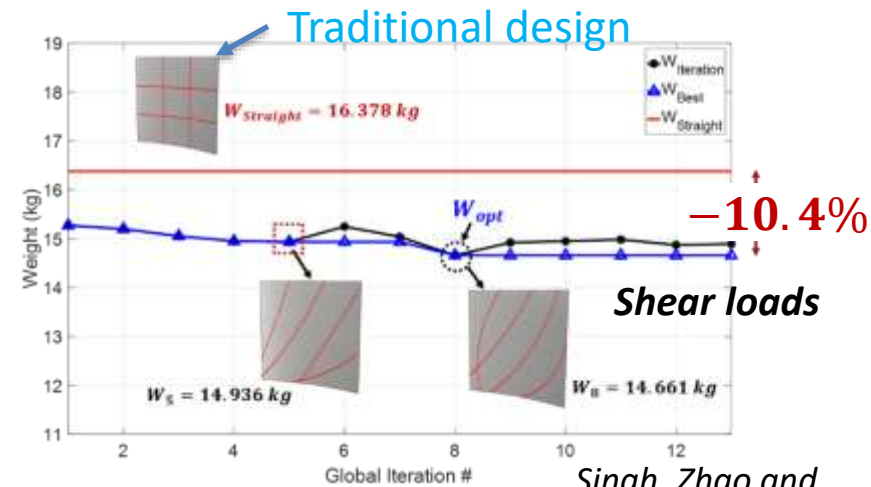
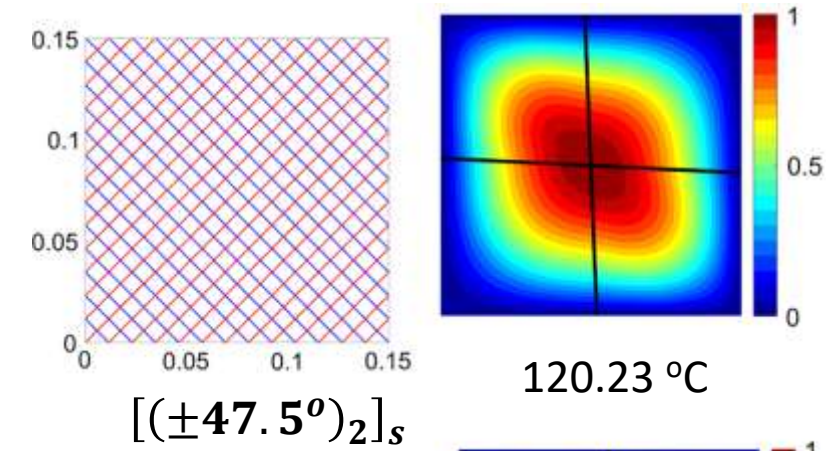
Weight minimization of cylindrical panel using curvilinear stiffeners

Weight minimization of cylindrical shell using curvilinear stiffeners

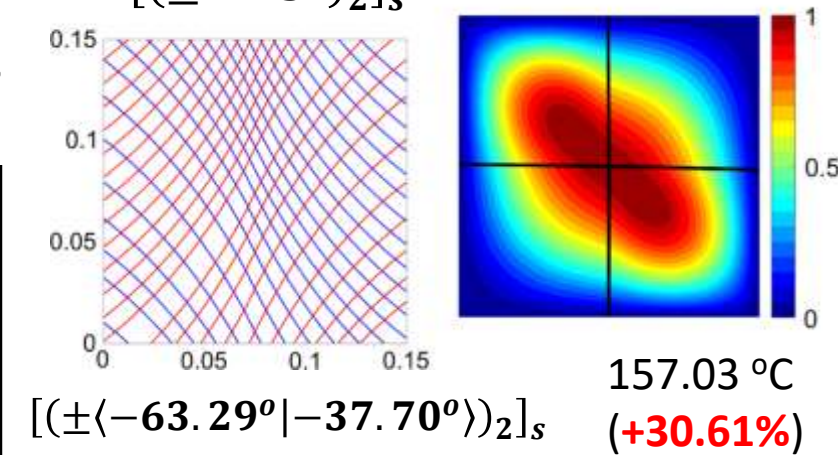
Thermal buckling temperature maximization (Weight fixed)
Stiffeners and steered-tow laminates



Shell weight: 19.50 kg



Shell weight: 17.79 kg (**-8.76%**)



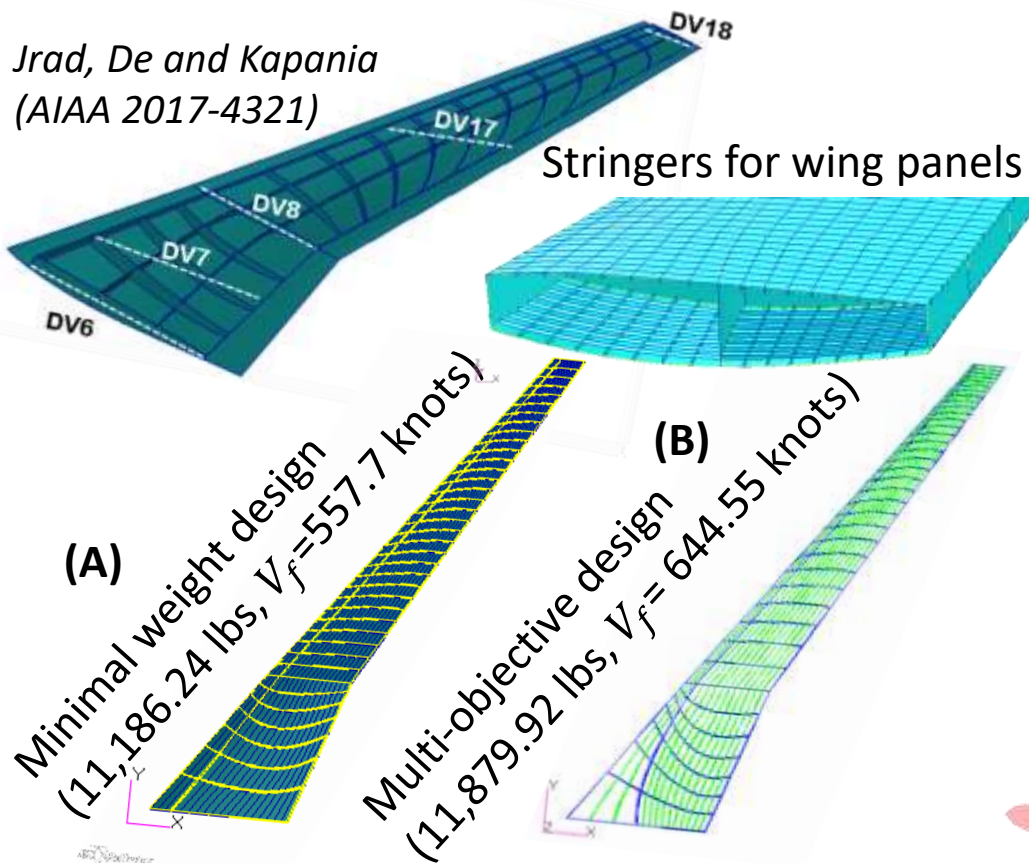
Zhao, Singh and Kapania (2018)

VA Tech – SpaRibs : Optimization of Entire Wing Box



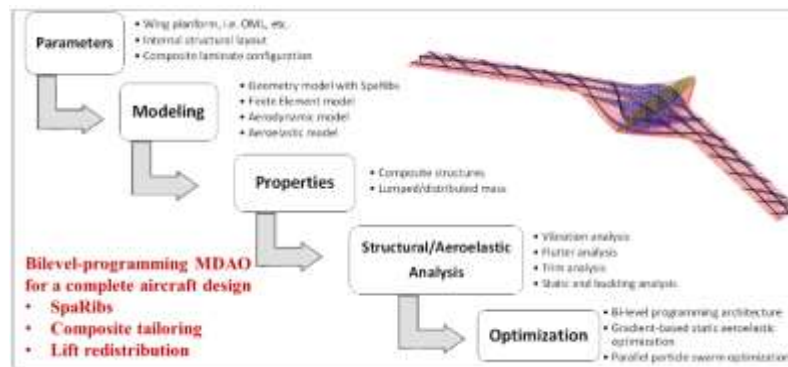
CRM weight minimization and flutter speed maximization with SpaRibs

Jrad, De and Kapania
(AIAA 2017-4321)

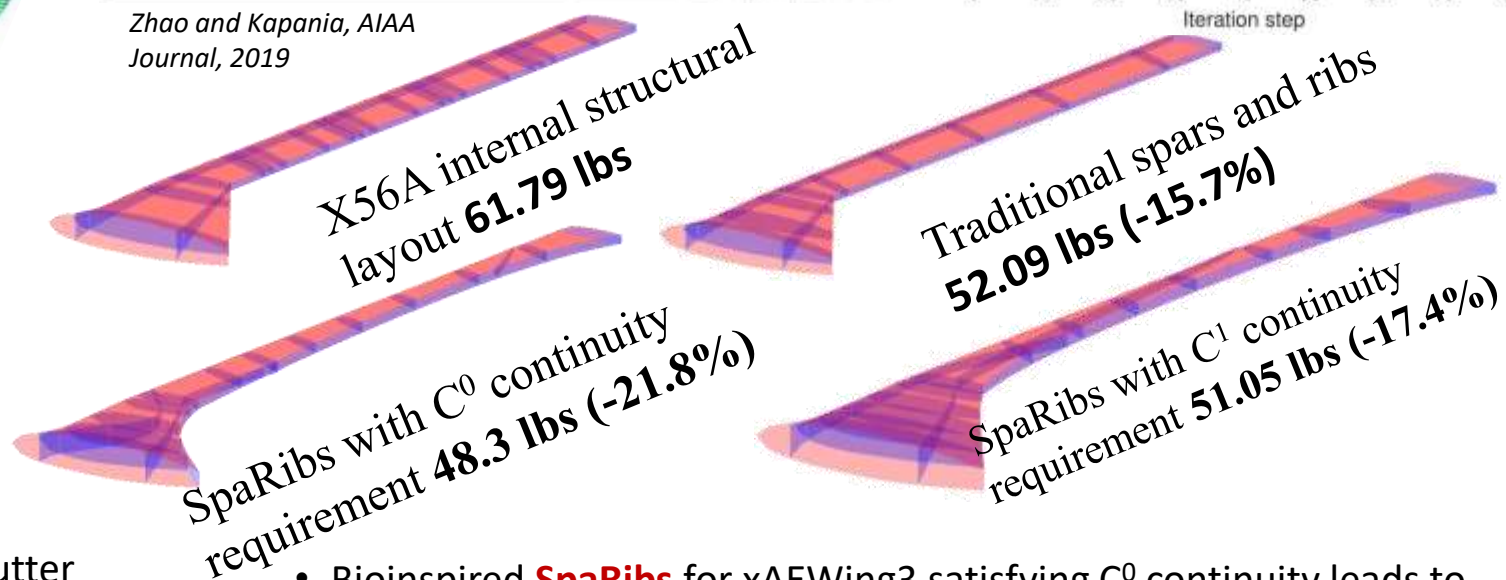
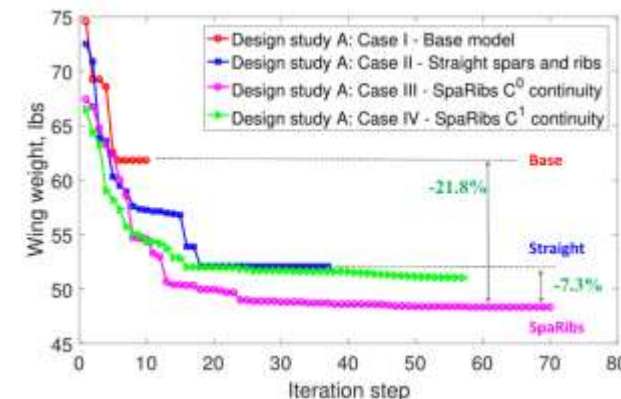


- +6.2% weight penalty and +15.6% improvement in flutter speed as compared to Design A

Weight minimization of a complete flexible flying-wing test article for use in the NASA performance adaptive aeroelastic wing program



Zhao and Kapania, AIAA
Journal, 2019



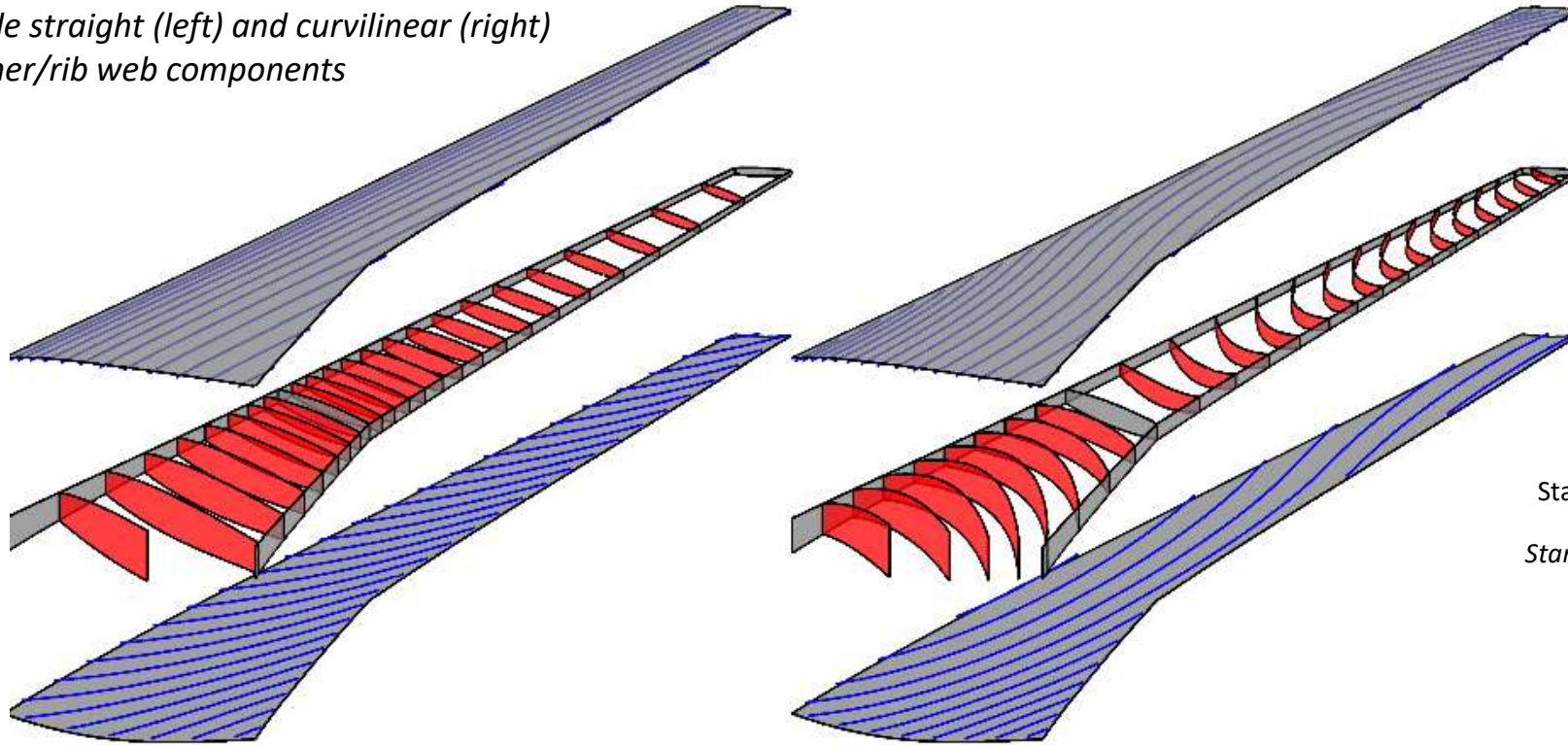
- Bioinspired **SpaRibs** for xAEWing3 satisfying C^0 continuity leads to **21.8% weight** reduction as compared to the base model, and **7.3%** weight reduction as compared to the wing with straight spars & ribs

NASA – Aeroelastic Structural Tailoring Key Contributors



- **Bret Stanford**, NASA Langley
- **Christine Jutte**, Craig Technologies, Inc.
- **Jim Moore**, NASA Langley
- **Carol Wieseman**, NASA Langley
- **Christian Coker**, Graduate Research Assistant, MS State Univ.
- **Peter Dunning**, Lecturer, School of Engineering, Univ. of Aberdeen, UK

*Sample straight (left) and curvilinear (right)
stiffener/rib web components*



Stanford, B., *J. Aircraft*, 2018.

Stanford, B., Jutte, C., Coker, C.,
AIAA J. 2019.

