Structural Load Alleviation Applied to Next Generation Aircraft and Wind Turbines

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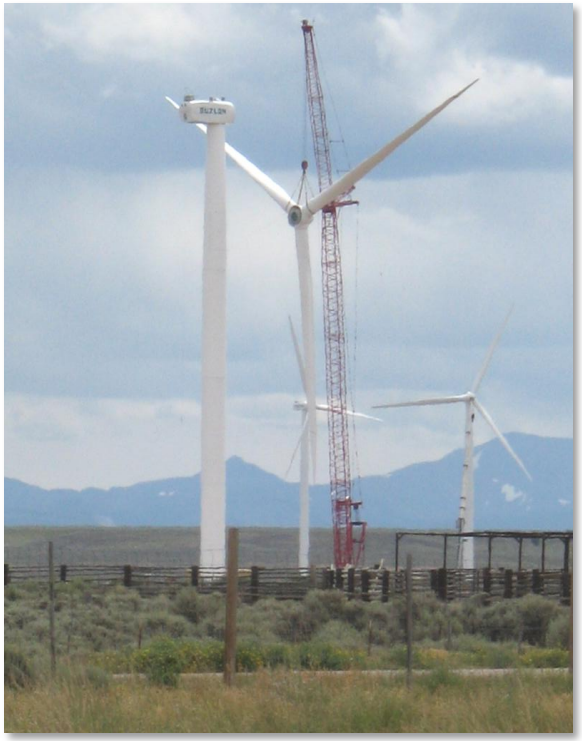
NASA Subsonic Fixed Wing Project, Fundamental Aeronautics Program

Outline

- NASA goals for increased aircraft efficiency
- Proof of concept architecture for flight control with load feedback
- Optimal control allocation with load constraints
- Wind energy challenges
- Wind turbine blade damage
- Adaptive contingency control



SUGAR Ray design by NASA sponsored team led by The Boeing Company

Subsonic Fixed Wing Project

WHAT

- Reduce environmental impact of aviation
- Increase aircraft efficiency
- Improve mobility of aircraft in airspace

WHY?

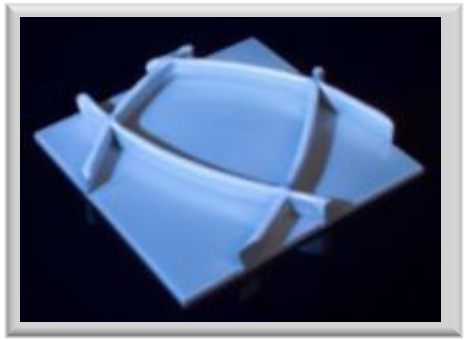
- Unacceptable community noise and other environmental emissions
- Need to reduce fossil fuel consumption
- Demands from NextGen airspace
- Air transportation plays key role in our economy and quality of life

HOW!

- Create prediction and analysis tools for design
- Develop concepts and technologies for significant improvements in noise, emissions and performance
- Partner with academia, industry, and government

Weight Reduction for Increased Efficiency

- Create new fabrication processes for lightweight materials, esp. large structures
- Design lightweight wing structures with aeroelastic tailoring to eliminate heavy control surfaces
- Use aerogels for super-lightweight insulation
- Increase temperature capability of composites for greater use in engines



Electron Beam Freeform Fabrication (EBF3)

Polymer-enforced aerogel

Fan containment system with high temperature capability

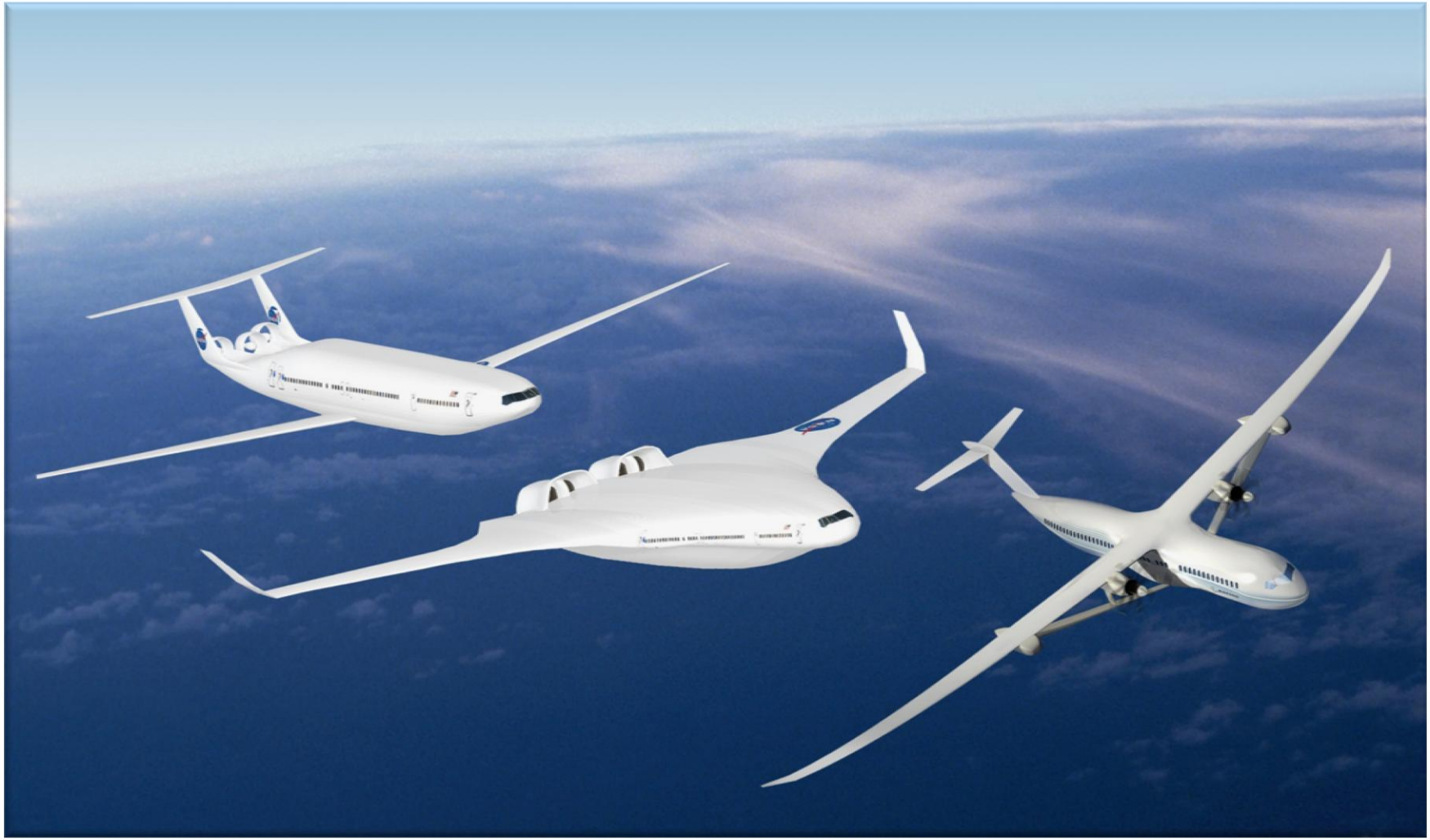
Drag Reduction for Increased Efficiency

Formation flight for drag reduction

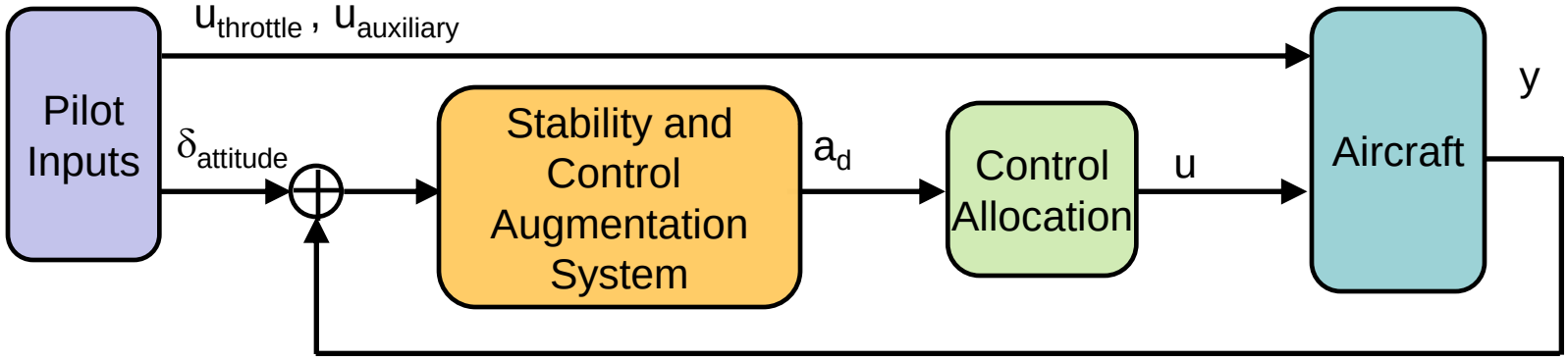
D-8 (double bubble) has natural laminar flow on wing bottom, design by MIT team

- Increase laminar boundary layer by delaying transition to turbulent flow
  - Design surfaces with favorable pressure gradients (natural laminar flow)
  - Include active or passive local suction surfaces (hybrid laminar flow)
- Use active aeroelastic tailoring of wing to reduce drag during cruise
- Advanced CONOPS – formation flight
- Develop & validate CFD codes for design & analysis of advanced drag reduction concepts

NextGen N+3 Concept Aircraft



Traditional Flight Control System

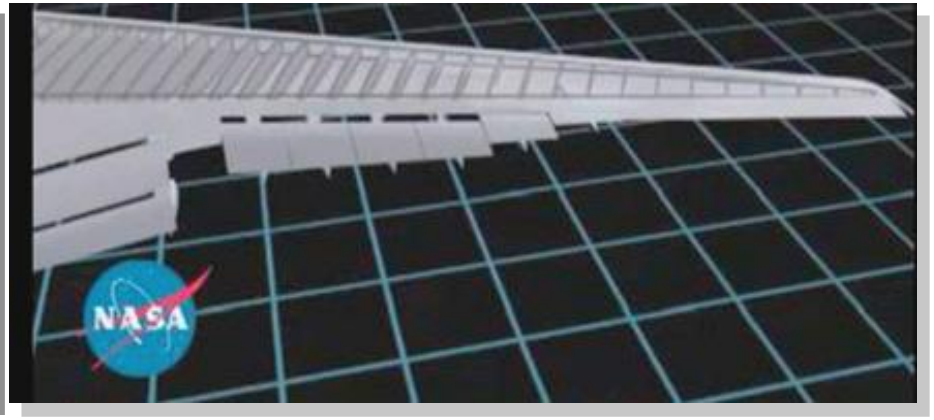


Control Allocation: Determine surface deflections needed to achieve desired rates