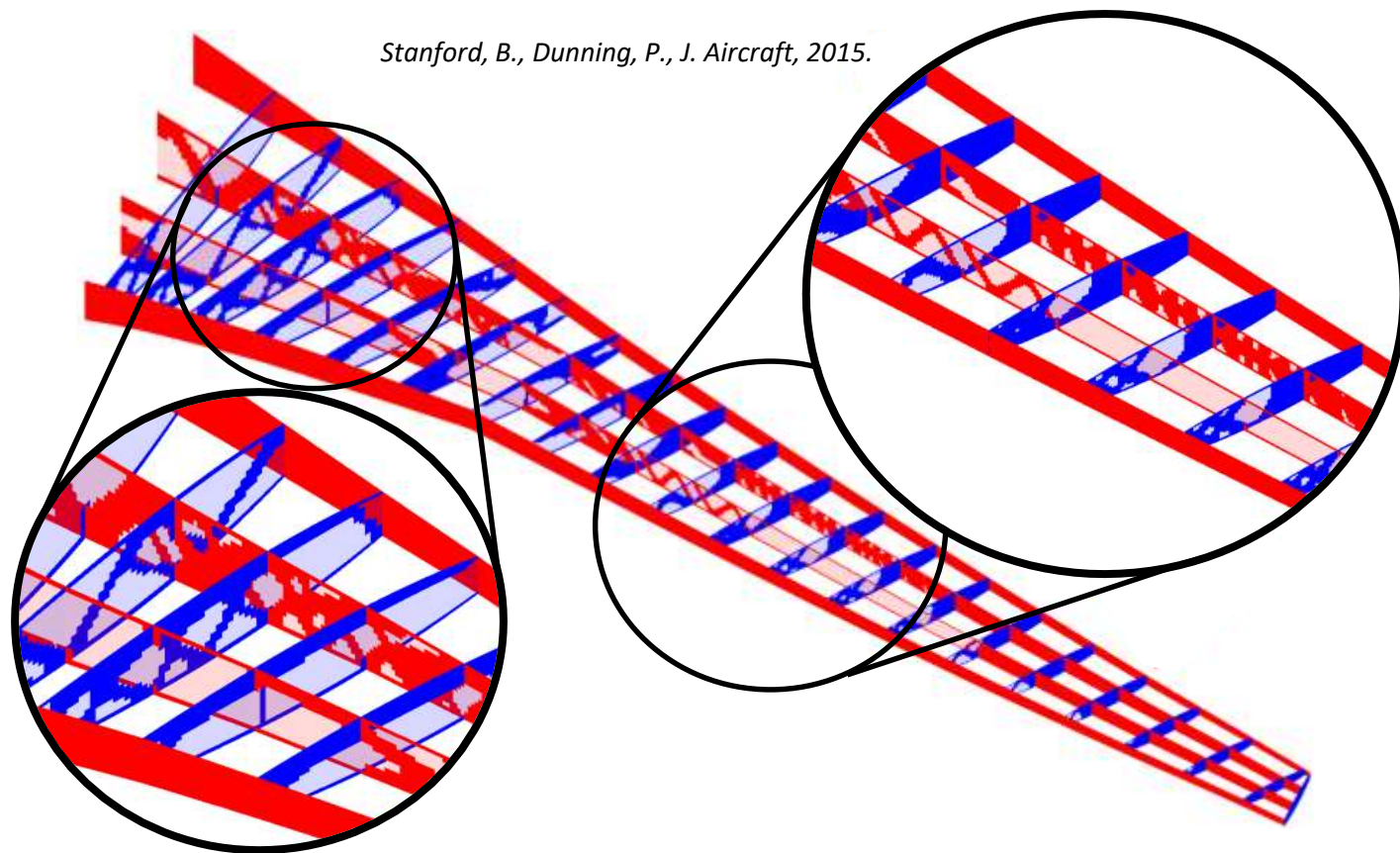
- Introduction of curvilinear ribs and stiffeners in wingbox (all-aluminum)
 - Topology is optimized with straight ribs and stiffeners to minimize mass
 - Increase design variables to compute optimal location, orientation, spacing, curvilinearity of ribs and stringers
 - Optimize component sizing simultaneously: challenging mixed integer/continuous optimization problem
- 1.2% reduction in wing mass compared to straight rib baseline

NASA – Rib/Spar Lightning Holes



- Independent load cases used topology optimization within ribs and spars to locate the best position of lightning holes, truss/cross-bracing, etc.
- Static aeroelastic metrics included: elastic wing compliance under trim loads and taxi loads, stress distribution, and crushing loads
- Dynamic aeroelastic metrics included: aileron effectiveness under a constant roll rate, natural vibration frequency and flutter
- Determines relationship between topology and aeroelasticity in subsonic transport wings to aid in complex designs considering simultaneous load cases

Stanford, B., Dunning, P., J. Aircraft, 2015.



Topology optimization within ribs and spars enables structural optimization at equivalent weight, or weight optimization at equivalent load performance

GA Tech – Wing Through-Thickness Topology Optimization



Problem

Traditional manufacturing techniques limit the material placement and configuration in the wingbox interior. If new manufacturing techniques such as additive manufacturing removed these constraints, what would be the optimal through-thickness topology for a wing?

Objective

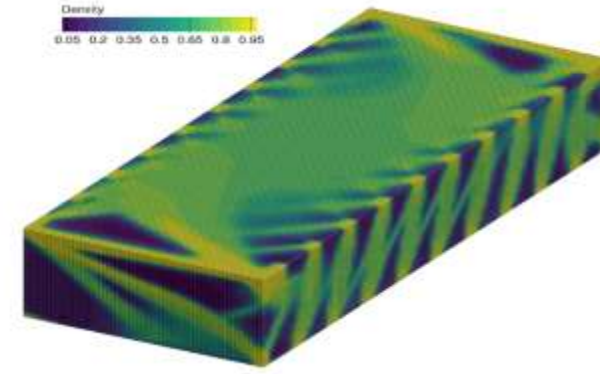
Optimize, fabricate via additive manufacturing, and test a scaled wingbox which employs a novel through-thickness topology which reduces wingbox weight and/or improves static or dynamic aeroelastic performance.

Approach

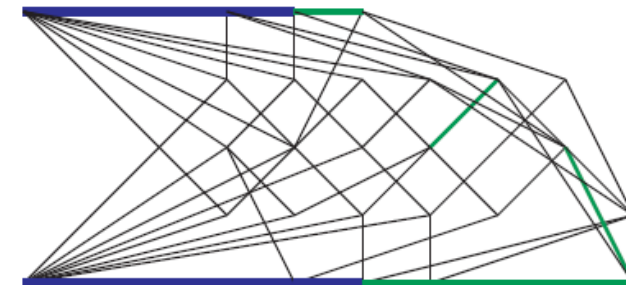
The wingbox interior material placement is optimized using either 1) a through-thickness topology approach or 2) a truss-like ground structure optimization approach.

Significance

As additive manufacturing technologies mature and scale, new topologies which may be a significant departure from the traditional rib-string approach may provide a cost-effective weight or performance benefit to high-aspect ratio wings.



Volumetric Through-Thickness Optimization

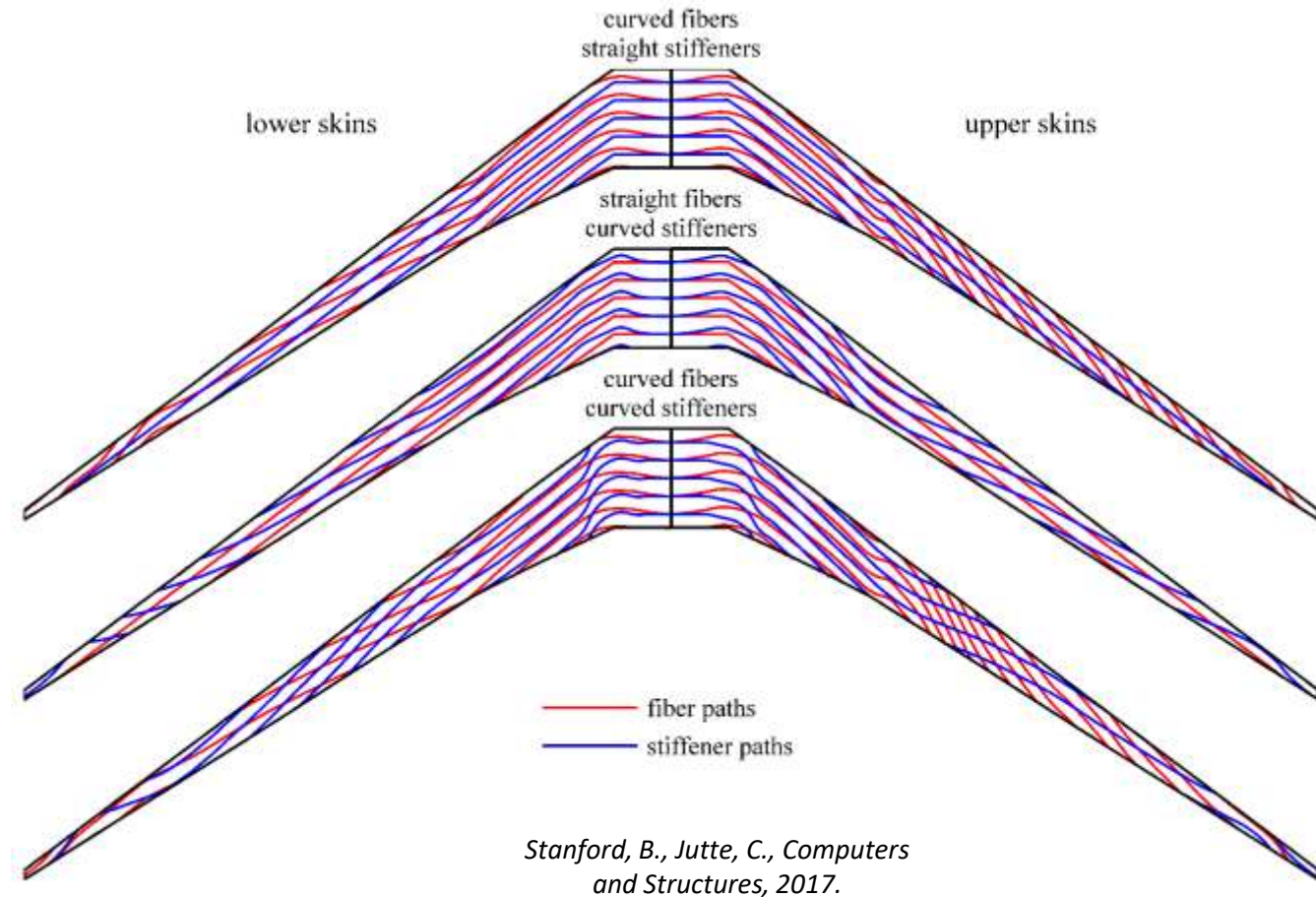
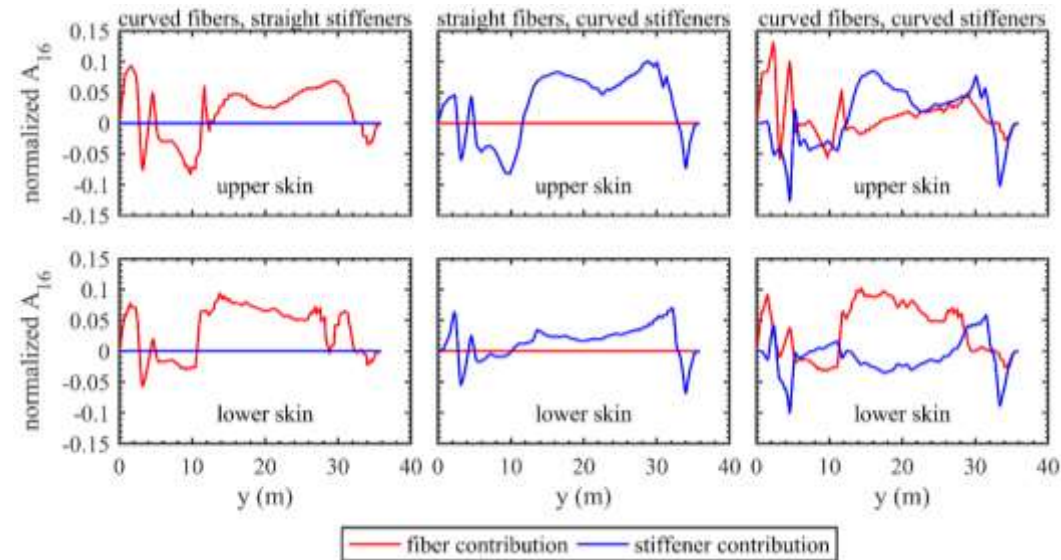


Ground Structure Optimization Approach

NASA – Tow-Steered Composites + Curvilinear Stiffeners



Design	Structural Mass	% Drop
straight stiffeners and straight fibers	15,036 kg	-
straight stiffeners and curved fibers	13,700 kg	8.8%
curved stiffeners and straight fibers	13,751 kg	8.5%
curved stiffeners and curved fibers	13,323 kg	11.4%



Stanford, B., Jutte, C., *Computers and Structures*, 2017.

- Assessment of impact of combining curvilinear stiffeners and tow-steered composite skins to reduce weight while passively controlling aeroelastic performance
- 8.8-11.4% reduction in wing mass compared to straight stiffener/straight fiber baseline

UMich – Aero-structural Optimization Key Contributors



- **Joaquim Martins**, Professor, Aerospace Engineering at Univ. of Michigan
- **Tim Brooks**, Aurora Flight Sciences
- **Gaetan Kenway**, NASA ARC
- **Graeme Kennedy**, Assistant Professor, Aerospace Engineering at GA Tech
- **Carlos Cesnik**, Clarence "Kelly" Johnson Professor, Professor and Director, Active Aeroelasticity and Structures Research Laboratory, Aerospace Engineering at Univ. of Michigan

UMich – High-fidelity Aeroelastic Optimization of Highly Flexible Wings



Problem

High-aspect ratio wings require a much tighter coupling between aerodynamic and structural analysis and design.

Objective

Further develop tools for high-fidelity aerostructural design optimization to include buffet constraints, and to create publicly available aerostructural models.

Approach

RANS CFD is coupled to a detailed wingbox FEM, and structural sizing is optimized simultaneously with aerodynamic shape to minimize fuel burn.

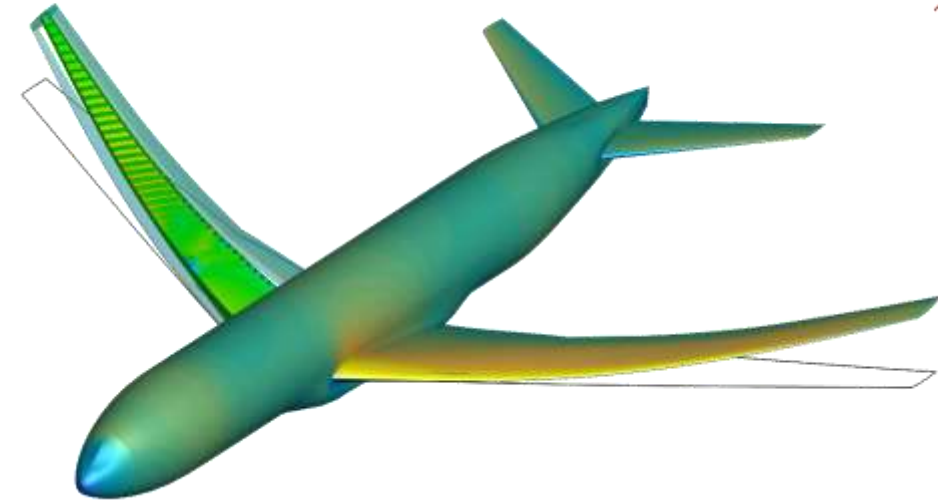
Results

Two models have been created (uCRM-9 and uCRM-13.5). High-fidelity aerostructural optimization successfully applied to both designs while enforcing buffet constraints.

Significance

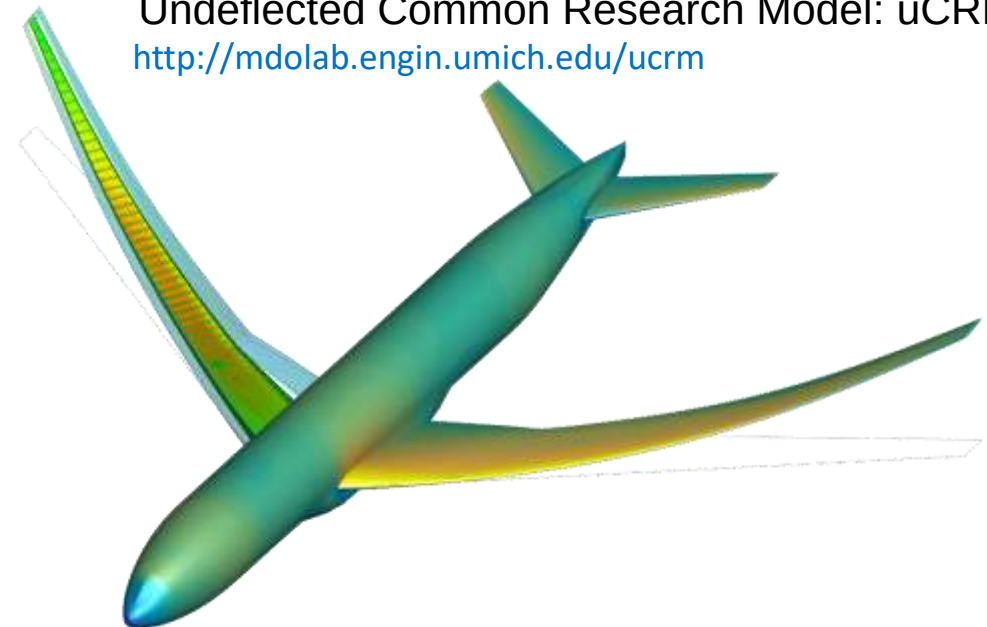
Newly developed high-fidelity aerostructural optimization tools are being used to optimally leverage new technologies such as morphing trailing edge and tow-steered composites.

Brooks, Kenway, Martins. Benchmark aerostructural models for the study of transonic aircraft wings. *AIAA Journal*, 2018.



Undeformed Common Research Model: uCRM-9

<http://mdolab.engin.umich.edu/ucrm>

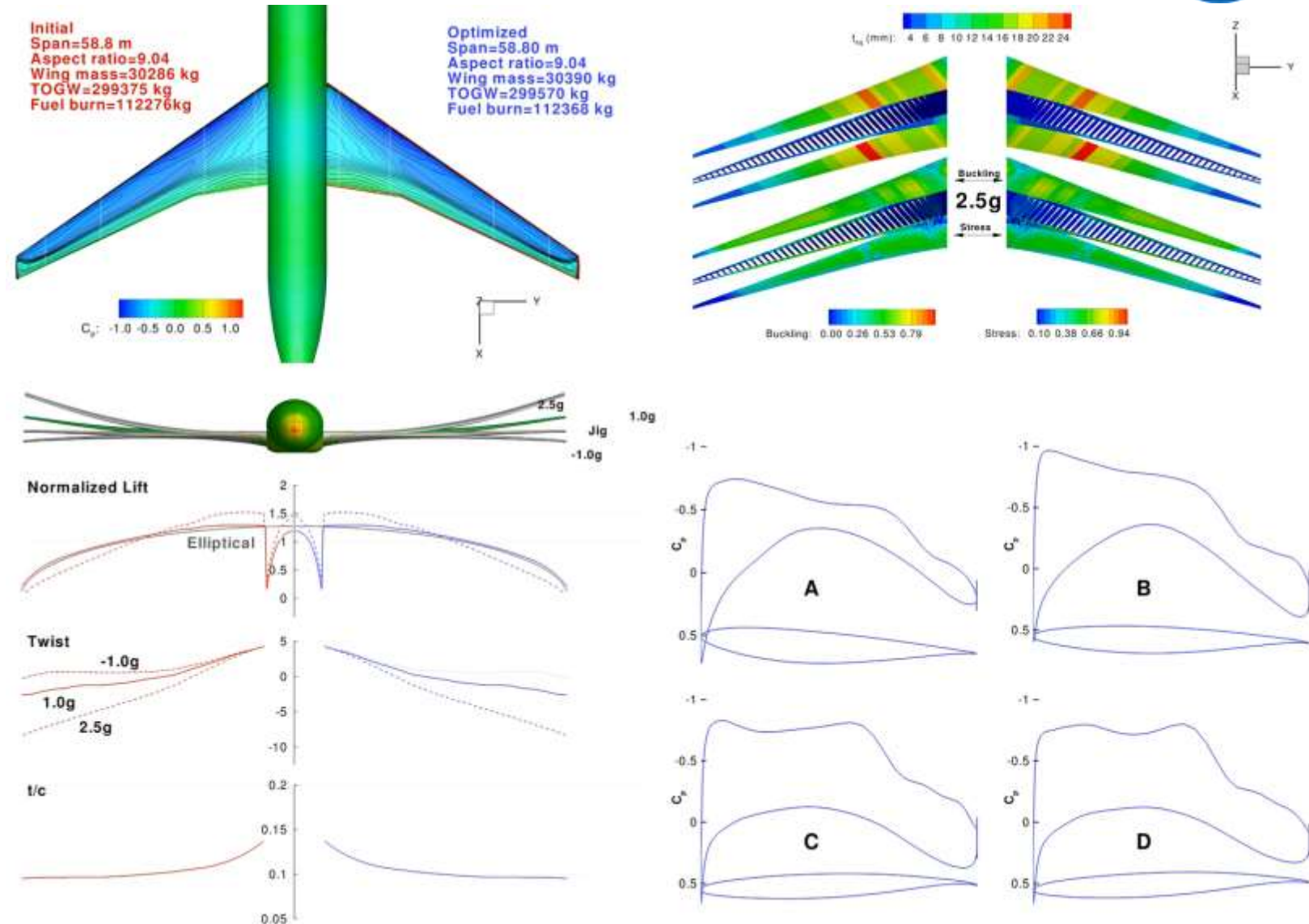


High AR undeformed Common Research Model: uCRM-13.5

UMich – High-fidelity Aeroelastic Optimization of Highly Flexible Wings



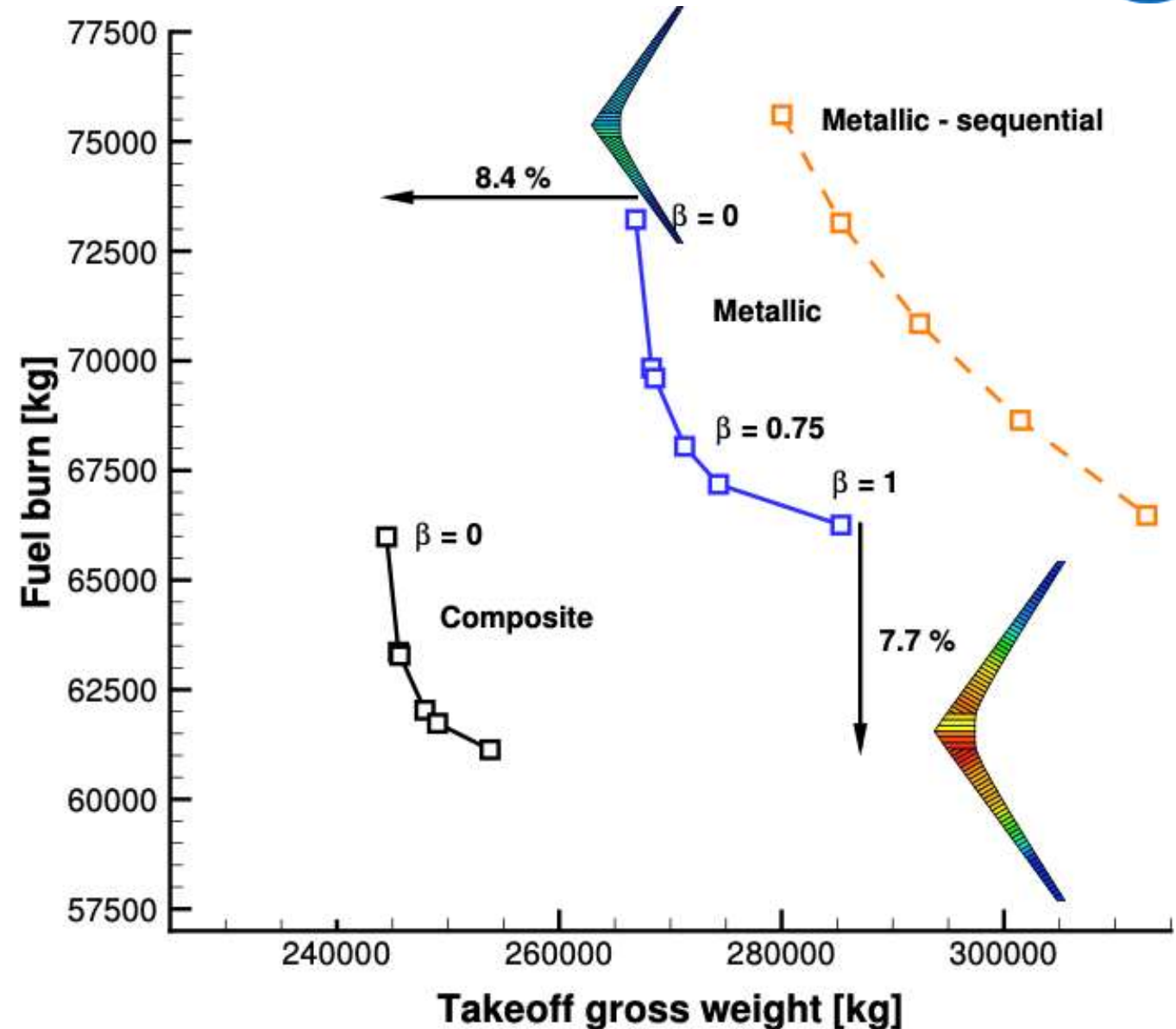
- MACH framework optimizes aerodynamic shape and structural sizing simultaneously
- Planform variables such as span and sweep also included
- Optimal planforms depend on the objective function
- Optimization with almost 1000 design variables takes 48 hours on 1000 processors



Kenway and Martins. Multipoint high-fidelity aerostructural optimization of a transport aircraft configuration. *Journal of Aircraft*, 2014



- MACH framework demonstrated the importance of concurrent aerostructural optimization as opposed to sequential optimization
- Provides a way to take advantage of new airframe technologies, setting the stage for the tow-steered wing studies



Kennedy, Kenway, and Martins. High aspect ratio wing design: Optimal aerostructural tradeoffs for the next generation of materials, AIAA SciTech, 2014

UMich – Tow-steered Wing Aerostructural Optimization



Problem

Tow-steered composite manufacturing provides more design freedom, but there is no experience on how to utilize it.

Objective

Further develop tools for high-fidelity aerostructural design optimization to design tow-steered composite wings with passive load alleviation.

Approach

Develop a new design parametrization and formulate manufacturing constraints within the high-fidelity aerostructural optimization framework (MACH).

Results

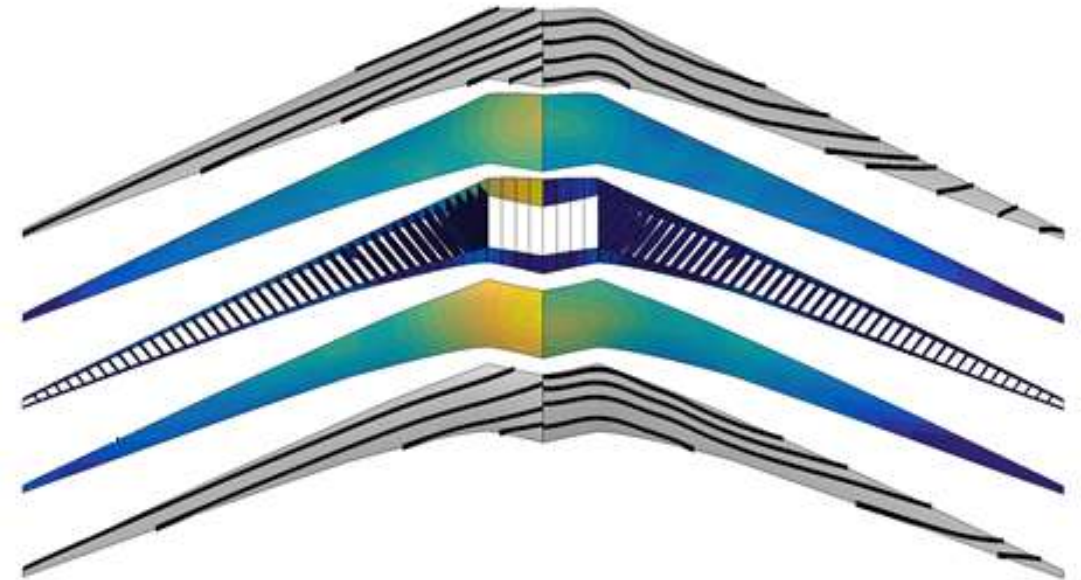
Produced a scaled high aspect ratio tow-steered wing design based on the uCRM-13.5 that was built and tested. Optimized a series of tow-steered wings for the full scale aircraft to explore the design space.

Significance

Newly developed tools enable the design of wings that utilize advanced tow-steered manufacturing in an optimal way.

Conventional Composite

Tow-Steered Composite



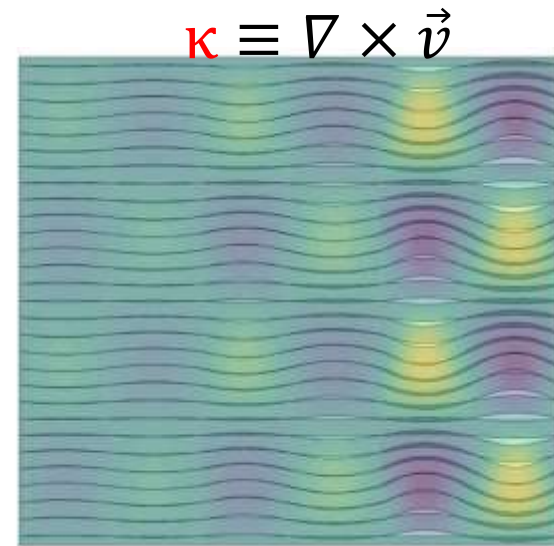
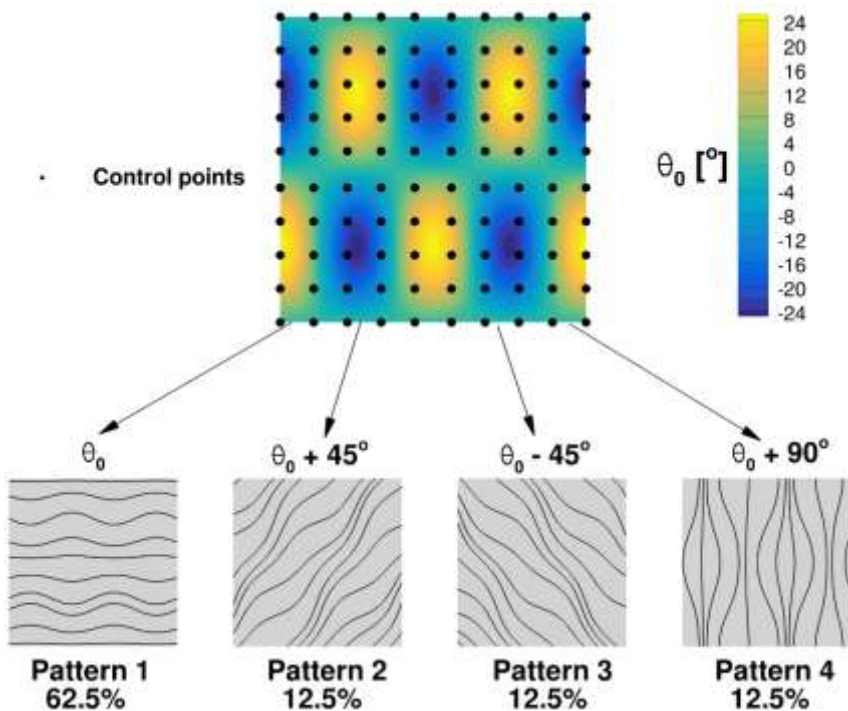
Brooks, Martins, and Kennedy. High-fidelity aerostructural optimization of tow-steered composite wings. *Journal of Fluids and Structures*, 2019.

Image credit (entire slide): Univ. of Mich.19

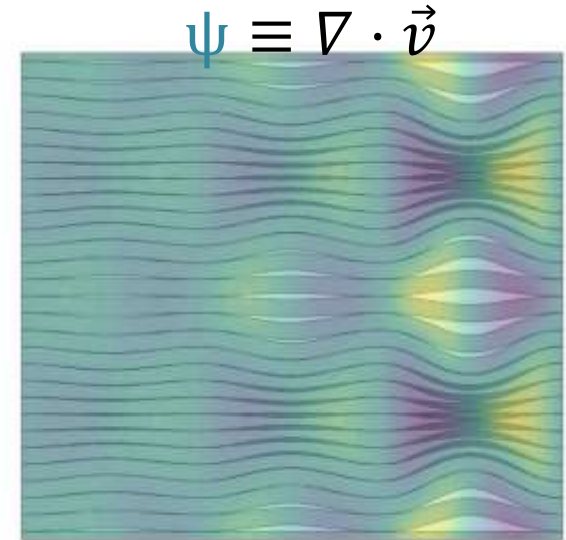
UMich – Tow-steered Wing Aerostructural Optimization with Manufacturing Constraints



- Developed parametrization for tow-steered composites
- Developed turning radius and cut length constraints for manufacturability



$$-\frac{1}{R_{\min}} \leq \kappa \leq \frac{1}{R_{\min}}$$



$$-\frac{\ln\left(\frac{a_o + 1}{2(a_g - 1)}\right)}{L_{\text{cut}}} \leq \psi \leq \frac{\ln\left(\frac{a_o + 1}{2(a_g - 1)}\right)}{L_{\text{cut}}}$$

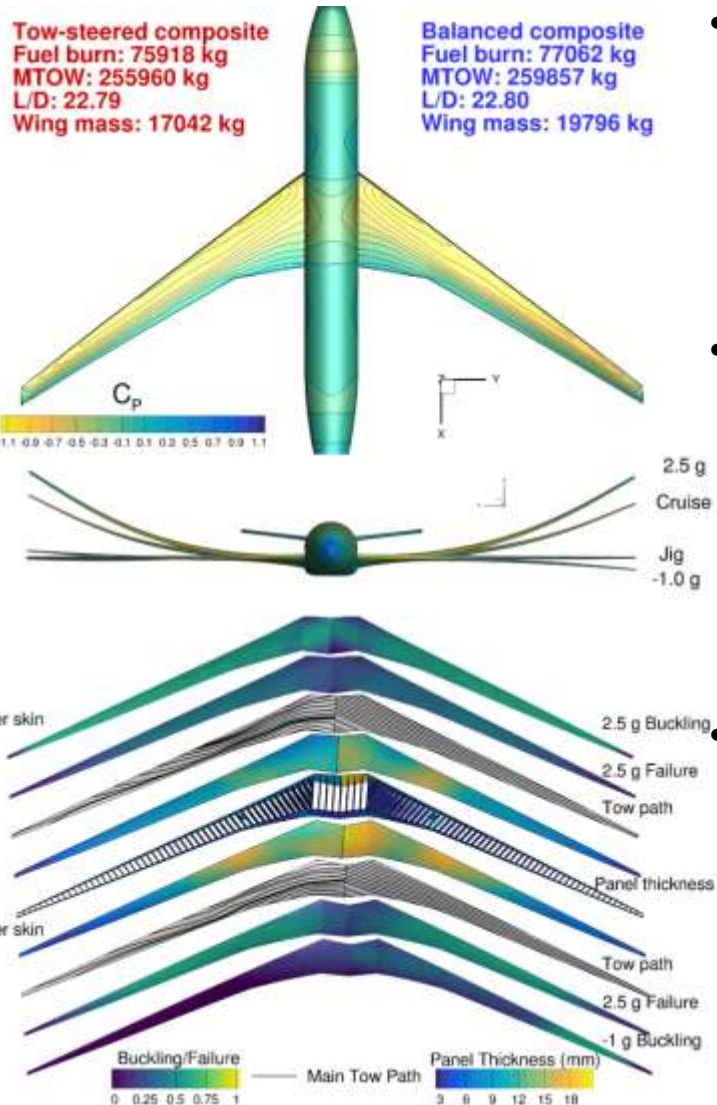
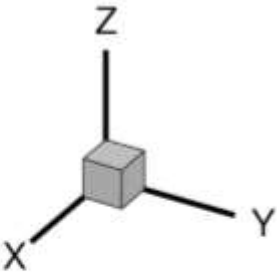
Brooks and Martins. On manufacturing constraints for tow-steered composite design optimization. *Composite Structures*, 2018.