- **Traditional Approaches for Control Allocation**
  - **Ganging of Actuators**: use elevator for pitch, ailerons for roll, rudder for yaw
  - **Mixers**: fixed combination of surfaces to achieve commands
- **Structural Limits**
  - Design engineers determine critical load paths in aircraft
  - Mostly concerned with bending, torsion, and shear loads
  - Load limits are determined through ground tests and flight tests
  - Load limits imposed by restricting flight envelope; position & rate limiting actuators

New Challenges for Flight Control Systems

- Many redundant effectors
- Surfaces affecting multiple axes
- Actuator rate & position saturation
- Low control authority
- Lighter more flexible structures



Optimal Control Allocation

Given $\boldsymbol{B}$, a desired vector $\boldsymbol{u_p}$ and ε>0, find $\boldsymbol{u}$ such that

$$J = \underbrace{\left\| Bu - a_d \right\|}_{\text{error minimization}} + \underbrace{\varepsilon \left\| u - u_p \right\|}_{\text{control minimization}}$$

No Structural Constraints!!

is minimized subject to $u_{\min} \le u \le u_{\max}, \quad |\dot{u}| \le \dot{u}_{\max}$

Feasibility Study

Objective:

Use multiple control surfaces in most effective way, while remaining within structural load limits

Approach:

Replace traditional control allocation with optimal control allocation with load constraints and real-time load feedback

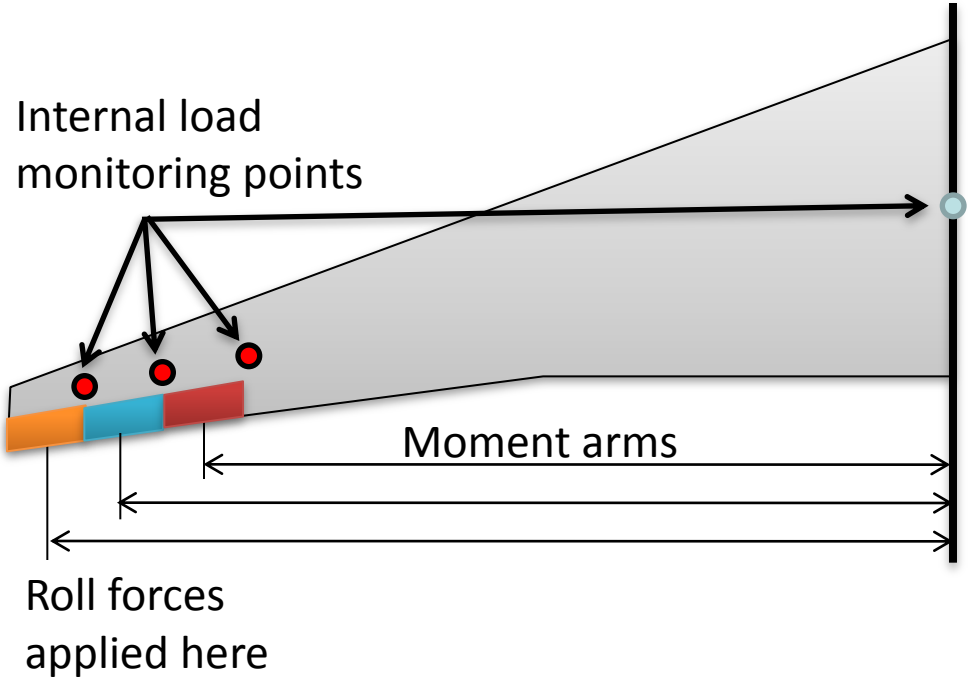
- Measure internal (structural) loads along critical load paths
- Use aircraft aerodynamic and structural models to determine incremental loads due to incremental surface deflection
- Include structural load constraints and measured loads in optimal control allocation problem

Significance:

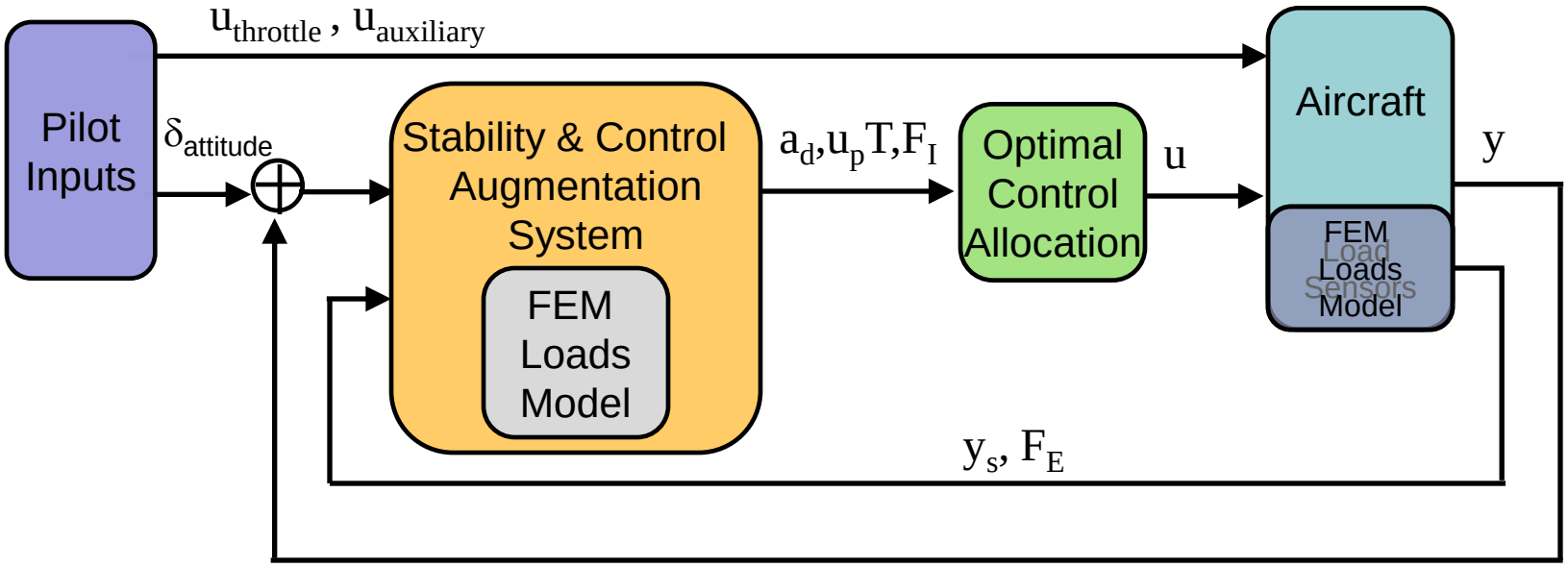
This approach enables fuel efficient aircraft with many multi-purpose control surfaces to achieve acceptable performance & safety

Study Assumptions

- Only considering static loads due to lift and rolling forces
- Finite element model (FEM) of aircraft wings and tail
- Loads due to lift and roll are applied to nodes in FEM model
- Bending moments calculated using finite element analysis (FEA)
- A select number of load points are monitored and included in the optimal control allocation constraints



Proposed Framework



a_d	desired accelerations
u_p	preferred delta surface positions
B	control effectiveness matrix
T	incremental loads matrix, where Tu gives the incremental loads at critical points
y_s	structural loads from sensors (or model in sim)
F_E	external forces due to lift and body moments
F_I	internal structural loads at critical points

Optimal Control Allocation

Optimal Control Allocation Problem:

Given $\boldsymbol{B}$, a desired vector u_d and ε>0, find u such that

$$J = \underbrace{\left\| Bu - a_d \right\|_1}_{\substack{\text{error} \\ \text{min}}} + \underbrace{\varepsilon \left\| u - u_d \right\|_\infty}_{\substack{\text{control} \\ \text{min}}}$$

is minimized subject to:

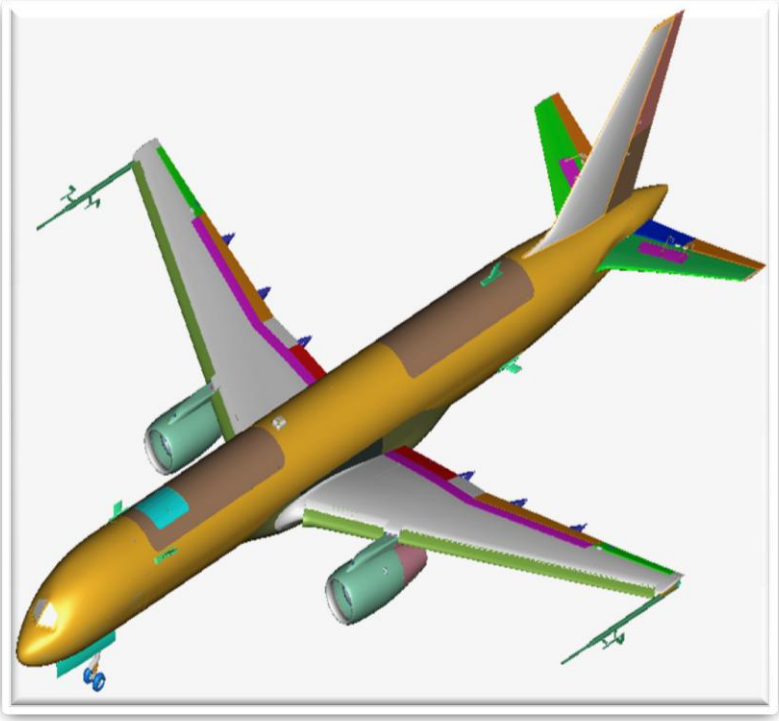
$$u_{\min} \le u \le u_{\max}, \quad F_I + Tu \le F_{I,\max}$$

where $\boldsymbol{F}_{\mathrm{I,max}}$ are critical point load limits

Can also be formulated with load minimization, using constraints given above and cost function:

$$J = \left\| Bu - a_d \right\| + \varepsilon \left\| u - u_d \right\| + \underbrace{\gamma \left\| F_{I,\max} - F_I + T(u - u_p) \right\|}_{\text{load min}}$$

Up-scale GTM Simulation



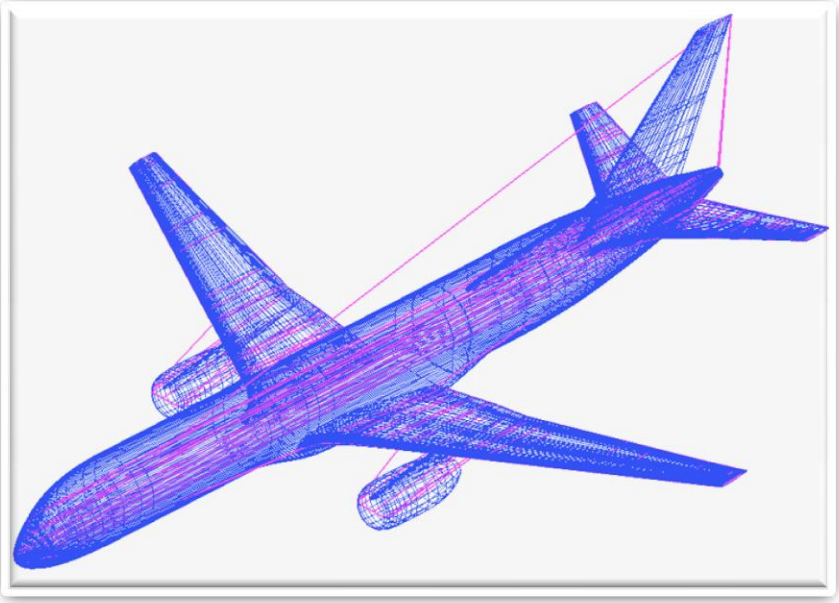
5.5% GTM-T2 Solid Model

Up-scale GTM Simulation

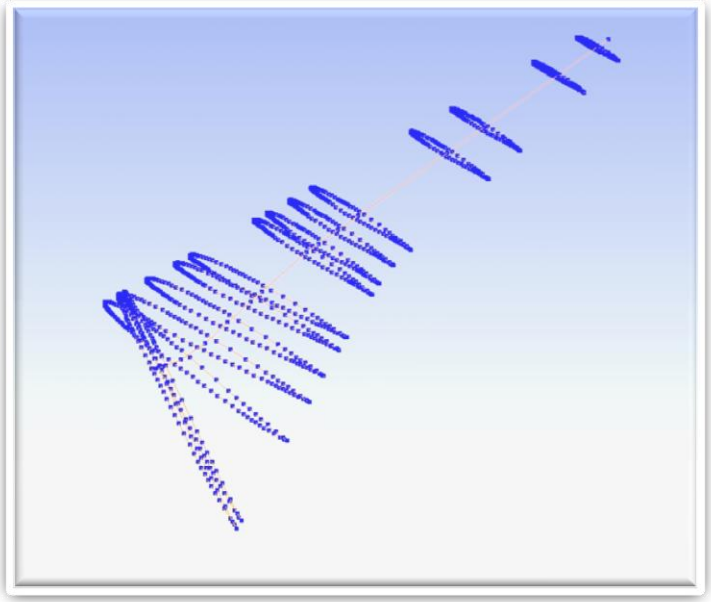
- Simulink model based on 5.5% dynamically scaled aircraft derived from wind tunnel & flight test data
- Up-scaled by incorporating Reynolds adjusted aero tables
- Actuator models sized for up-scale GTM
- NASA Glenn's Simp2 engine (simplified version of C-MAPSS40k)
- GTM bare airframe
- 6 ailerons, 4 elevons, 2 rudders, 2 stabs, 2 flaps
- Vehicle Management System
  - sensor processing module
  - mission manager
  - guidance/control
- Vehicle Control Augmentation System
  - reference model dynamic inverse controller
  - optimal control allocator

Finite Element Modeling Approach

- Wings/tails modeled as cantilever beams with fixed ends at roots
- Constant thickness hollow aluminum shells following outer mold line give beam cross section properties
- Beam nodes located at centroids of wing cross sections



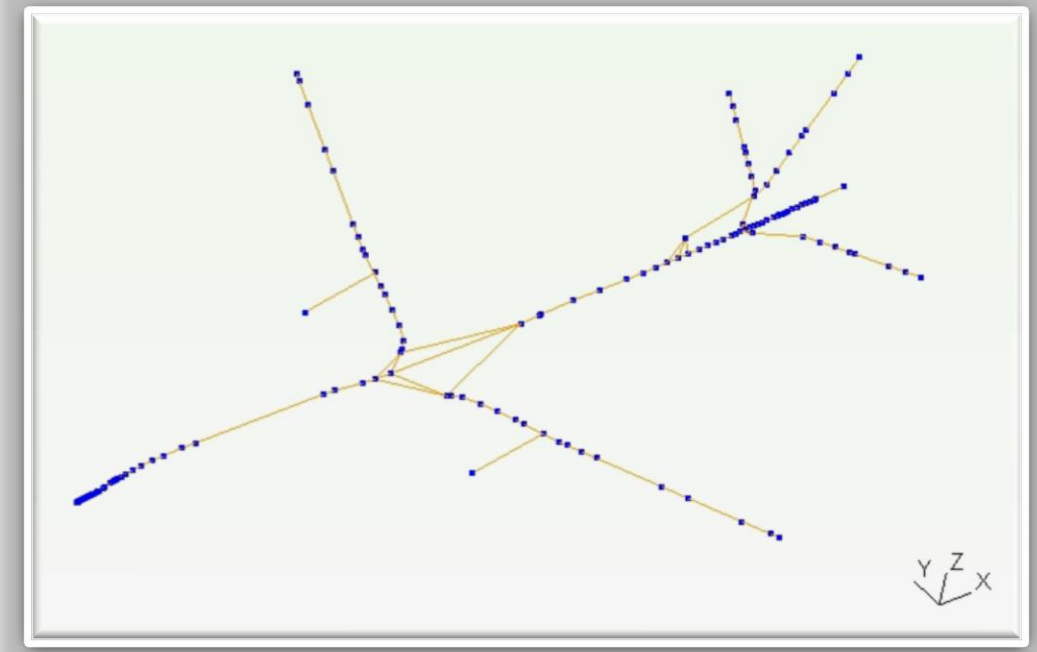
Vortex-lattice model of aircraft



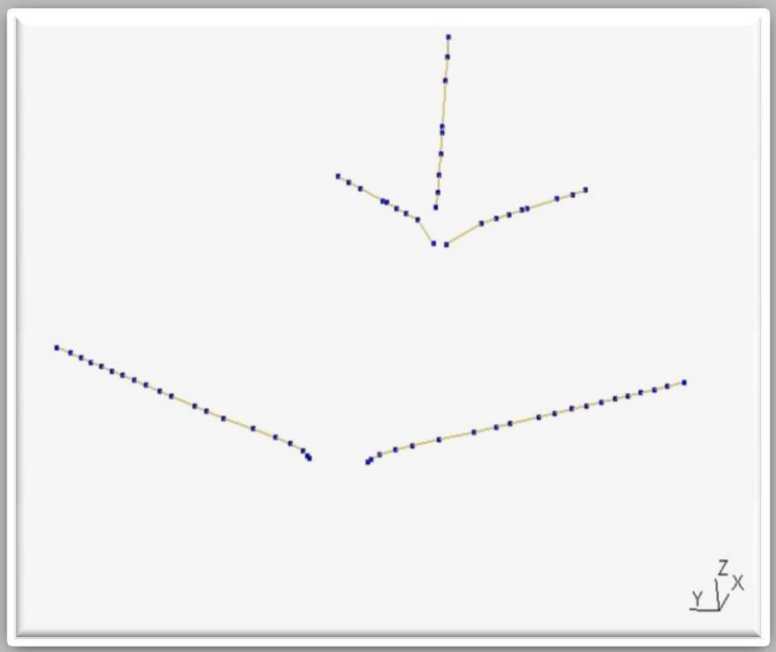
Wing cross sections

Finite Element Model of GTM

- Beam mesh for each wing has 20 nodes and 19 beams
- Each beam has 6 degrees of freedom – 3 translation & 3 rotation