Passive Aeroelastic Tailored Wing Test Key Contributors



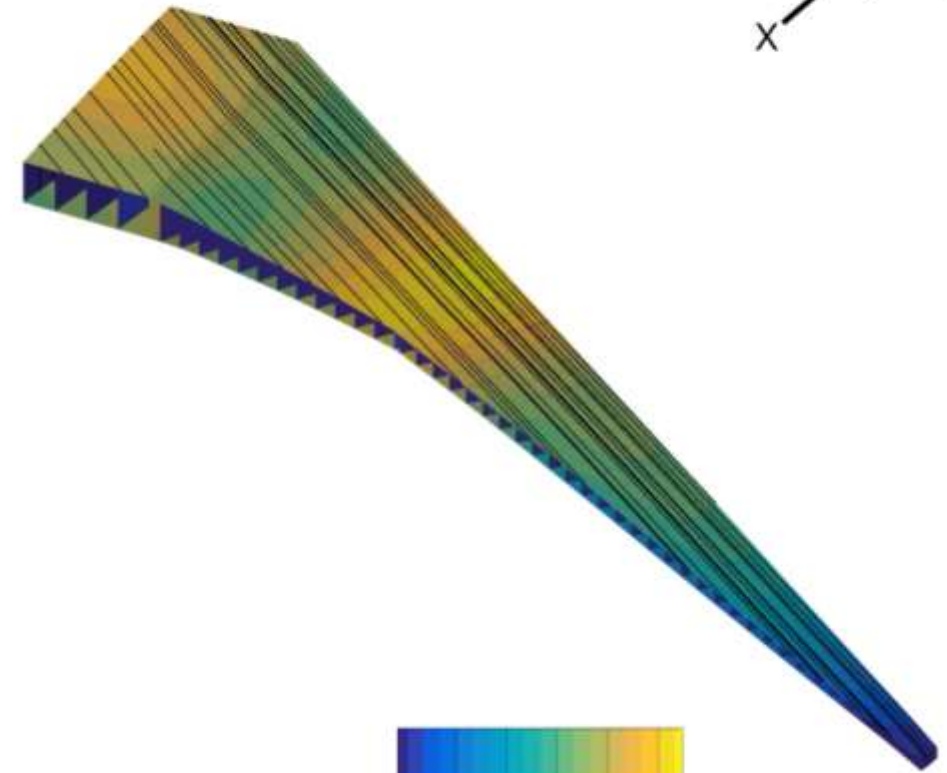
- Advanced Air Transport Technology Project NASA
- Aurora Flight Systems
 - Ben Smith, Larry Wirsing
- University of Michigan
 - Quim Martins, Tim Brooks, Carlos Cesnik, Christopher Lupp
- NASA Armstrong Flight Research Center
 - Larry Hudson, Natalie Spivey, Eric Miller, Frank Pena, Andrew Holguin, and test support crew
- NASA Langley
 - Karen Taminger, Carol Wieseman, Andrew Lovejoy, Christine Jutte, Bret Stanford, Dawn Jegley, Ray Grenoble
- ATA Engineering
 - Kevin Napolitano

UMich - Tow-steered Wing Aerostructural Optimization



- Leveraged MACH framework and uCRM to:
 - Design the test article
 - Perform studies on full scale aircraft with variable planform
- Tow-steered designs achieved better performance than conventional composite ones:
 - Up to 2% in fuel savings
 - Up to 24% reduction in wing weight
- Improvements due to:
 - Structural tailoring to increase local strength-to-weight ratio
 - Aeroelastic tailoring taking advantage of passive load alleviation

Iteration: 0



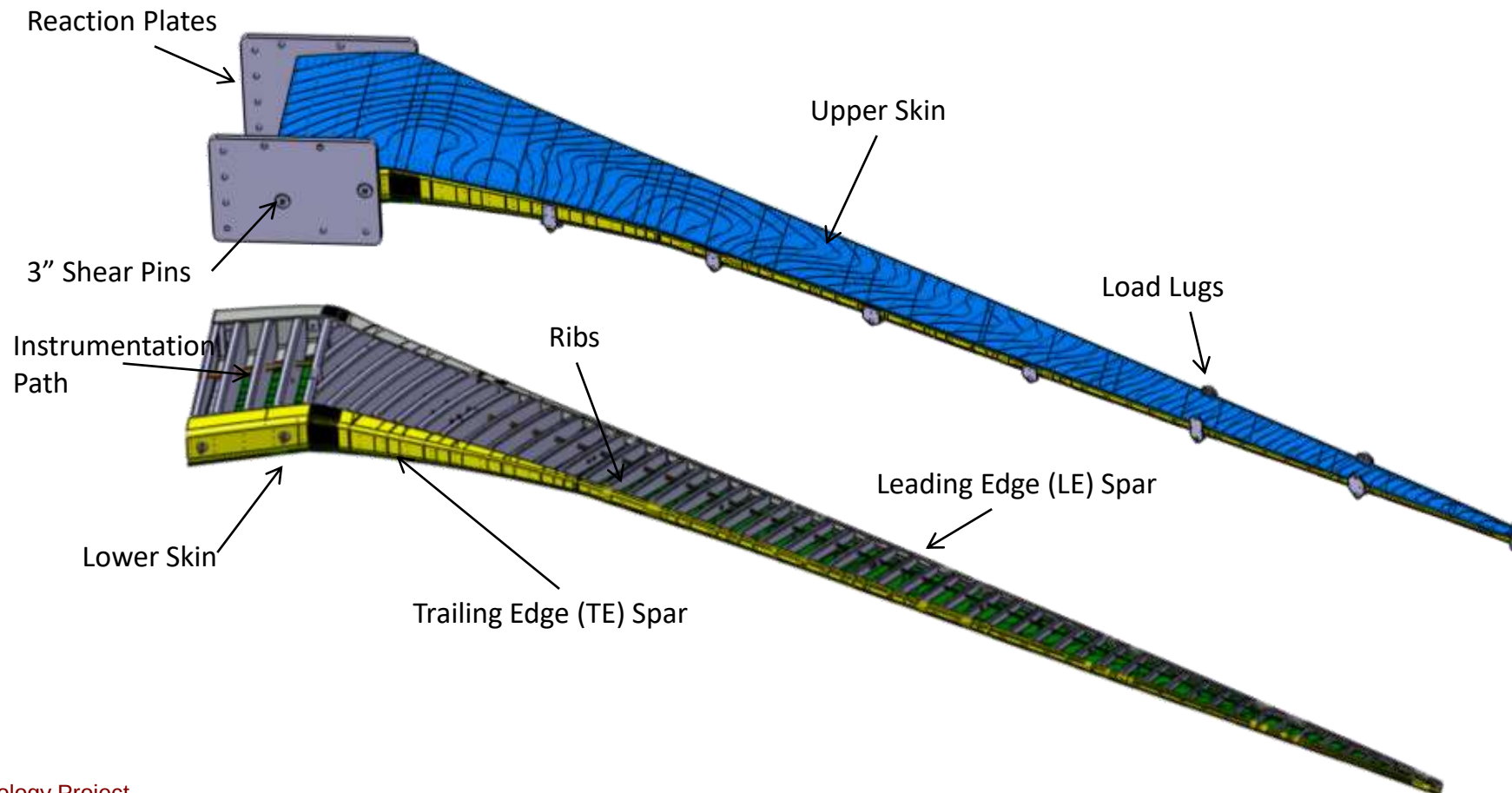
Aurora – PATW Test Article Design Overview



2 Skins
2 Spars
58 Ribs

14 load lugs
2 reaction plates
12 instrumented ribs

>3400 fasteners
~900 lb before mounting hardware



Aurora – PATW Upper Skin AFP Layup (Tow-steering)



Automated Fiber Placement (AFP)
Tow-Steering for Aeroelastic Tailoring
uCRM-13.5 27% Scaled Test Article Wing Skins

October 2016

© 2016 Aurora Flight Sciences Corporation. All Rights Reserved.

Video of Aurora AFP fabrication with tow-steering of PATW upper skin

NASA – PATW Ground Vibration Test (GVT) Set-up



- 3 configurations:
 - 10, 12, or 14 shakers/load cells
 - 10 seismic accels (drive points) / 270 Accelerometers
- True random input
 - Flexibility in signal processing
- Used Fixed Base Correction (FBC) method for boundary conditions
 - Tested physical boundary conditions (dynamically active) for data corrections
- GVT Test goal = extract all fixed base modes through first torsion mode (near 55 Hz)



NASA – PAT Wing GVT Test Results

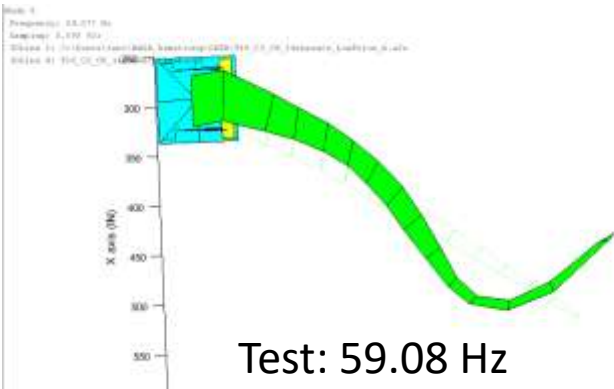


- Configuration 3 (14 shakers)
- FEM assumes everything but wing is fixed
- Fixed Base Correction method measured boundary conditions during GVT
- Test results correlated within 6% or better for 11 of 12 modes with FEM analysis

Test Self MAC Table												
Test Shapes												
Test Shapes	1	2	3	4	5	6	7	8	9	10	11	12
	3.48	10.05	11.02	21.22	30.15	35.23	52.20	56.67	59.08	77.40	98.45	#####
1	3.48	100	30	13	6							
2	10.05	30	100	37	12							
3	11.02			100	33				8		8	
4	21.22	13	37		100	35	9					
5	30.15			33		100			37		8	
6	35.23	6	12		35		100	25		5		
7	52.20				9		25	100		22		8
8	56.67							100			8	
9	59.08			8		37			100			
10	77.40					5	22			100		21
11	98.45			8		8		8			100	
12	106.17						8			21		100

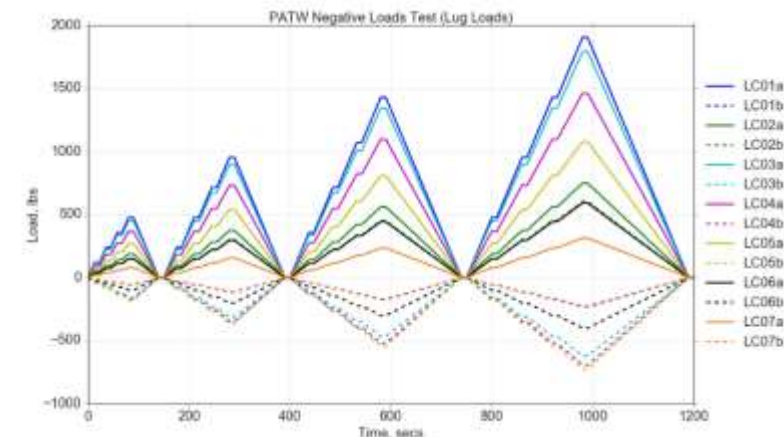
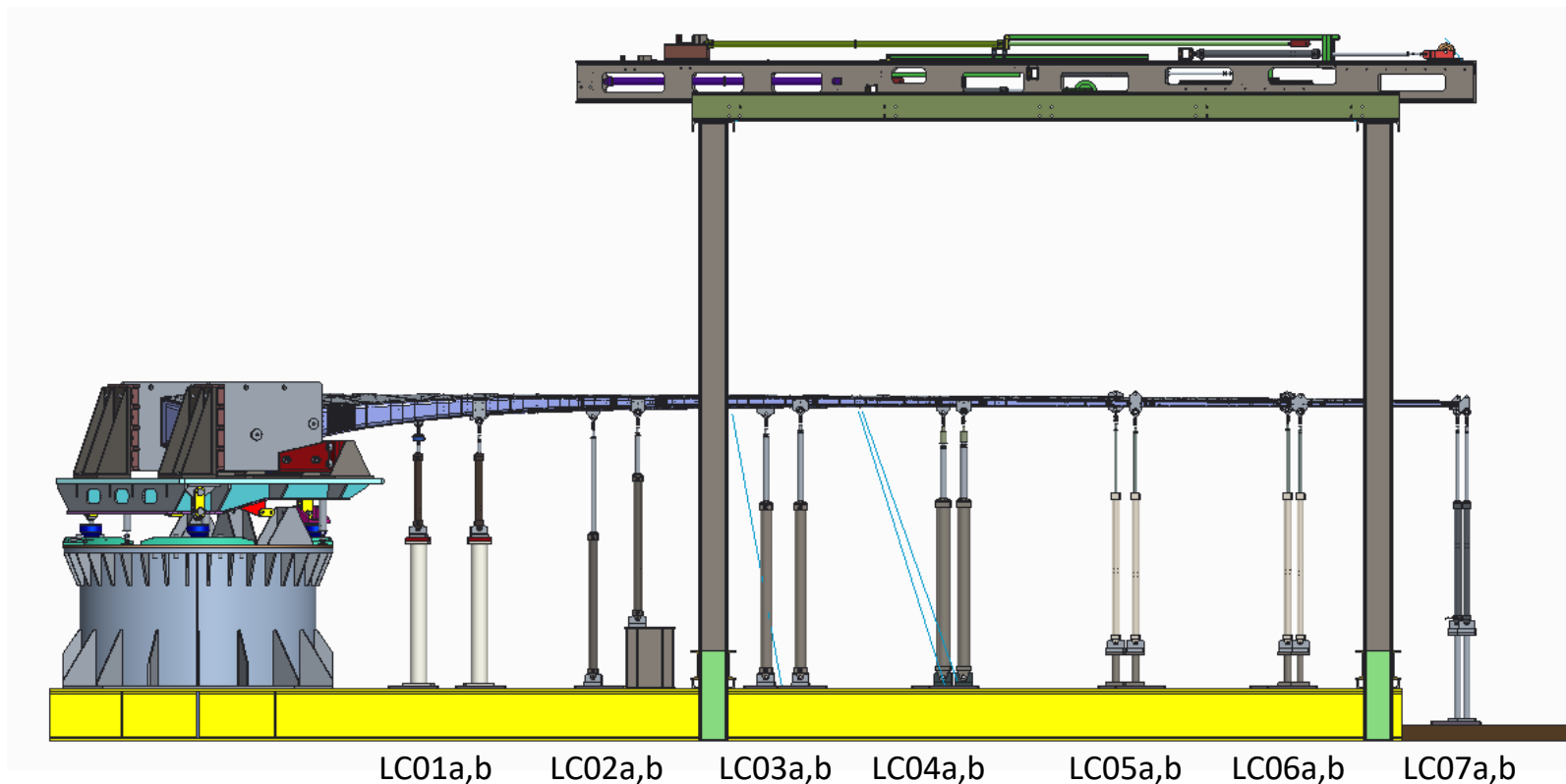
FEM/Test Cross MAC Table												
FEM Shapes												
Test Shapes	1	2	3	4	5	6	7	8	9	10	11	12
	3.39	10.45	11.35	22.64	31.98	37.46	51.94	55.54	65.92	77.43	93.69	102.17
1	3.48	99	29									
2	10.05	31	98		40							
3	11.02			97		26						
4	21.22		35		99		41					
5	30.15			41		96			25			
6	35.23				31		96		20			
7	52.20					20	62	29		22		
8	56.67						42	57				
9	59.08				46				79			
10	77.40									83		22
11	98.45										95	
12	106.17											74
CRSS	3%	99	99	98	99	98	98	79	75	89	91	97
CRSS	All	100	100	100	100	99	99	100	99	96	96	99