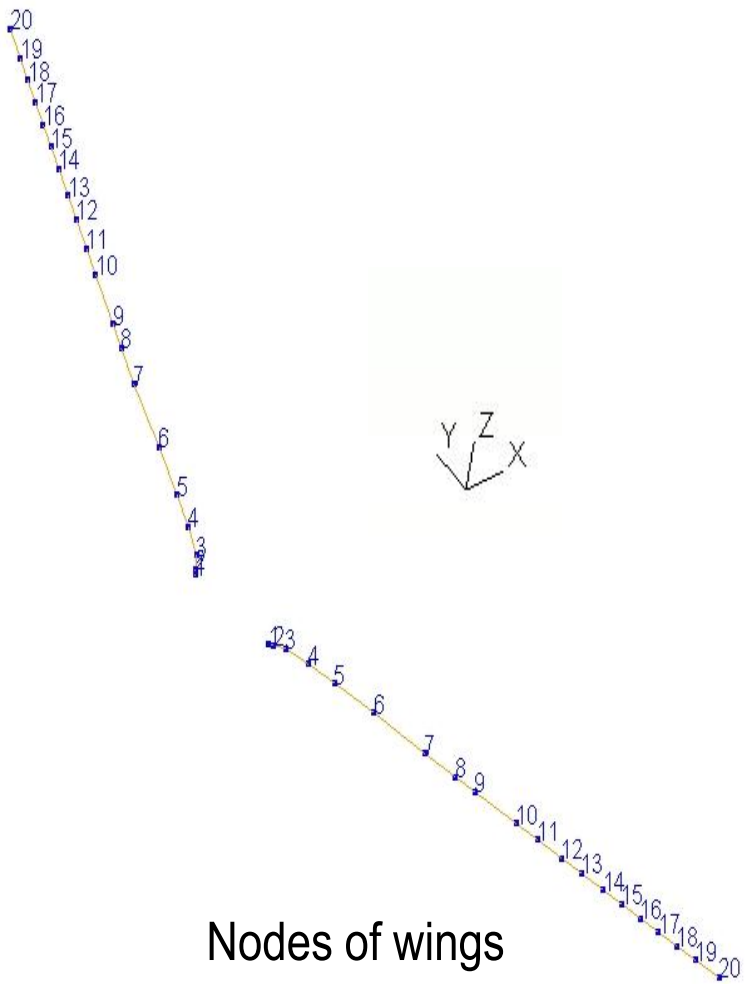
FEM of GTM aircraft



FEM of wings and empennage

Finite Element Analysis

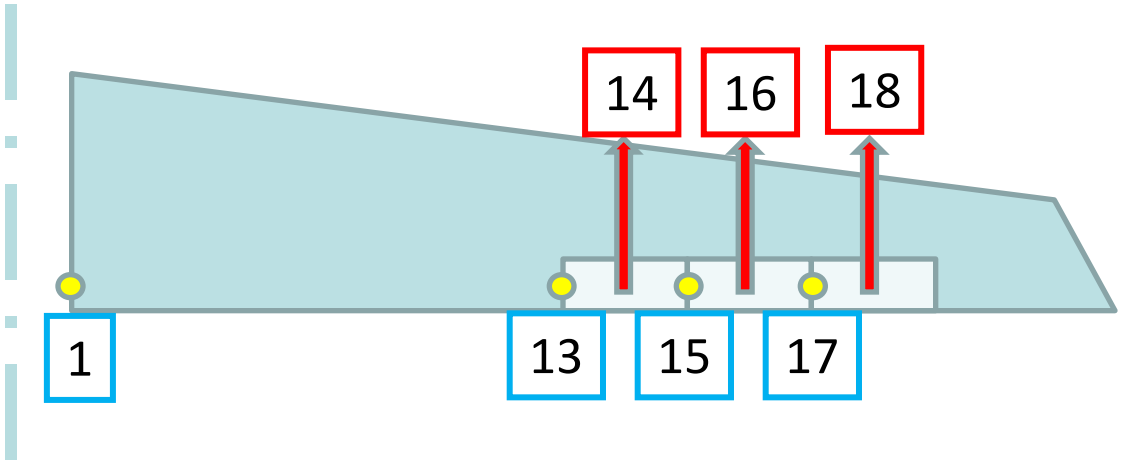
- Assume static loads and static response, $F = Kx$
- Stiffness matrix $\boldsymbol{K}$ is derived from FEM
- $\boldsymbol{K}^{-1}$ is computed off-line
- Static loads applied during simulation to FEA nodes
- Measured loads are calculated from deflections using $\boldsymbol{K}^{-1}$

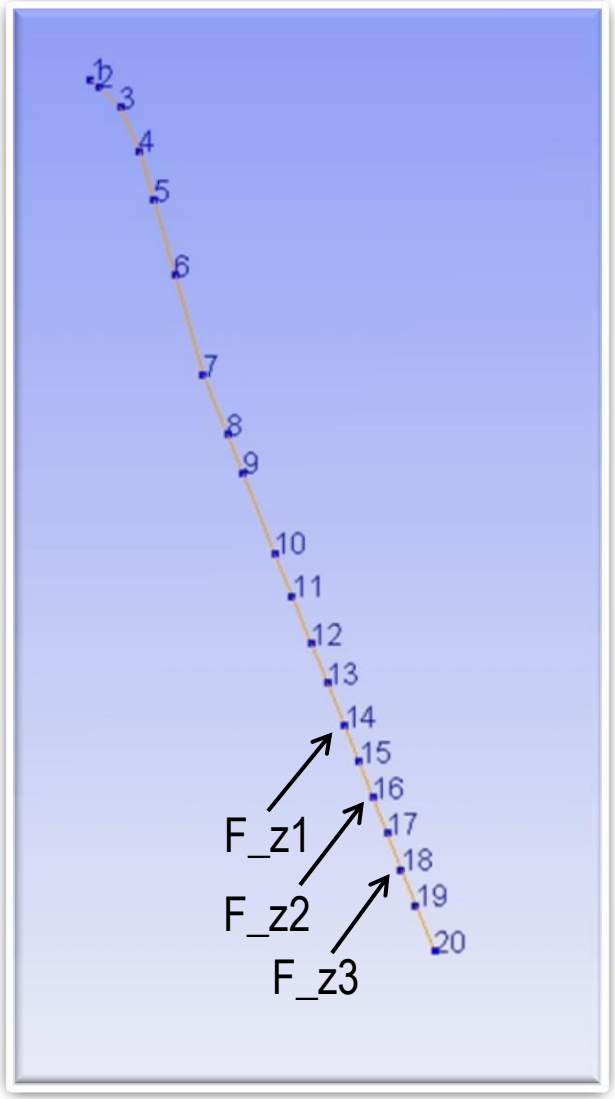


Nodes of wings

Application of External Static Loads

- Elliptically distributed lift load applied to nodes along wings and horizontal tail
- Loads arising from roll moments applied as concentrated forces in z-direction on each aileron in proportion to aileron deflection

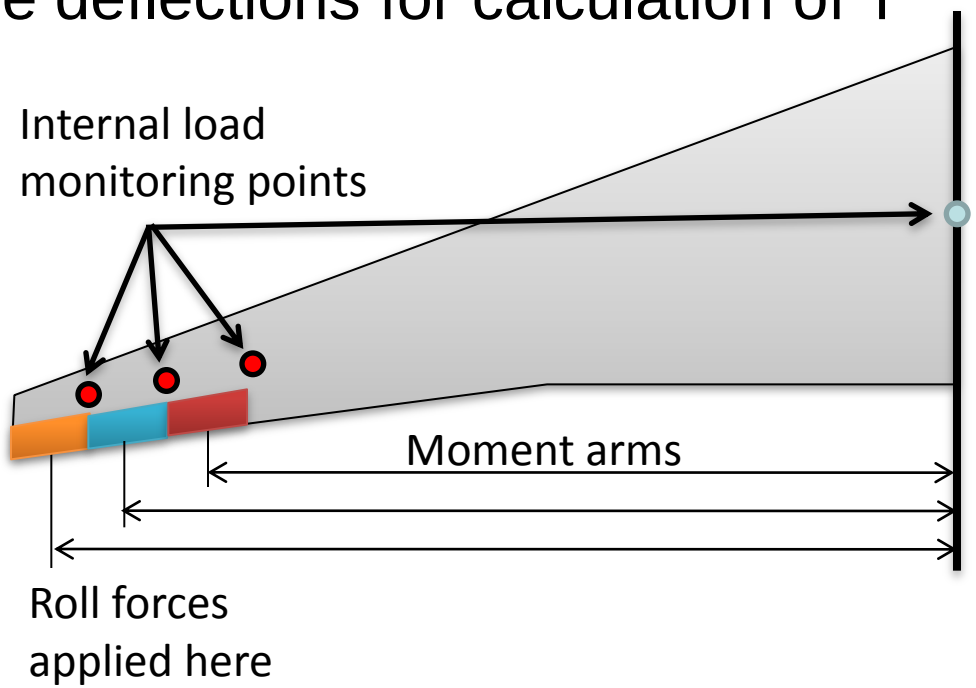




Roll force locations

Integration with Simulation

- Flap-wise bending moment at critical points are calculated & passed to control allocator
- K^{-1} and B are used during simulation to determine incremental loads matrix T
- Aileron forces are assumed to be proportional to surface deflections for calculation of T



Test Cases

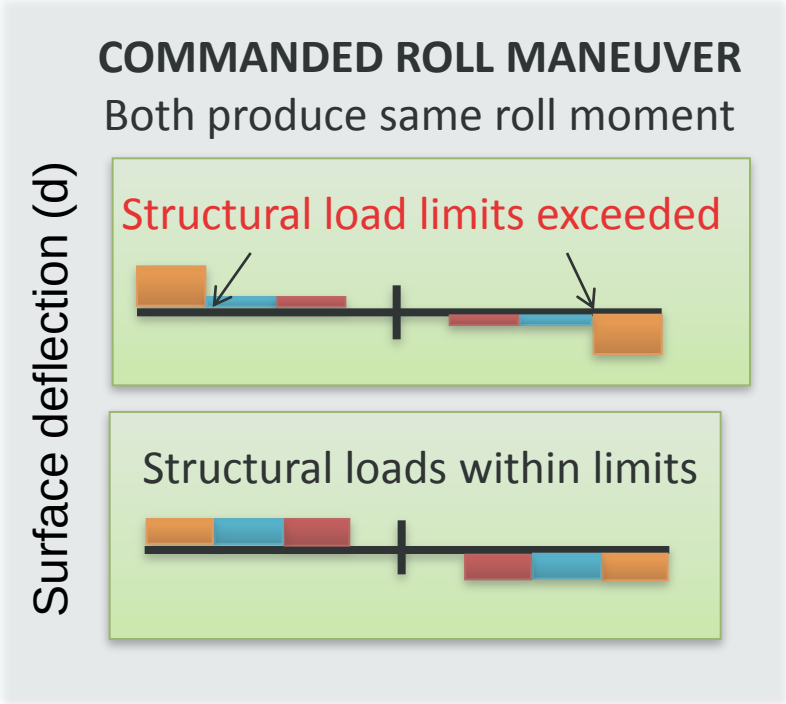
Flight conditions:

- Altitude 30,000 ft
- Mach 0.85

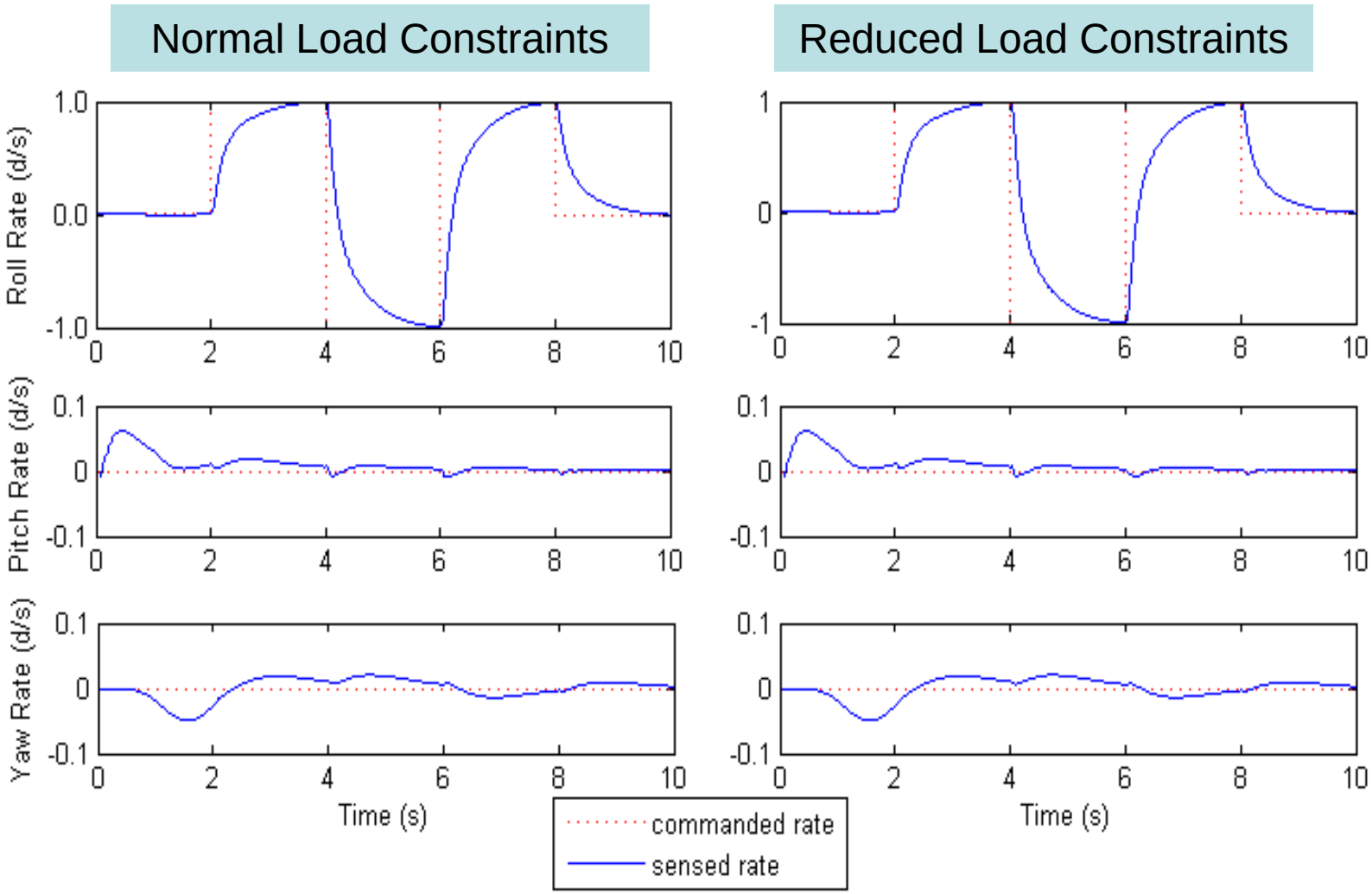
Test cases:

- **Normal case**
  Load limits set to values determined for safe flight
- **Case I**
  Right aileron load limit set to 55,000 ft-lb
- **Case II**
  Left outboard aileron deflection limits set to ±0.01 deg

Example of control allocation gone bad

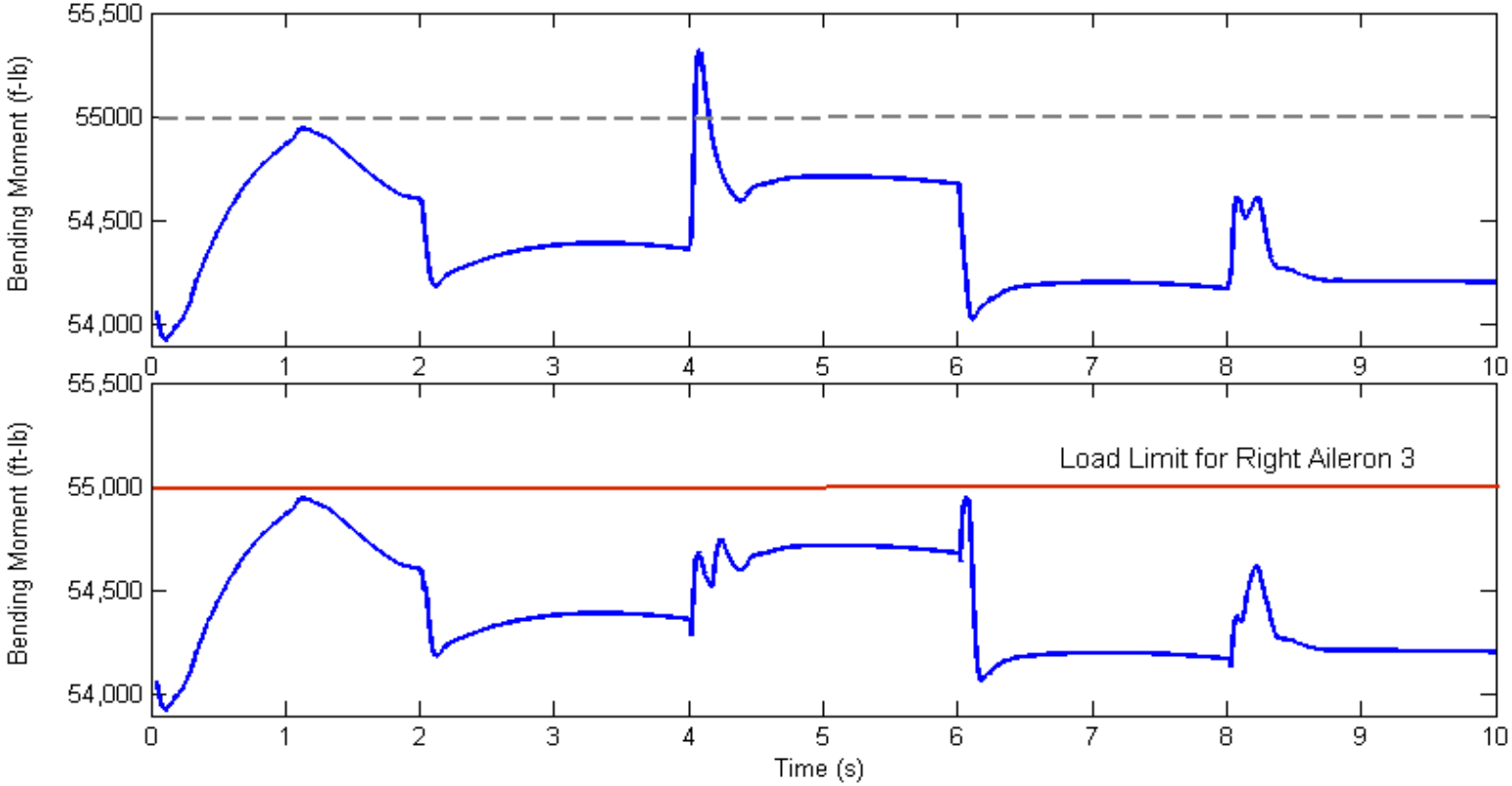


Roll Doublet Case I



Bending Moment for Right Outboard Aileron

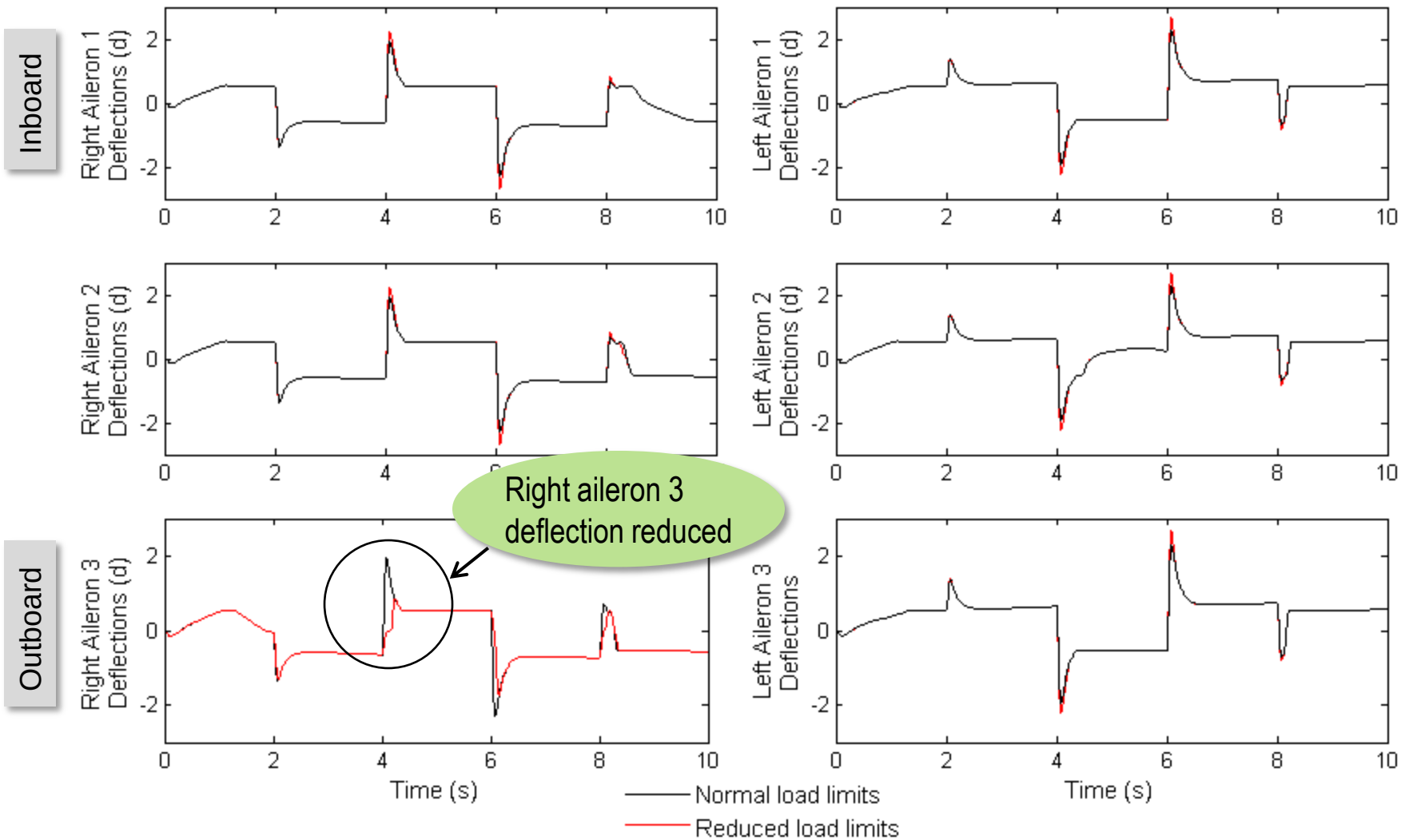
Case I: Outboard aileron critical point limit set to 55,000 ft-lb