Test Mode No.	FEM Mode No.	Test Freq (Hz)	FEM Freq (Hz)	Freq Pct Diff	Cross Ortho	CRS XOrtho 3%	CRS XOrtho All
1	1	3.48	3.39	-2.4	99	99	100
2	2	10.05	10.45	4.0	98	99	100
3	3	11.02	11.35	3.0	97	98	100
4	4	21.22	22.64	6.7	99	99	100
5	5	30.15	31.98	6.1	96	98	100
6	6	35.23	37.46	6.3	96	98	100
7	7	52.20	51.94	-0.5	62	79	100
8	8	56.67	55.54	-2.0	57	75	100
9	9	59.08	65.92	11.6	79	89	99
10	10	77.40	77.43	0.0	83	91	99
11	11	98.45	93.69	-4.8	95	97	100
12	12	106.17	102.17	-3.8	74	86	99



Test: 59.08 Hz
Fore-Aft mode, Pin joint slip

NASA – Static Load, -1g Test Configuration

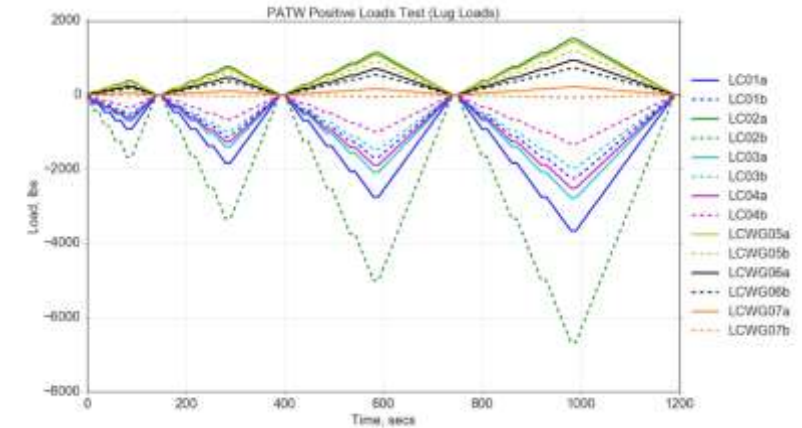
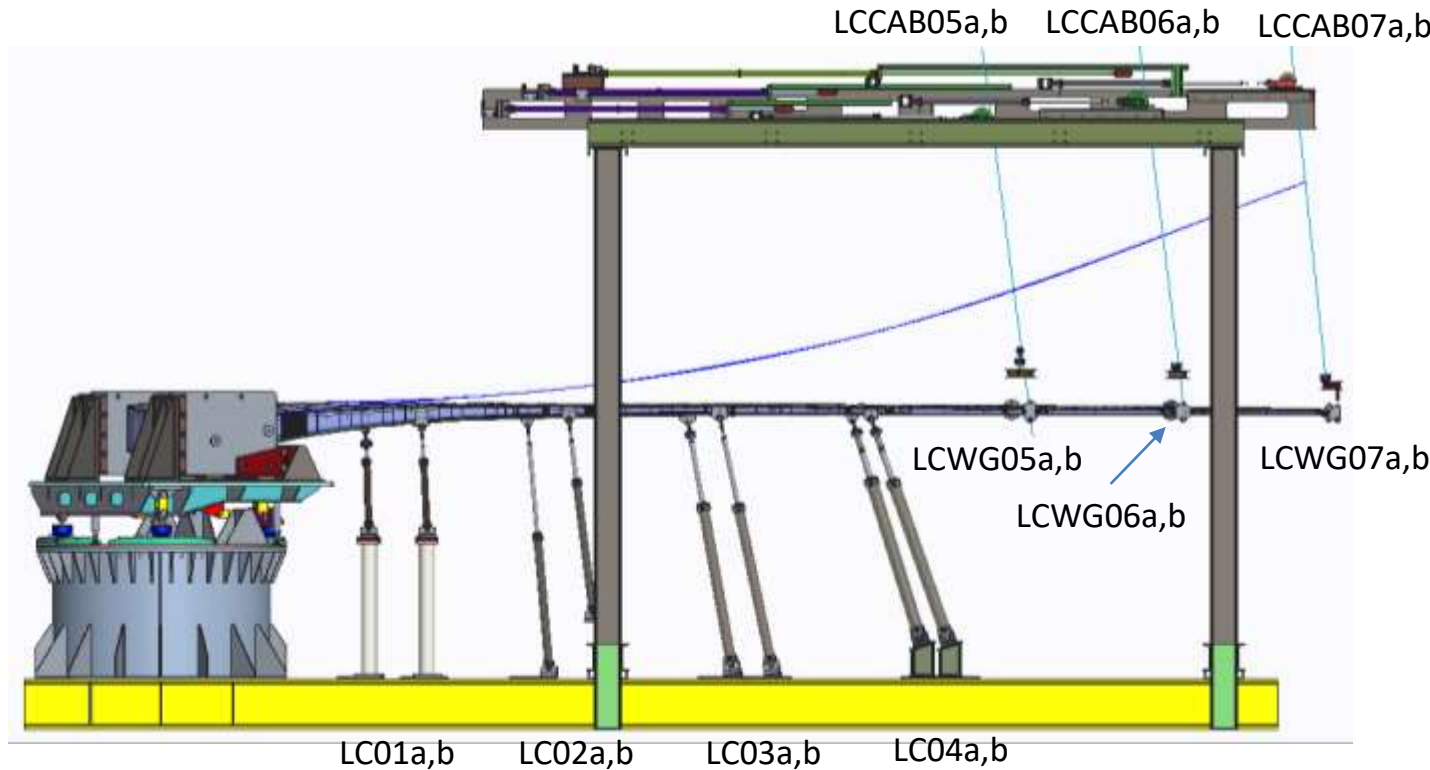


Negative Loads – Actuator is in Compression

Positive Loads – Actuator is in Tension

- For -1g static load test, all 14 actuators attached from underneath wing
- Distributed loads simulated in-flight load predictions
- Test was incrementally loaded and unloaded in 4 increments ramping up to maximum test load

NASA – Static Load, +1g, +2.5g Test Configuration

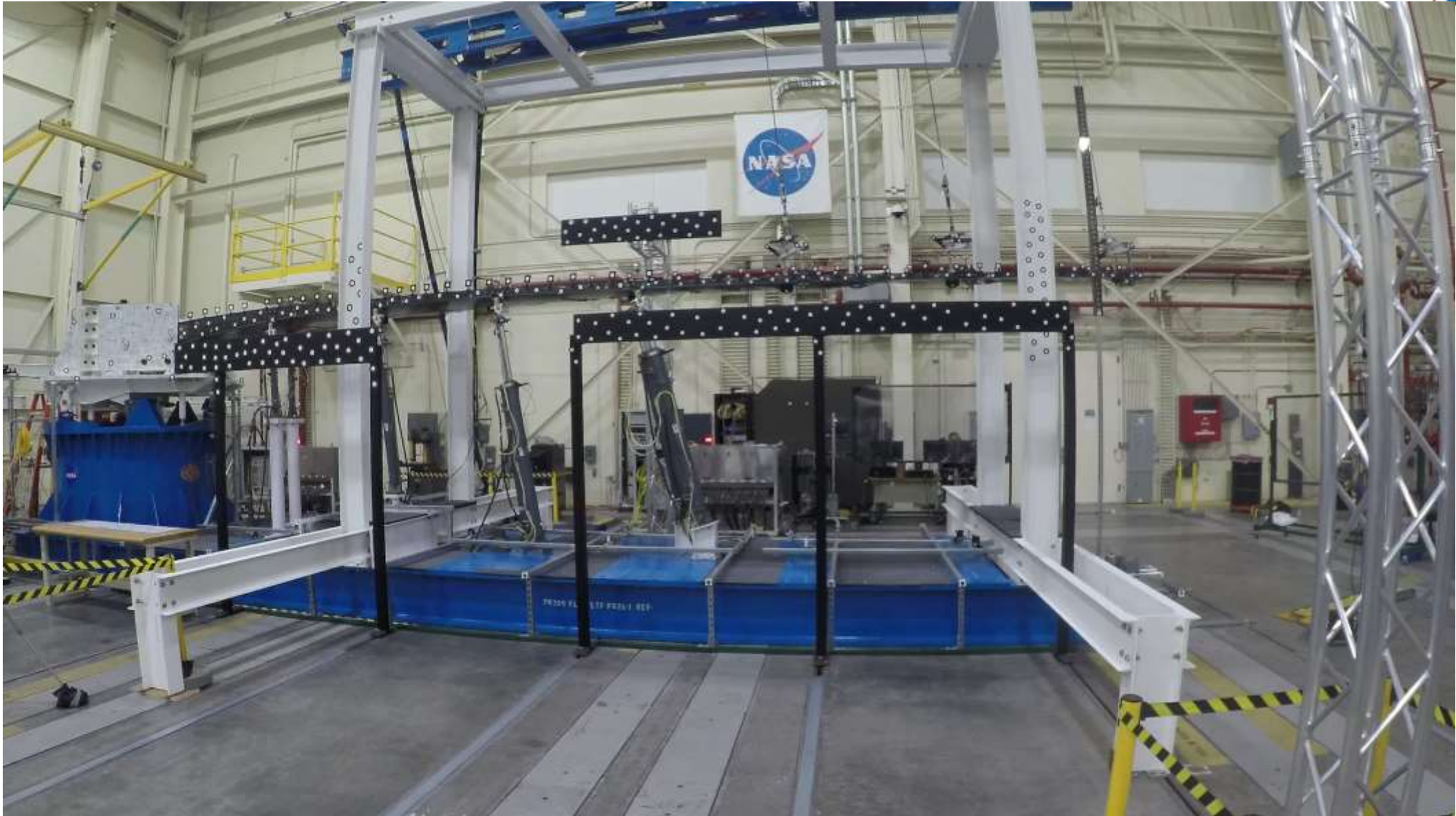


Negative Loads – Actuator is in Compression

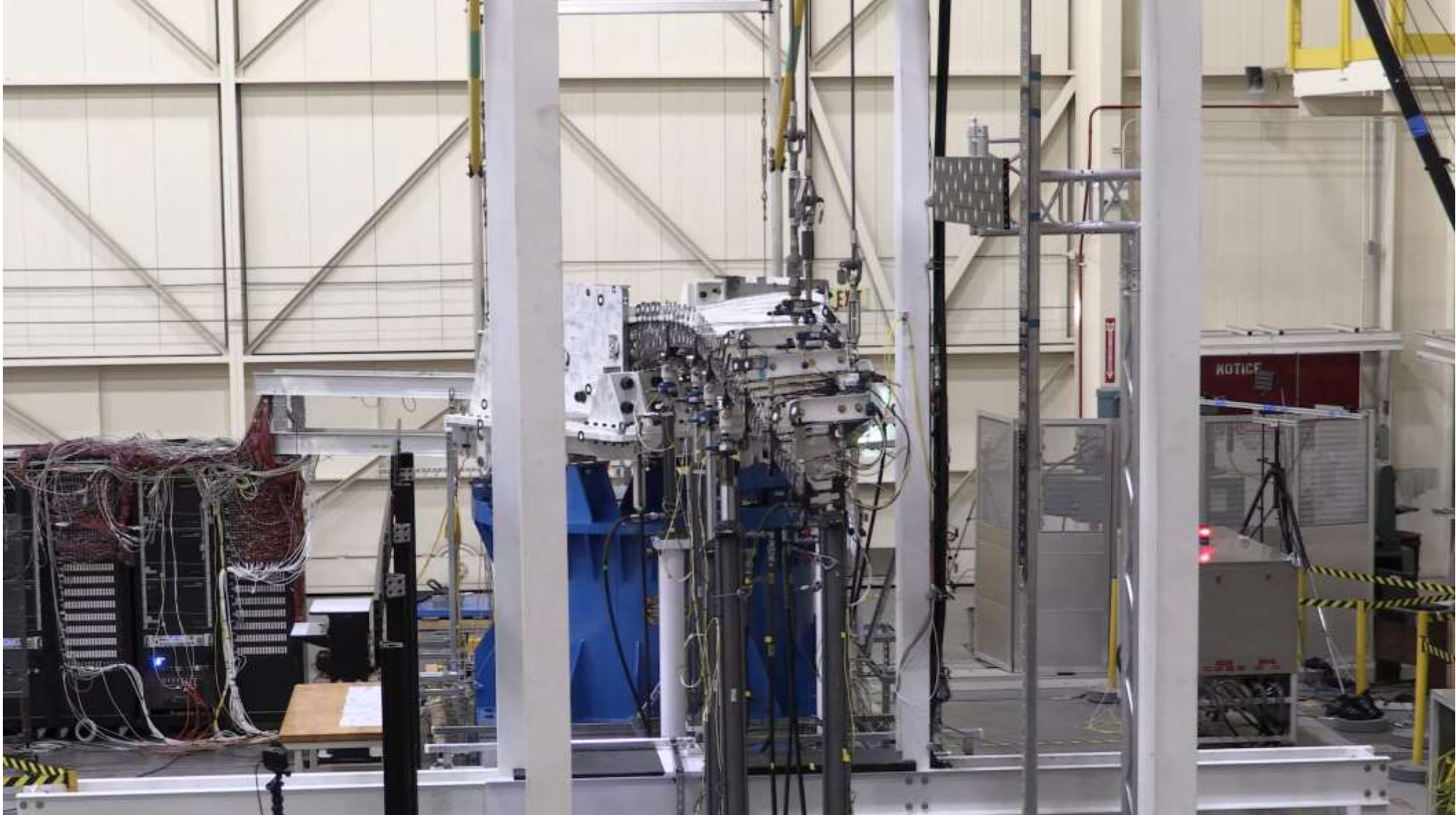
Positive Loads – Actuator is in Tension

- For +1g and +2.5g static load tests, inboard 8 actuators attached from underneath wing, outboard 6 actuators attached to cables with moving pulleys to accommodate high deflections
- Distributed loads simulated in-flight load predictions
- Test was incrementally loaded and unloaded in 4 increments ramping up to maximum test load

NASA – Front View of 50% Load Test, +2.5g Configuration



NASA – End View of 50% Load Test, +2.5g Configuration



Passive Aeroelastic Wing Test Results



- 39-ft. long wing test article is the largest variable steered test article ever designed, built, and tested
- Trends for strains, deformation, and flexural axis match closely between FEM and test article, validating the modeling approach for tow steering; we expect that the displacement and curvature discrepancies are due to boundary conditions and the modeling of non-tow-steering portions of the FEM (fasteners, liquid shim, wing depth from cover to cover, etc)
- Optimized tow steering offers structural weight reductions through both global load alleviation, such as bend-twist coupling, and also localized tailoring for buckling improvements (U of Michigan)
- Current comparisons between conventional and tow-steered fibers at an aspect ratio of 13.5 show a 14% reduction in wing box structural weight and a 1.5% reduction in fuel burn (U of Michigan)
- As the aspect ratio increases, tow steering offers diminishing returns with respect to load alleviation (U of Michigan), but critical flutter and gust constraints were not considered and are recommended for future comparisons

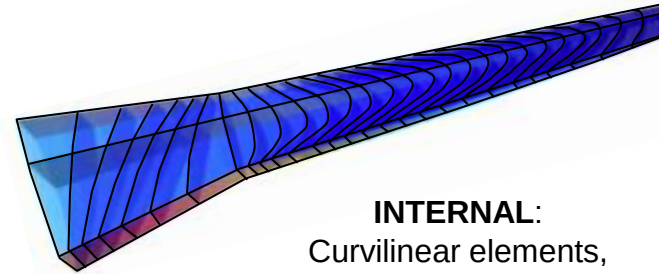
NASA – Aeroelastic Tailoring Research Thrusts



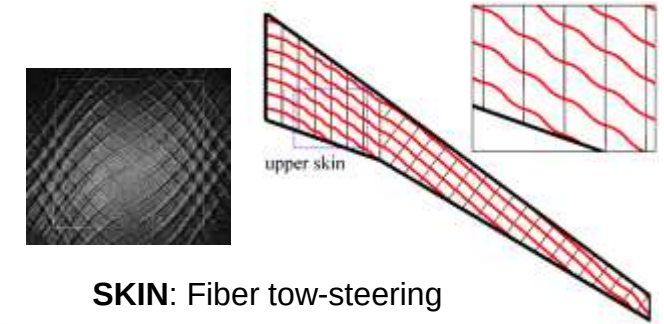
Objective: Explore and develop aerodynamic, structural, and control technologies to expand the optimal wing system drag vs. weight design trade space for reduced energy consumption. Enable a 1.5-2X increase in the aspect ratio of a lightweight wing with safe structures and flight control.

Passive aeroelastic tailoring

- Curvilinear stiffened internal structure
- Topology optimized internal structure
- Tow-steered composite skins



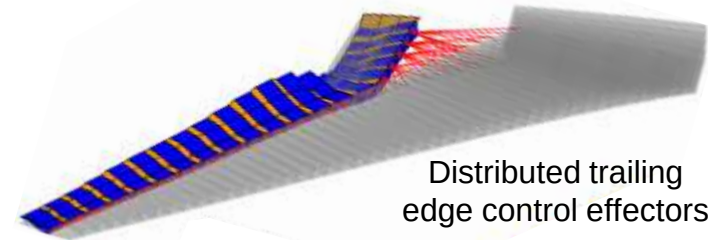
INTERNAL:
Curvilinear elements,
Topology optimization



SKIN: Fiber tow-steering

Active aeroelastic tailoring

- Novel control effectors, integrated sensors, and control laws
- Control of flexible wings demonstrating active maneuver load alleviation, gust load alleviation, off-design cruise drag reduction, and flutter suppression
- Flight and wind tunnel testing



Distributed trailing
edge control effectors

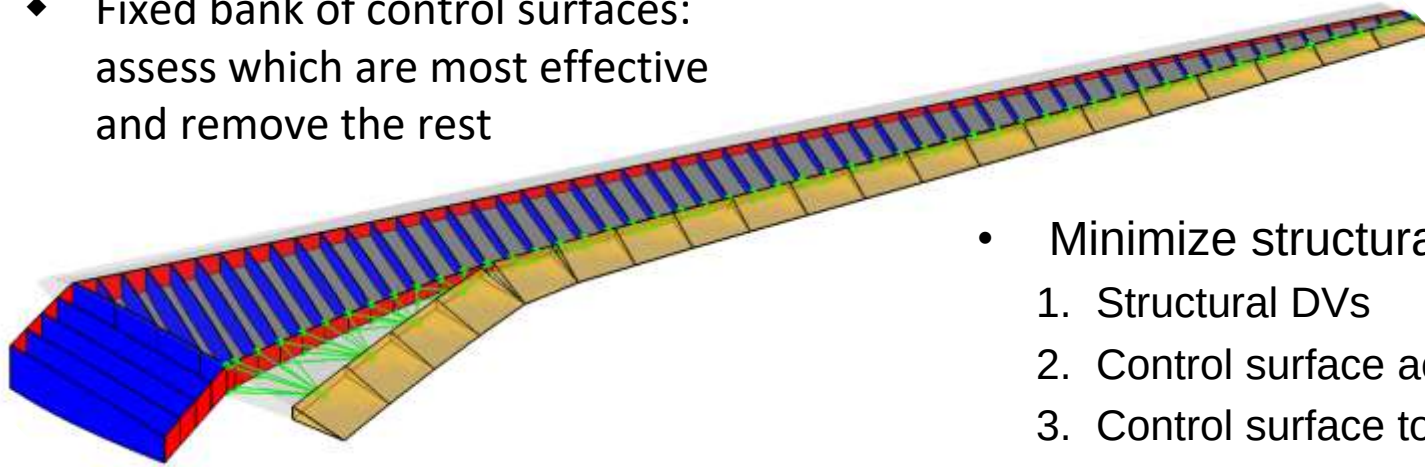


6 dof control of flexible wings

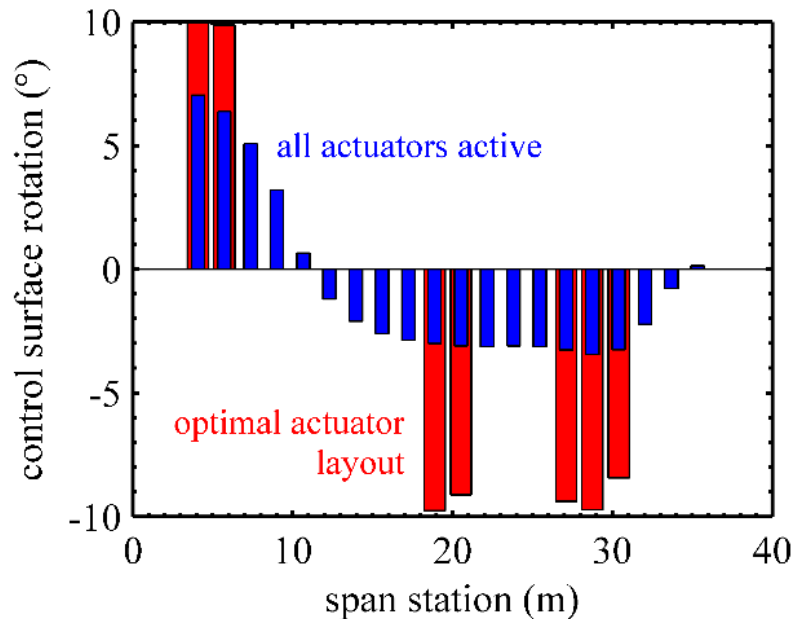


Wind tunnel testing (TDT) for ASE
control of flexible wings

- ◆ Fixed bank of control surfaces:
assess which are most effective
and remove the rest



- Minimize structural weight + actuator weight
 1. Structural DVs
 2. Control surface actuation DVs (QS + oscillatory)
 3. Control surface topology (0/1) DVs



Addition of control surface layout design variables:

- **69% reduction** in actuator mass
- **3.2% increase** in structural wingbox mass
- **8.8% reduction** in total mass

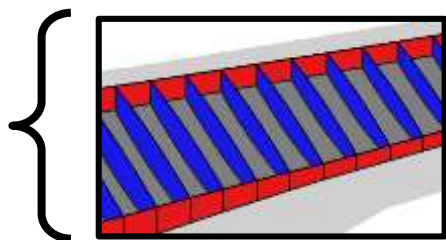
Stanford, B., AIAA J. 2017.

NASA – Optimal VCCTEF Deflections



Structural design

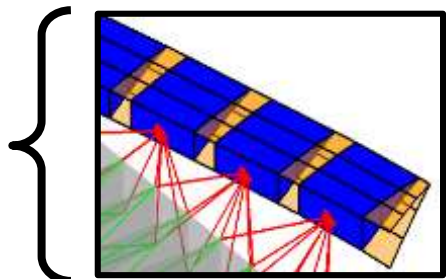
variables: shell thickness, stiffener thickness, and stiffener height of each design patch (711 total)



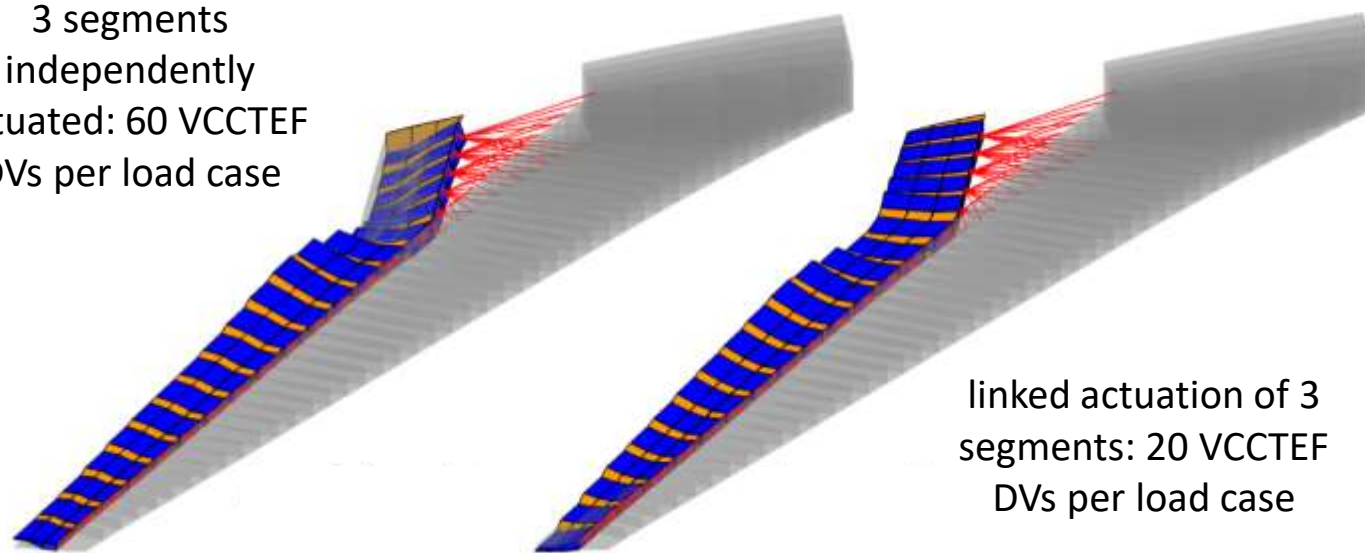
Variable Camber

Continuous Trailing Edge Flap design variables:

quasi-steady commanded actuation of each segment, during each closed-loop load case (120 total)



3 segments independently actuated: 60 VCCTEF DVs per load case



actuation scaled 3x

linked actuation of 3 segments: 20 VCCTEF DVs per load case

Stanford, B., JGCD, 2016.

- Key difference: linked actuation case cannot use 3rd segment as a trim tab, so no IBD actuation without violating hinge moment constraints.
- **Linked actuation case is not as effective at maneuver load alleviation, so optimal wingbox structure is 11% heavier.**

NASA – X-56A Team Members



- NASA AFRC
 - Cheng Moua, Scott Howe, Chris Miller, Gary Cosentino, Jacob Schaefer, Matthew Boucher, Jeffrey Ouellette, Peter Suh, Alex Chin, Samson Truong, Keerti Bhamidipati, Jason Lechniak, Mei Li, James Smith, Robert Jensen, Justin Hall, Kirk Caldwell, John Bosworth
- NASA LaRC
 - Jared Grauer
- AFRL
 - Gregory Reich, Robert Mitchell, Peter Flick, Chris Meckstroth
- Lockheed Martin
 - Daniel Caraway, Mriganka Ghosh



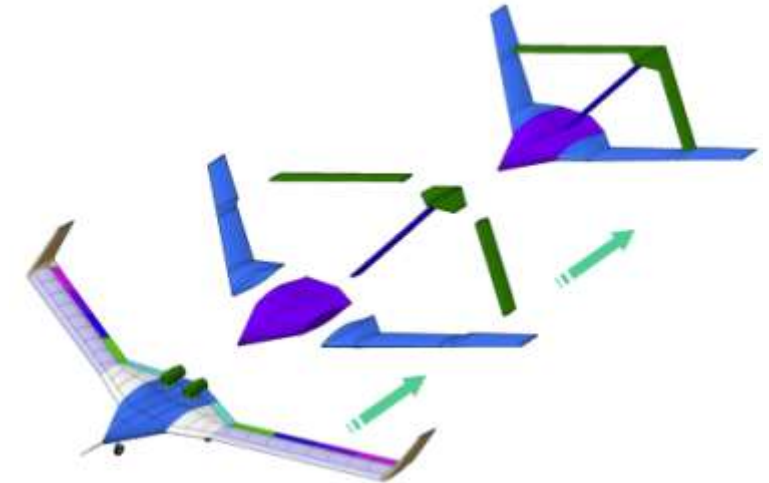
NASA – X-56A Multi Utility Technology Test-bed (MUTT)



- Background
 - Partnership between NASA, AFRL, and Lockheed Martin
 - Vehicle to investigate Active Flutter Suppression and Gust Load Alleviation
 - 8 flights on rigid wings with Lockheed Martin flight controller
 - 8 flights on rigid wings with NASA classical flight controller
 - 30 flights on flexible wings with NASA flight controller
- Research Flight Objectives with flexible wings
 - Demonstrate inflight active suppression of at least one unstable flutter mode
 - Evaluate controller robustness criteria for the design of control laws for flexible vehicles with complex rigid-body and structural coupling
 - Investigate methods of flight validation of the aeroelastic models
 - Collect distributed strain sensor data from the candidate Fiber Optic Strain Sensor system



X-56A (MUTT) testbed for flight testing of control laws



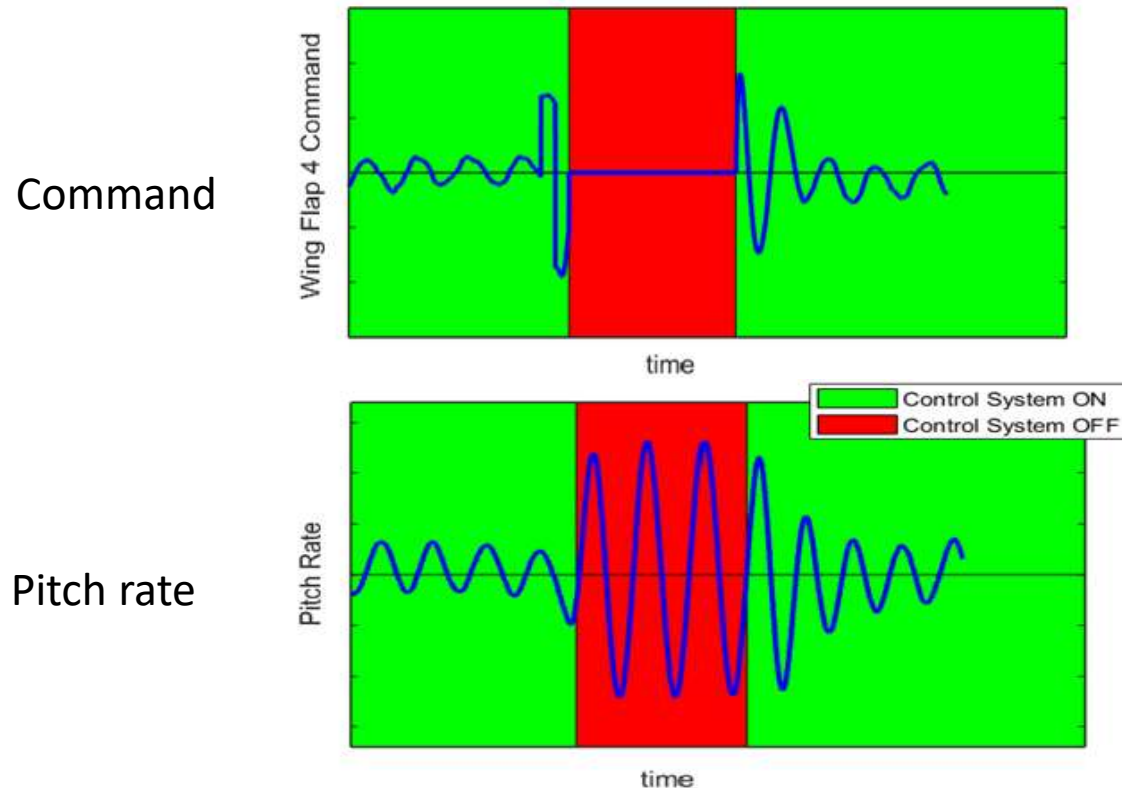
X-56A modular design allows testing of control theories using stiff and flexible wings

NASA – X-56A Flutter Successfully Suppressed

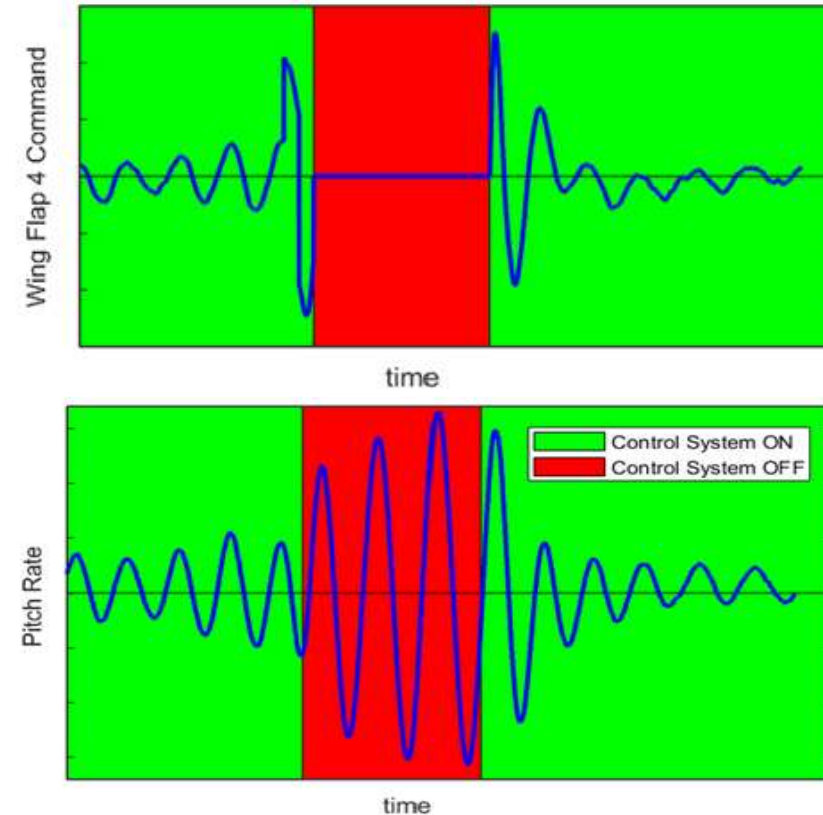


- Turned control system off in flight to demonstrate flutter, momentarily, (and suppression of it)

Right Before Flutter



Slightly Past Flutter



NASA – X-56A Video



UMN – Performance Adaptive Aeroelastic Wing (PAAW)

Goal: Suppress flutter, control wing shape and alter shape to optimize performance