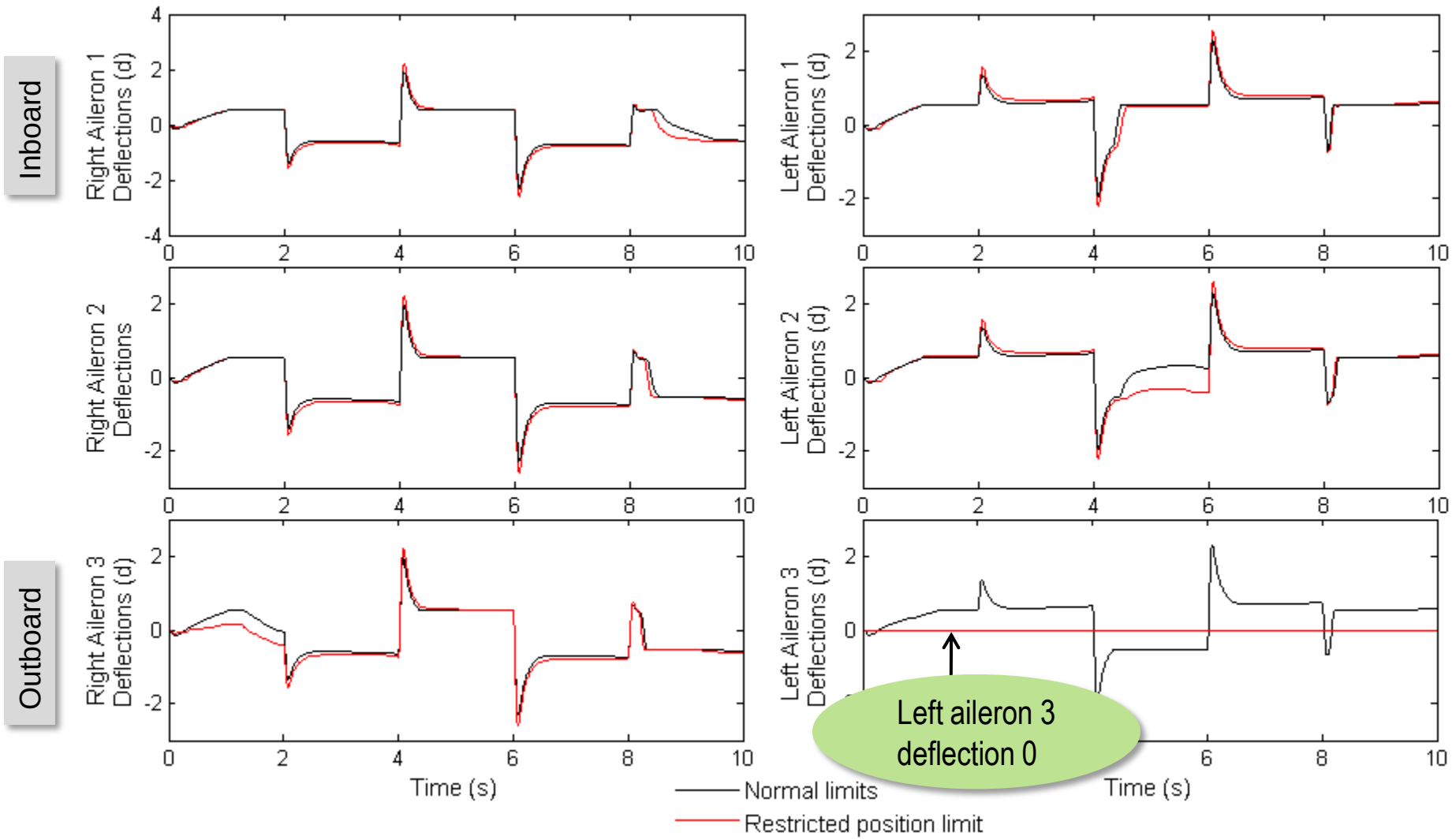
Normal Load Constraints

Reduced Load Constraints

Aileron Deflections Case 1



Aileron Deflections Case II



Formulation & Solution Approaches

Mixed Optimization Formulation

Find u that minimizes $J = \left\|(CB)u - a_d\right\| + \varepsilon\left\|u - u_p\right\|$

subject to $u_{\min} \le u \le u_{\max}$, $\left|\dot{u}\right| \le \dot{u}_{\max}$

Solution Approaches Using Different Norms

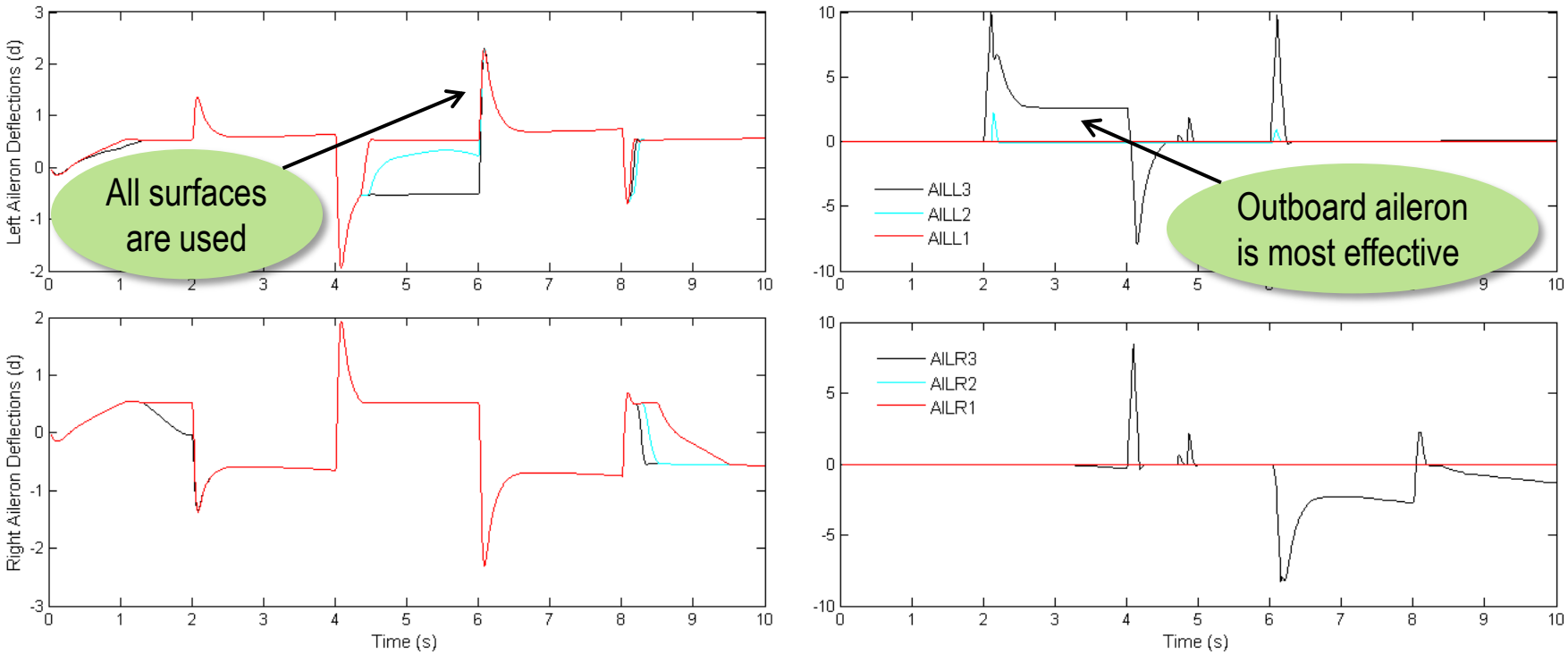
- **ℓ_1 norm:** $\left\|u\right\|_1 \equiv \sum_i \left|u_i\right|$

  Convert to linear programming problem
  - Simplex algorithms (Bodson)
  - Interior-point algorithms (Peterson, Bodson)
- **ℓ_2 norm:** $\left\|u\right\|_2 \equiv \sqrt{\sum_i u_i^2}$
  - Active Set Method with norms squared (Härkegård)
  - Interior-point algorithms
- **ℓ_∞ norm:** $\left\|u\right\|_\infty \equiv \max_i (u_i)$
  - Simplex algorithm (Bodson, Frost)