- Funding: NASA NRA with Dr. Jeffrey Ouellette as Tech. Monitor
- Team: UMN, VT, STI, CMSoft, Aurora, Schmidt & Assoc.
- Project Site: www.paaw.net



mAEWing1: BFF Replica



mAEWing2: Half-scale X-56A



*Schmidt &
Associates*



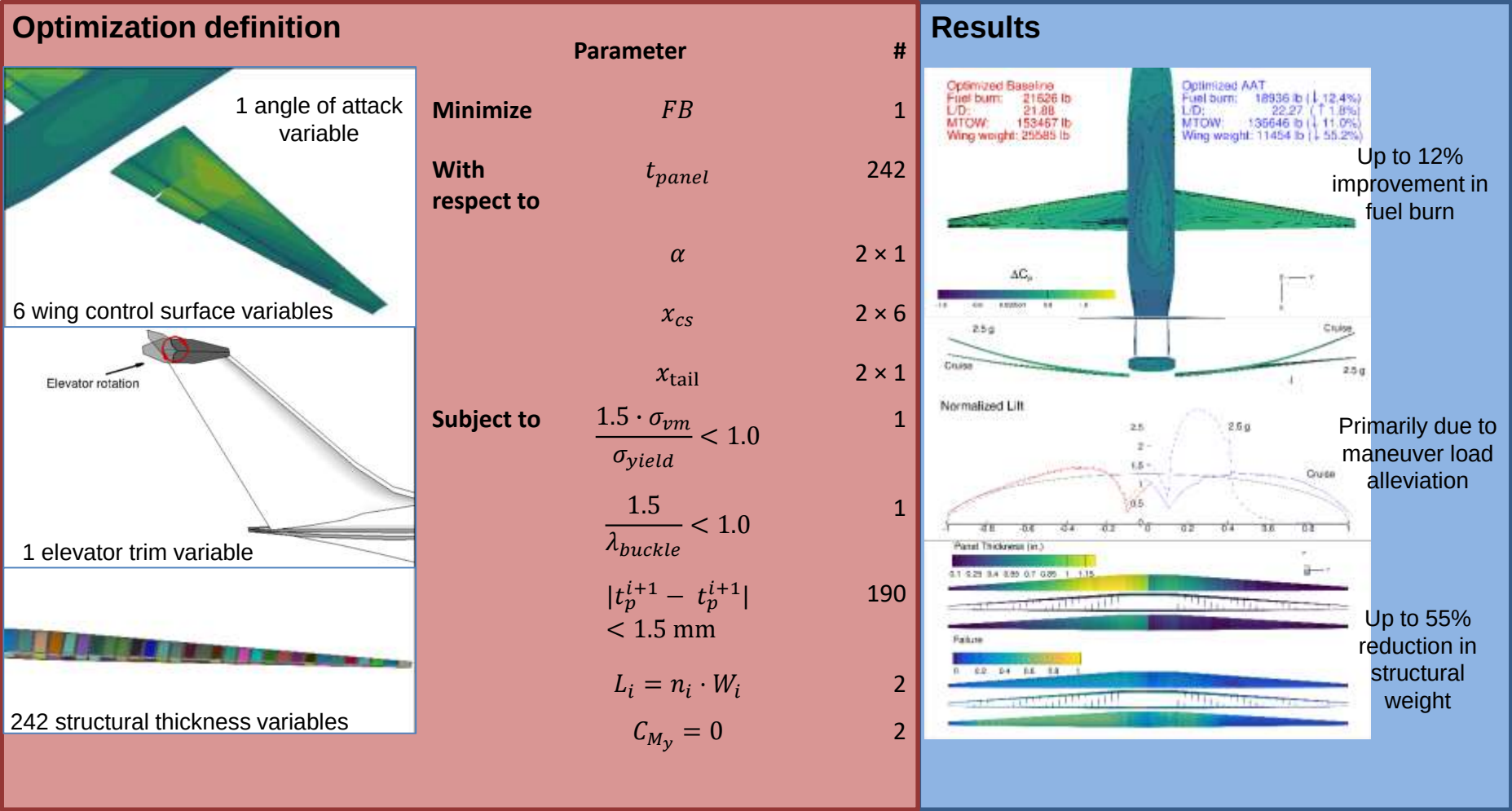
Aurora – Active Aeroelastic Tailoring Design



Aurora has investigated the benefits of active aeroelastic tailoring for N+3 aircraft through coupled FEA-VLM design optimization

Analysis predicts:

- Up to 12% improvement in fuel burn
- Primarily due to maneuver load alleviation
- Up to 55% reduction in structural weight



Up to 12% improvement in fuel burn

Primarily due to maneuver load alleviation

Up to 55% reduction in structural weight

UMN – Open-Loop Flutter at ~30m/s



Model Predictions:

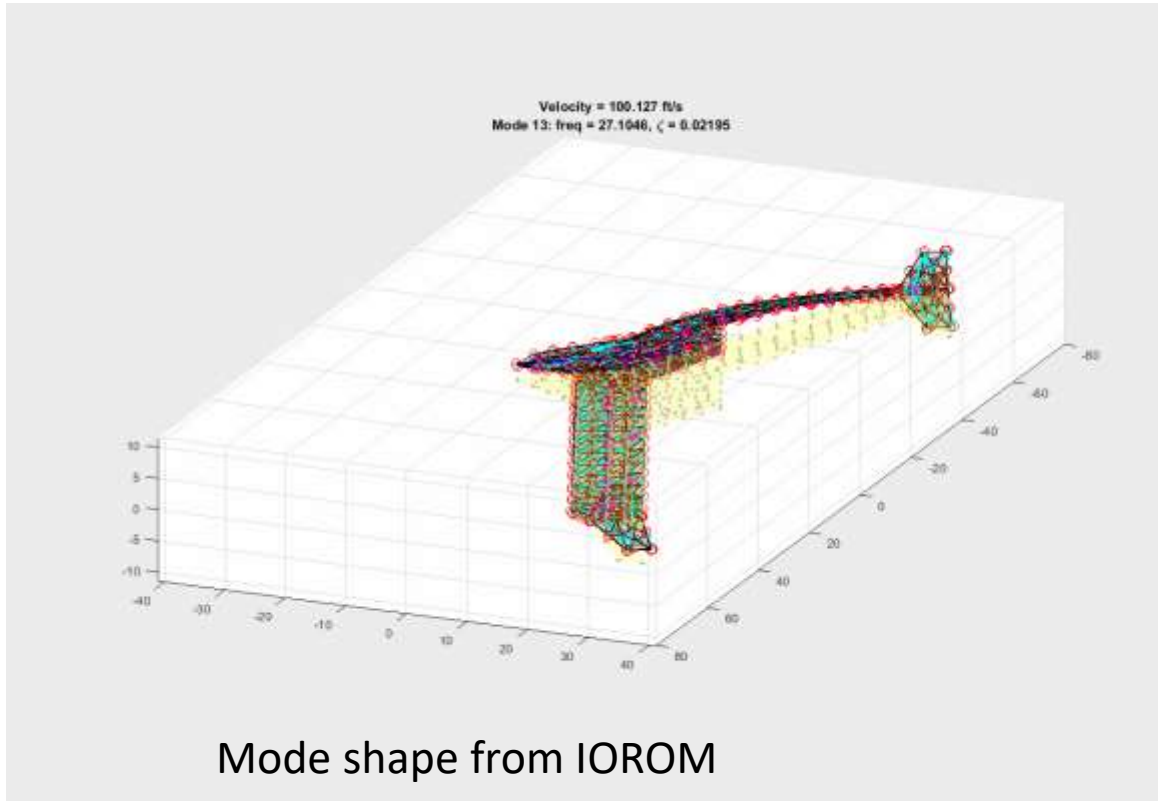
- Elasticized Flight Dynamics (Schmidt): 29.1 m/s
- NASTRAN (VT): 29.5 m/s
- CFD/CSD (CMSSoft): 30.8 m/s
- Input/Output Reduced Order Model (STI/CMSSoft): 31.7m/s



UMN – Open-Loop Flutter at ~30m/s



- **Mode Shape**: Coupling of rigid body short period and 1st symmetric wing bending
- Predictions closely match modes observed in-flight

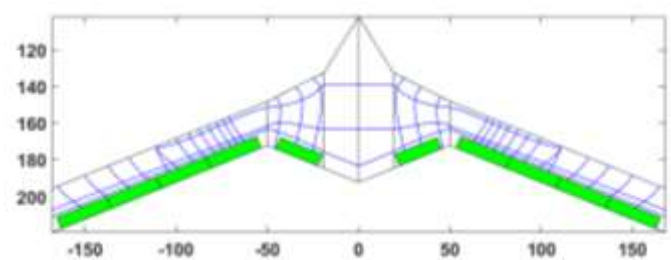


The BFF mode (genesis at SWB1) at a velocity near the flutter point.
The coupling of SWB1 and short period is apparent

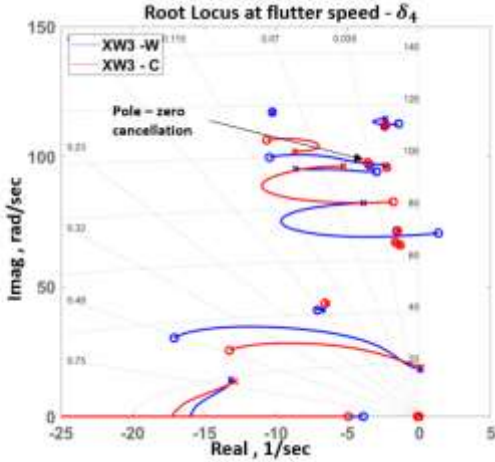
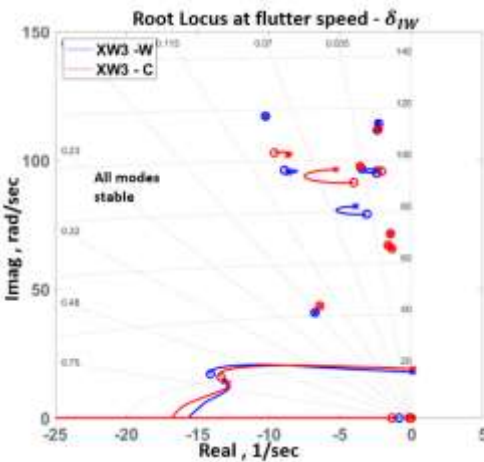
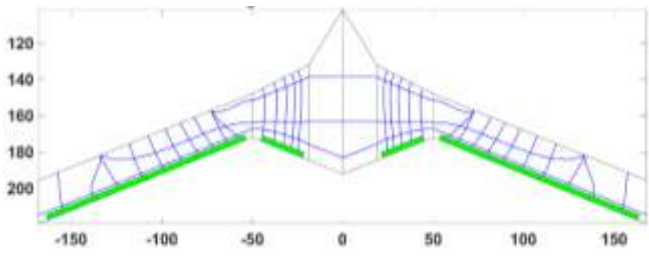
VA Tech – Control Maximization Optimization Study



Weight Minimized



Control Optimized

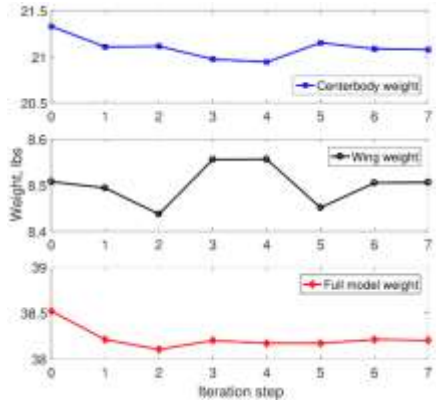
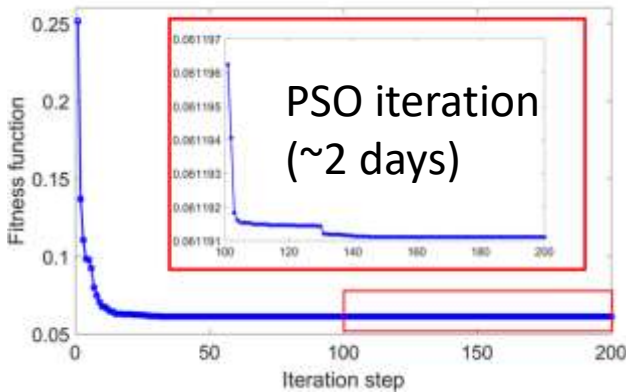


Gupta, Zhao and Kapania (AIAA Aviation 2019)

- Control optimized design has **4%** higher **weight**, fewer ribs, high curvature in spars, **smaller control surfaces** due to aft movement of spar
- Bioinspired **SpaRibs** for xAEWing3 satisfying C^0 continuity used for control maximization has very **flexible** design – **70% lower** hinge moments
- Provides **additional** control surface for **closed loop** stability at **flutter speed**

Optimization Enabled by Efficient FEM

Zhao et al. AIAA 2019-1814



GLO iteration (~1 hour)

Modal results for complete model

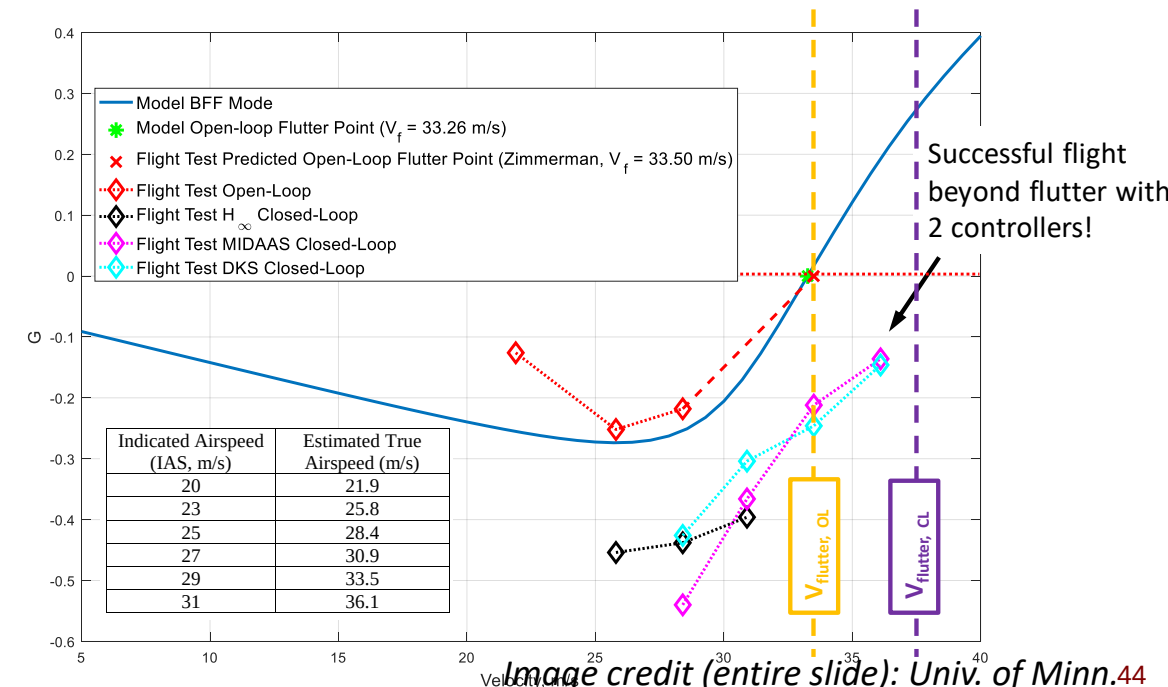
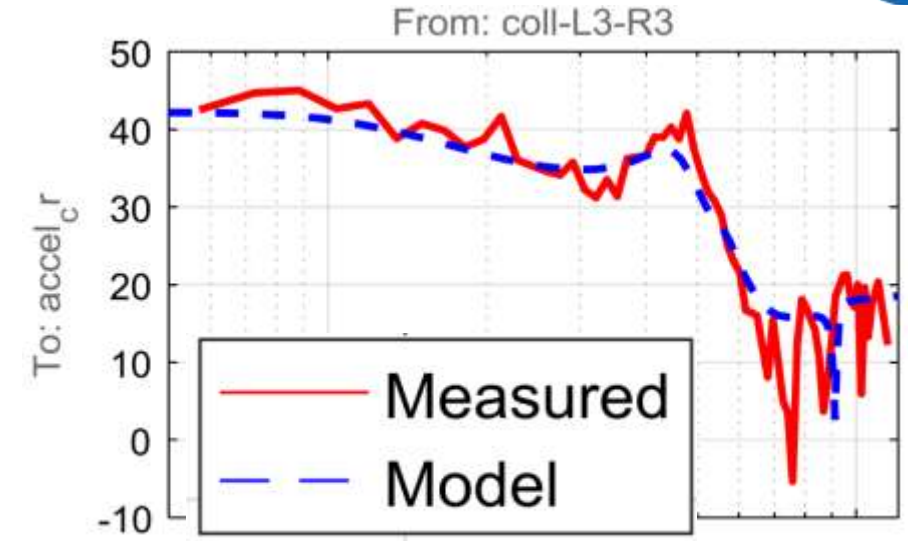
Mode Shape	updated FEM (GLO/PSO)	GVT	Diff. (GLO/PSO)	MAC (GLO/PSO)
SWB1, Hz	5.71/5.98	5.81	-1.72%/2.93%	0.988/0.989
AWB1, Hz	8.13/8.56	8.23	-1.22%/4.01%	0.996/0.997
SWB2, Hz	19.47/20.66	19.01	2.42%/8.68%	0.970/0.977
AWT1, Hz	26.97/27.00	26.43	2.0%/2.16%	0.917/0.906
SWT1, Hz	32.64/31.78	33.92	-3.8%/-6.31%	0.661/0.690