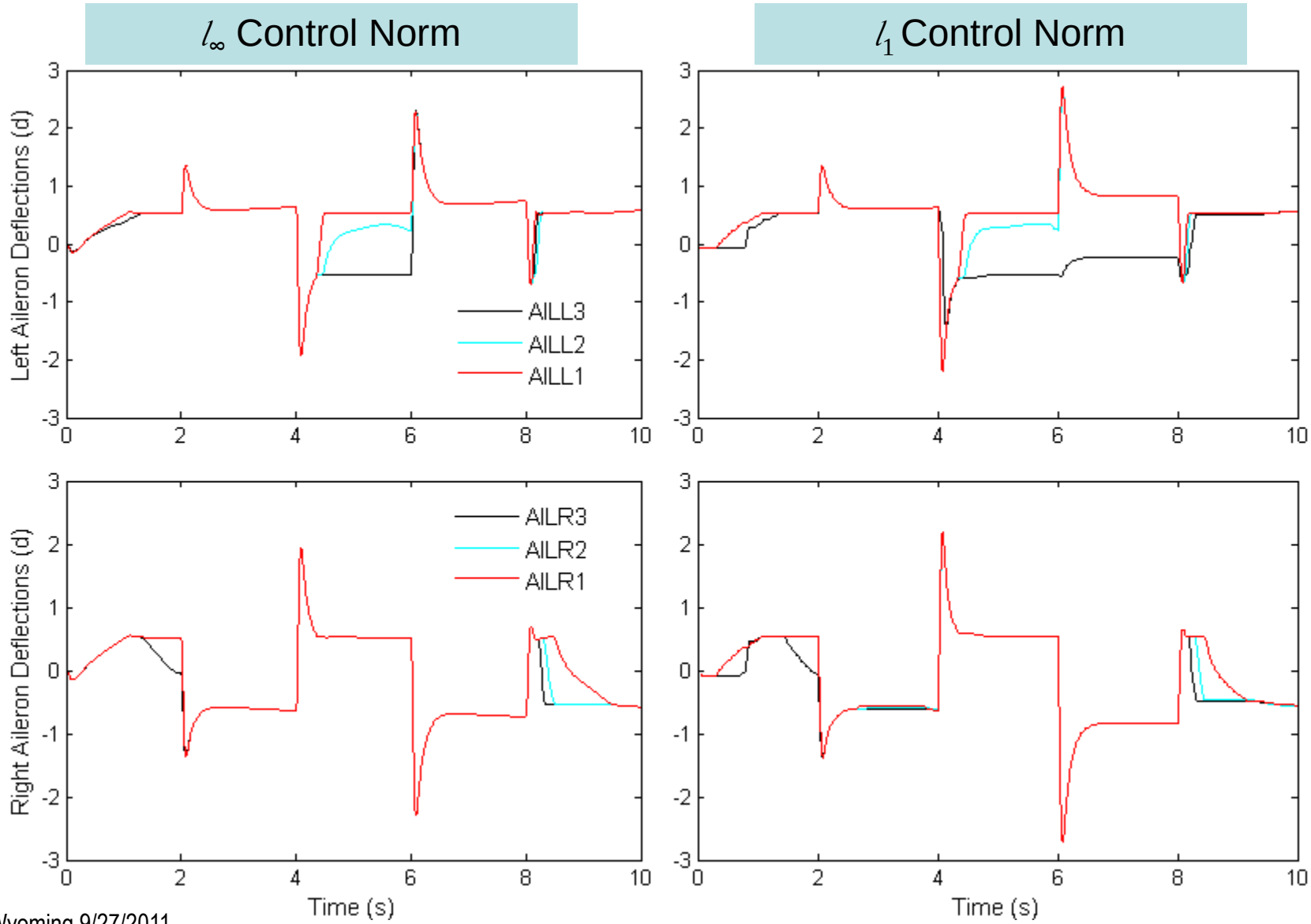
Normal Case with l_∞ versus l_1 Norm on Control

l_∞ Norm on Control

l_1 Norm on Control



Normal Case with l_∞ versus l_1 Control Norm



Conclusions & Future Work

Proposed framework performed adequately in simulation & proof of concept demonstration was successful

- Control allocation
  - Try load minimization
  - Use weights on surfaces and critical points depending on health of components
  - Explore non-feasible solutions
- Loads model
  - Investigate robustness, computation time, sensitivity
  - Include torsion, structural dynamics
- Work with sensors to measure loads
- Include aeroelasticity in simulation
- Flight test technology at Dryden Flight Research Center

Our Next Challenge: Distributed Control Effectors

Objective:

- Develop variable stiffness materials for distributed control effector skins

Approach:

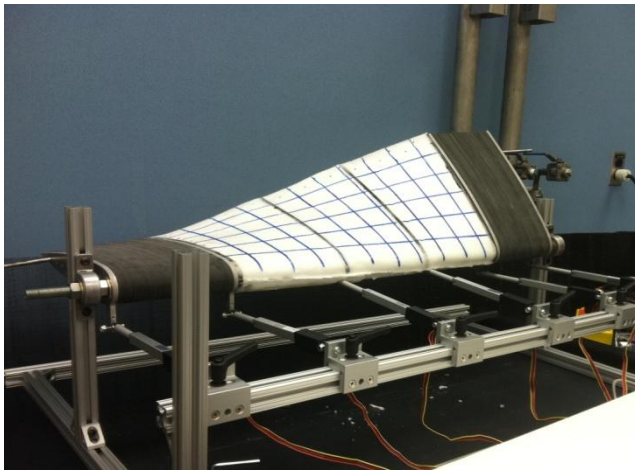
- Investigate mechanisms that can impart variable stiffness to material systems to enable novel control effectors to control lightweight flexible wings
- Test various concepts on distributed control effector model to determine feasibility as a structural element

Significance:

- Variable stiffness material systems can enable control of aeroelastically tailored lightweight wings to meet SFW fuel burn goals

Results:

- Bench model (shown top right) developed to study angles and deformations of distributed control effectors to develop requirements and test candidate variable flexibility control surface skins
- This activity will involve materials, structures, aeroelasticians, controls and dynamics experts working concurrently to design, analyze, build and test a distributed control surface concept



Above: Bench model of distributed control surface
Below: Sketch of aeroelastically tailored wing with distributed control effector on trailing edge

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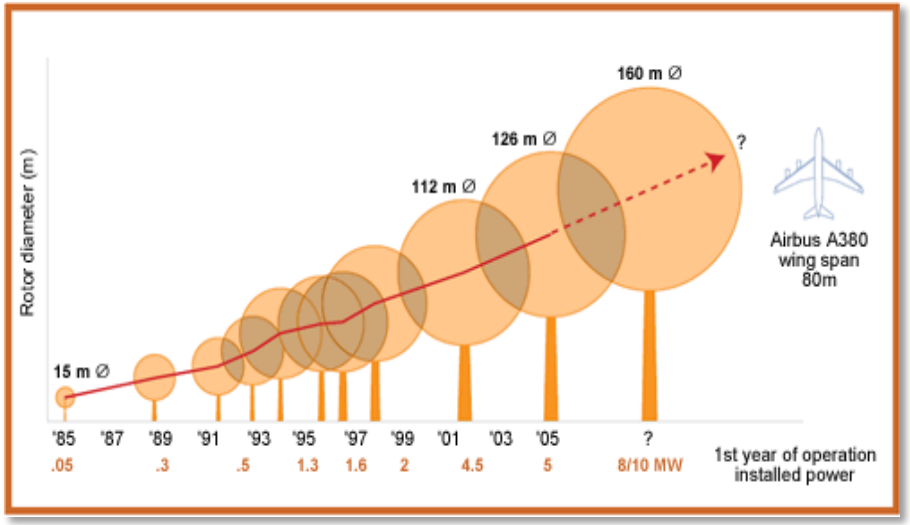
Wind Industry Observations

Wind Industry Practices

- Industry is relatively low-tech and very protective of IP
- Research funding is limited
- Very little vertical stratification
- New technologies need **quick** and **cost-effective** integration

Wind Industry Challenges

- Building large turbines (>5 MW)
- Operating & maintenance costs
- Turbine reliability
- Grid integration
- Community noise
- Wind farm siting

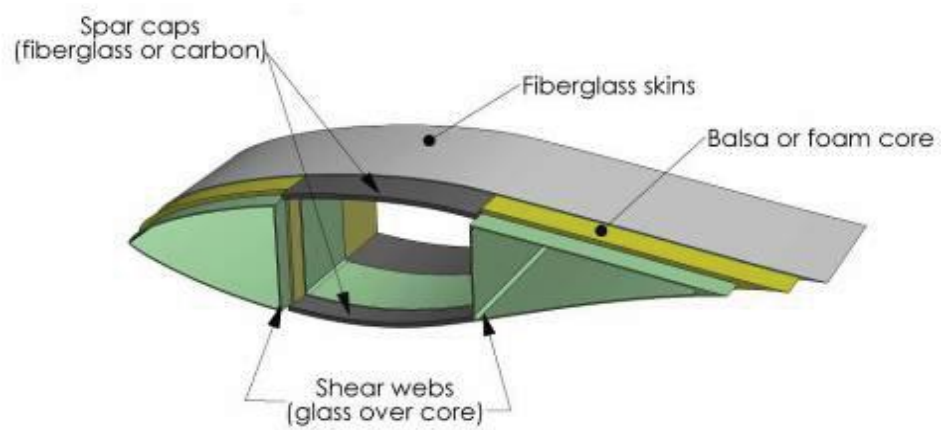


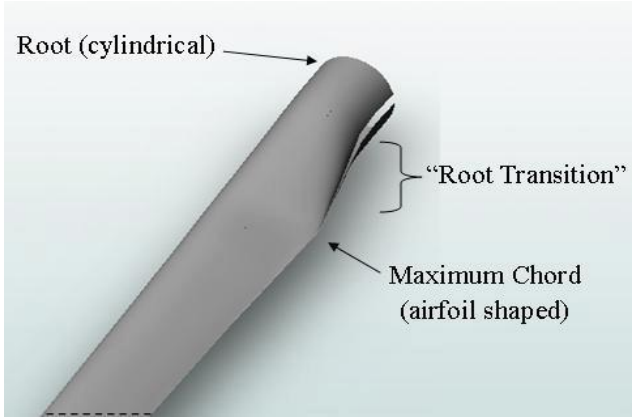
Condition Monitoring in Wind Turbines

- SCADA system
  - Supervisory Control and Data Acquisition for wind farm
  - Medium- and long-term changes in environmental & operating conditions
  - Minimal fault diagnosis
  - Lots of data, not always useful
- Short-term condition monitoring
  - Equipment set up for one month for vibration, acoustic, strain, nacelle acceleration testing
- Scheduled maintenance & inspection
- Acceptance of CM by operators/developers
  - Dependent on cost of CM system
  - Might affect warranty
- Some OEMs are moving towards guaranteed uptime

Image: www.vertigo.net.au

Leading Causes of Blade Failures[1]





1) Manufacturing defects - wrinkles in laminate, missing or incomplete bond lines, dry fibers
2) Progressive damage initiating from leading-edge erosion, skin cracks, transport, handling, or lightning strikes
3) Excessive loads from turbine system dynamics or dynamic interaction with control system
4) Out-of-plane forces and distortion of blade sections ("bulging/breathing" effect) mostly in root transition region, due to blade loading
5) Excessive loads due to unusually severe atmospheric conditions

[1]DNV Renewables, Seattle, WA, "Lessons Learned from Recent Blade Failures: Primary Causes and Risk-Reducing Technologies", D.A. Griffin & M.C. Malkin, 49th AIAA Aerospace Sciences Meeting, Jan 2011, paper no. 2011-259

Flexible Structure Control

Flexible Structure Control Challenge:

- Structural modes can be excited by feedback control
- Low pass filter can reduce problems, but they have limitations
- Residual mode filter (RMF) has model of structural mode, including phase and frequency, that can be removed from feedback
- Flexible structures ARE intrinsically modal systems

- Flexible aerospace structures are difficult to model and they operate in poorly known environments
- Adaptive control **helps**, but requires minimum phase plants (ASPR)
- Residual Mode Filters (RMF) can cancel transmission zeros, restoring ASPR

Recall: A system(A, B, C) is ASPR when $CB > 0$ and its closed-loop transfer function $P(s) = C(sI - A)^{-1}B$ is minimum phase.