- Optimization-based FEM updated based on GVT results
- Global-local optimization is more efficient than the all-in-one particle swarm optimization to update FEM

UMN – Flutter Suppression: Modeling, Control Design, Flight Tests



- Control-oriented elasticized flight dynamics model used for the control design
 - Ref: Schmidt, *Journal of Aircraft*, 2016
- Grey-box ID from flight tests
 - Ref: Danowsky, Schmidt, Pfifer, *AIAA 2017-1394*
- Three controllers designed to increase damping to BFF mode at 23 m/s
 - Hinf: Kotikalpudi, et al, *AIAA 2018-3426*
 - MIDAAS: Danowsky (STI), *AIAA 2017-4353*
 - Classical: Schmidt, *Journal of GCD*, 2016
- Flight Tests (Ref: Danowsky, Kotikalpudi, Schmidt, Regan, Seiler, *AIAA 2018-3427*)
 - All controllers added damping at and above the designed airspeed
 - MIDAAS & classical designs flown above open-loop flutter speed
- Next Step: Re-design to maximize “robust flutter speed”.
(Airspeeds where active flutter control has 6dB/45deg margins on all inputs & outputs)



Boeing – Integrated Adaptive Wing Technology Maturation (IAWTM)

Key Contributors



Boeing Research and Technology

- Greg Clark (PM), Jack Quindlen (PI), Jeff Jonokuchi, Frode Engelsen, Alex Lee, Zach Lively, Karl Balitaan, Pejmun Motaghedi, Jack Bourbonnais, Jasmine Minter-Levine, Ben Levine, Kamal Shweyk

Boeing Test and Evaluation

- Pete Wilcox, Gary Ige

NextGen Aeronautics

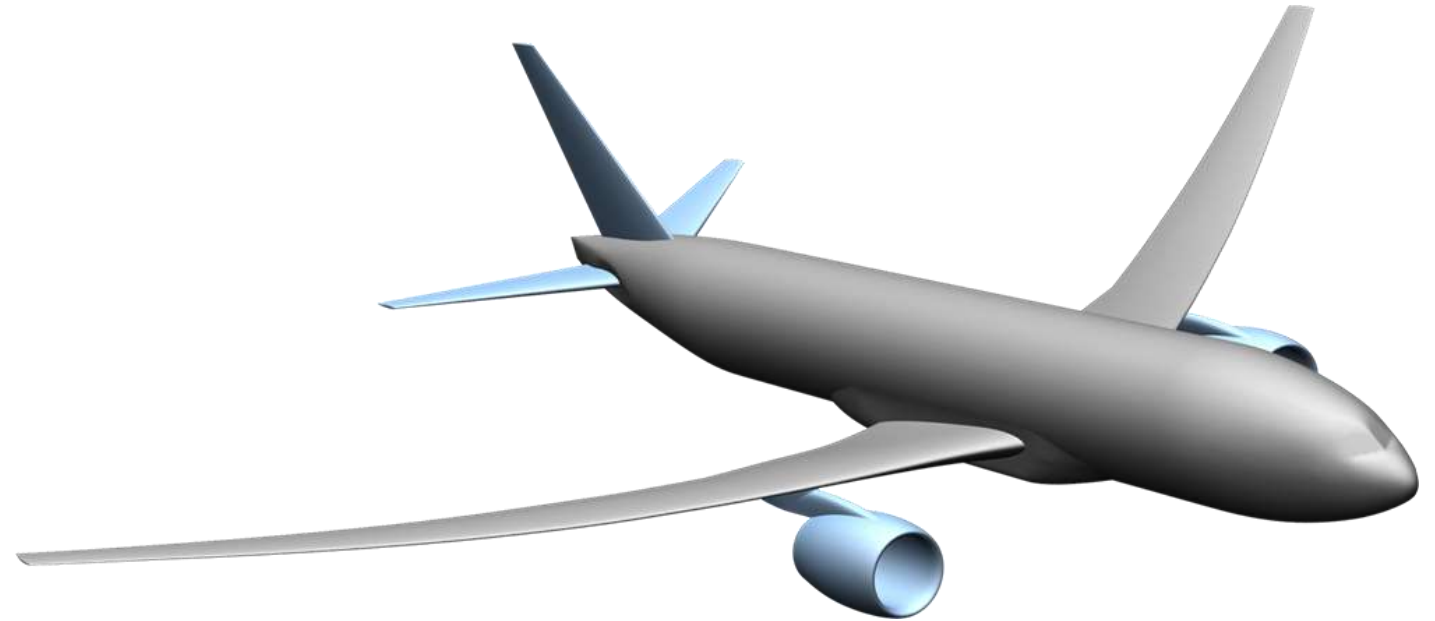
- Richard Bramlette, John Flanagan

SSCI

- Jovan Boskovic, Ben Krosner

NASA Langley

- Tom Ivanco, Patrick Heaney, Dave Coulson, Bret Stanford



Rendering of full-scale CRM13 aircraft used for IAWTM

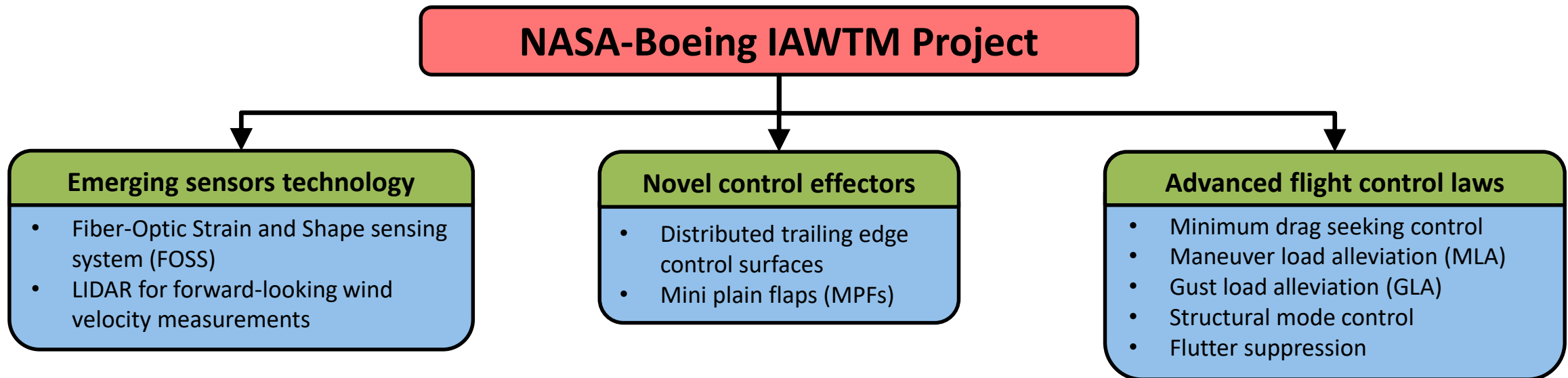


Boeing – IAWTM Project Overview



Objective: develop and test control and sensor techniques to enable and improve the performance of higher aspect ratio, flexible transport aircraft

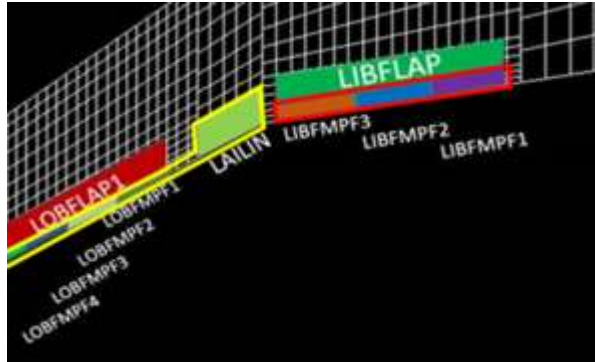
- Push the Technical Readiness Level (TRL) of relevant technologies towards integration on commercial aircraft
- Advance technology developments and research ... including
 - **Novel control effectors** and **advanced actuators** technology
 - **Robust and adaptive flight control laws (CLAW)** for drag reduction and wing/body load alleviation
 - **Advanced sensor technology** to be demonstrated in a configurable system capable of very accurate real-time measurement of aircraft wing and body



Boeing – IAWTM: Simulation Model of Full-Scale Aircraft



- NASA and Boeing have developed a non-proprietary, **full-scale** 6DoF simulation model of the CRM13 airframe for analysis of novel control system and sensor approaches



Distributed flight control surfaces

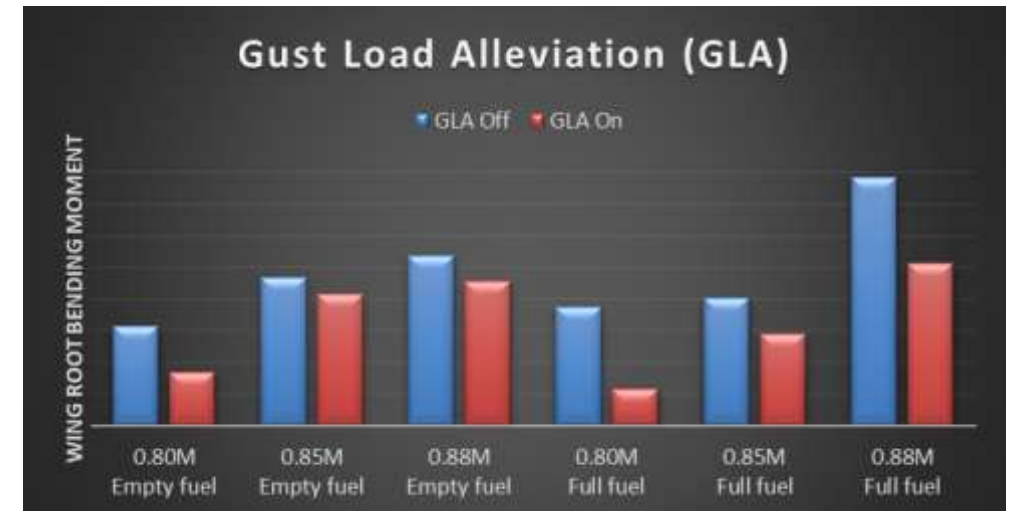
- 6 high-speed ailerons, 6 flaps
- 22 trailing-edge mini plain flaps (MPFs)

- Boeing developed **novel control laws** for the full-scale aircraft and examined performance benefits
 - Performance improvements with the new controllers:
 - GLA: **6-38% reduction** in wing root bending moment
 - MLA: **20-54% reduction** in wing root bending moment
 - Peak-seeking control: **up to 4.8% reduction** in fuel burn



Full aeroservoelastic (ASE) flexible wing dynamics

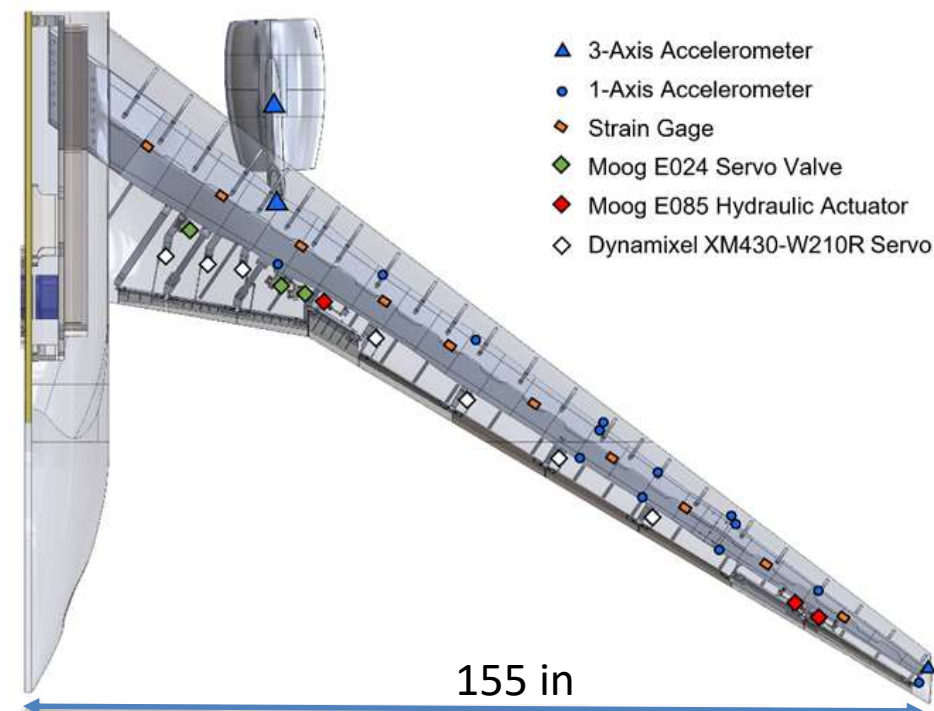
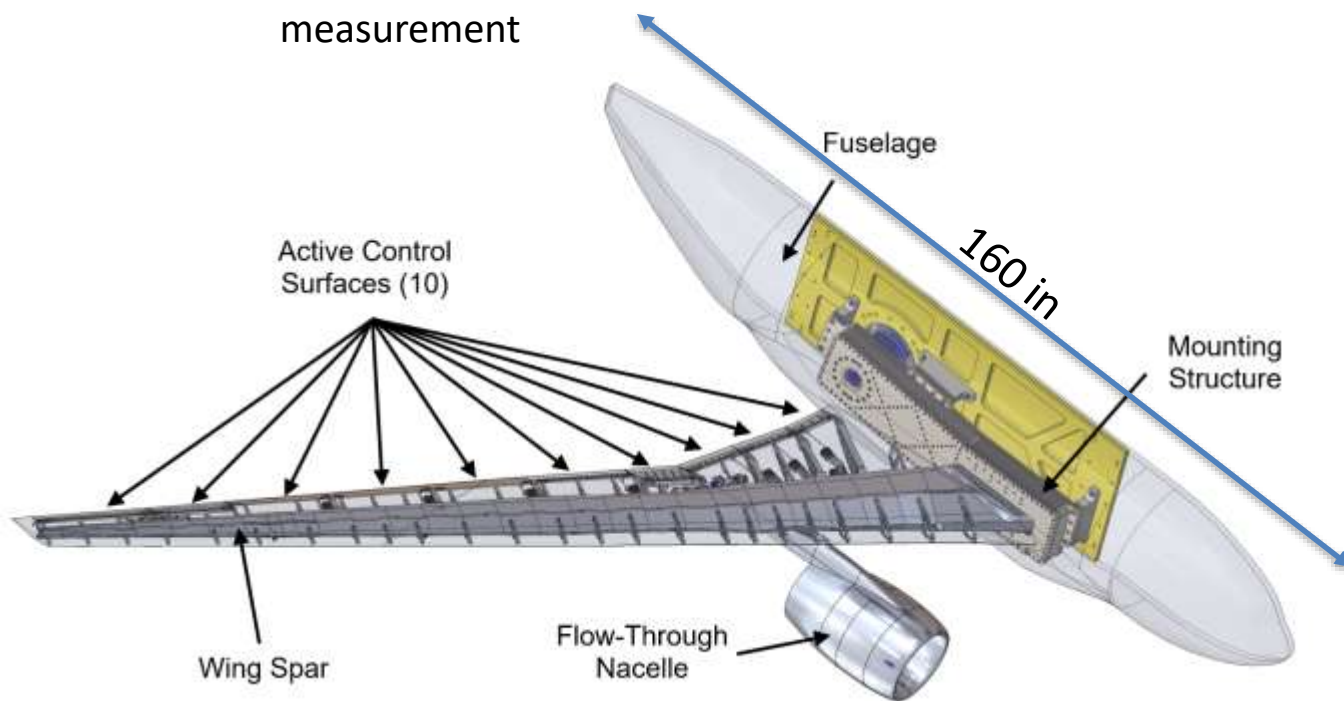
- 27 wing bending and torsion modes
- 563 state variables



Boeing – IAWTM: Aeroelastic Wind-Tunnel Test



- Culminates in closed-loop, half-span aeroelastic wind-tunnel test in NASA Langley's TDT in 2020
 - Heavy-gas tunnel for dynamic scaling at $M=0.7-0.95$, $Q=50-300$ psf
 - Dynamically-scaled metric wing + non-metric fuselage
 - Novel ETT-balance adapter to enable both dynamic aeroelastic testing **and** quality drag and maneuver load measurement
 - Distributed control surface architecture
 - 3 high-speed ailerons [hydraulic]
 - 7 trailing-edge mini plain flaps (MPFs) [electric servo]
 - Fully instrumented for closed-loop aeroelastic control
 - Fiber-Optic Strain and Shape sensing (FOSS) system
 - Distributed accelerometers, strain gauges
 - Gust generator and vane sensors for surrogate LIDAR



Aeroelastic Tailoring of High Aspect Ratio Wings : Summary



- NASA aeronautics research has aggressive fuel burn goals for future subsonic fixed wing transport aircraft
- Over a decade of multidisciplinary aeroelastic tailoring research invested
 - Passive aeroelastic tailoring
 - Curvilinear stiffened and topology optimized internal structural design and tow-steered composite skins
 - Active maneuver load alleviation, gust load alleviation, and flutter suppression
 - Novel control effectors, integrated sensors, and control laws
- New approaches address challenges introduced with new aircraft configurations
 - High aspect ratio, reduced drag
- Advanced materials, manufacturing, structures, and sensors make these approaches possible