Partition Plant into ASPR & non-ASPR

Assume original system $(\mathbf{A}_p, \mathbf{B}_p, \mathbf{C}_p)$ can be partitioned into:

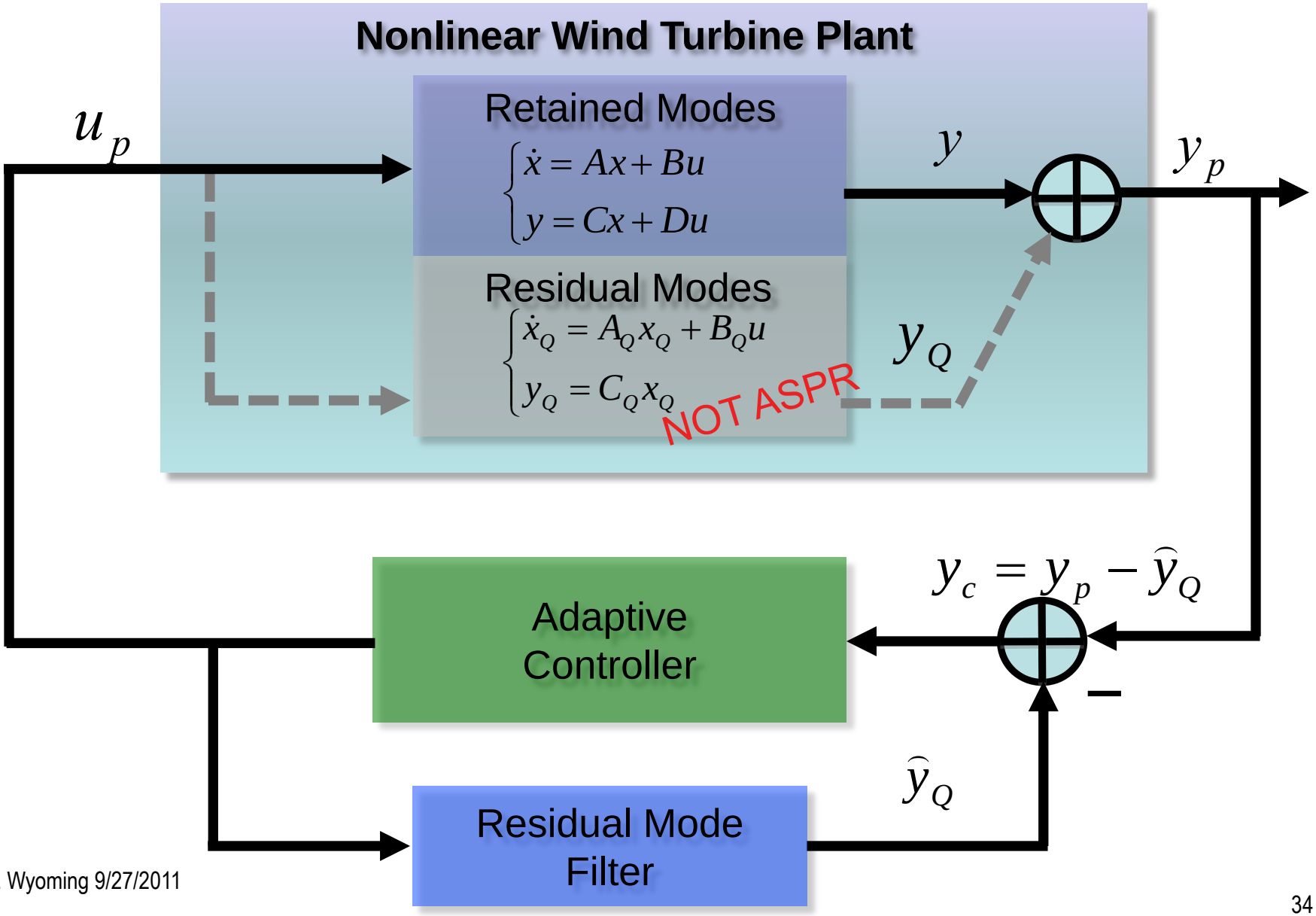
$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{x}_Q \end{bmatrix} = \begin{bmatrix} A & 0 \\ 0 & A_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix} + \begin{bmatrix} B \\ B_Q \end{bmatrix} u_p + \begin{bmatrix} \Gamma \\ \varepsilon \Gamma_Q \end{bmatrix} u_D \\ y_p = \begin{bmatrix} C & C_Q \end{bmatrix} \begin{bmatrix} x \\ x_Q \end{bmatrix}; \ \varepsilon \geq 0 \end{cases}$$

Use RMF to remove these modes from controller feedback

Controlled Plant

Reduced Order Model	All Residual Modes
All Open-Loop Unstable Modes that are ASPR	Q modes Open-loop stable not ASPR in Closed-Loop

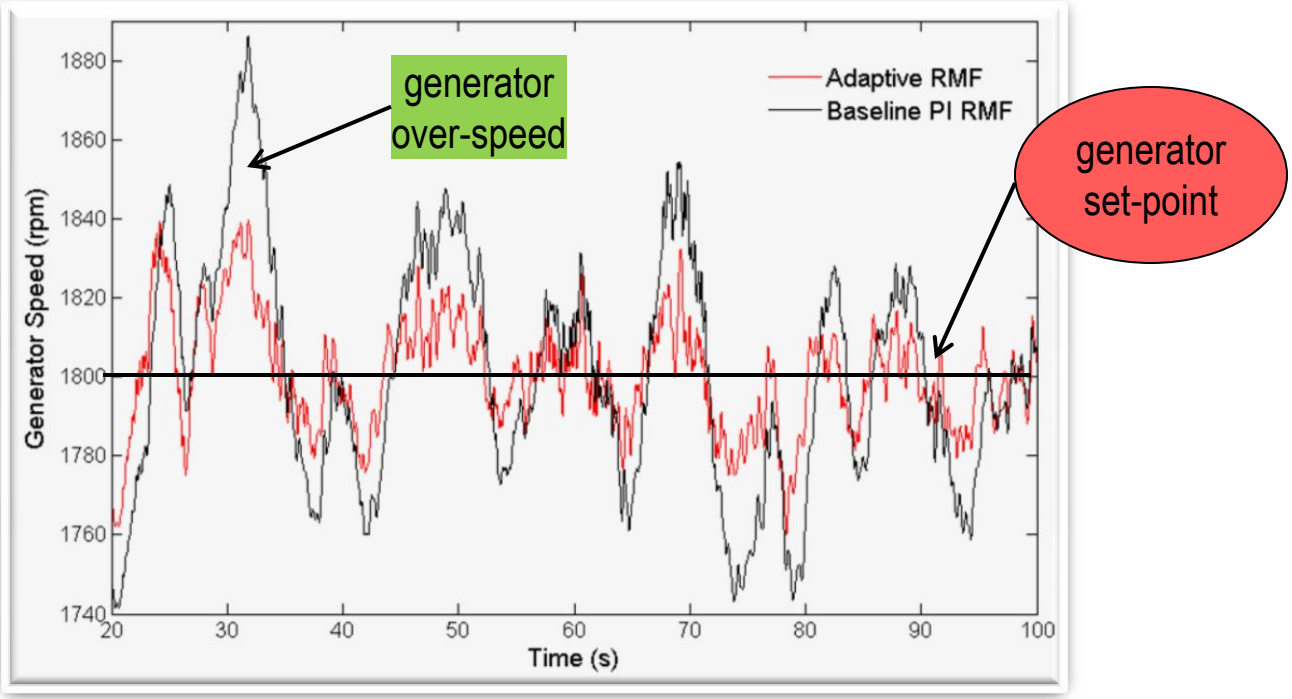
Adaptive Controller using RMF



Adaptive Pitch Control for FAST Simulator*

- **Objective**: Regulate generator speed and reject disturbances
- **Input:** Rotor speed
- **Output:** Collective blade pitch, constant generator torque
- **Disturbance:** Step function
- **How**: Model gusts as step functions
- **RMF** Designed for drive-train rotational flexibility mode

Generator speed for turbulent wind input
---- Baseline PI
---- Adaptive RMF

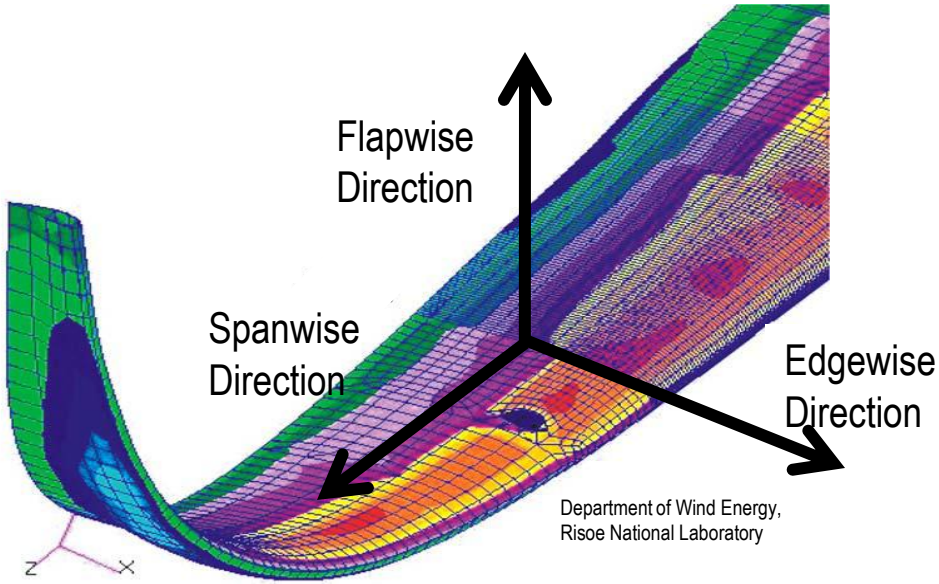


*NREL's FAST simulator of CART2 (high fidelity simulation of flexible 2-bladed wind turbine) see: http://wind.nrel.gov/designcodes/

FAST Turbine Blades

FAST blade configuration files:

- 21 distributed stations along span
- Flapwise & edgewise stiffness
- Flapwise & edgewise bending modes



Assumption:

Blade damage can be represented by reduction in flapwise & edgewise stiffness

Damaged blade configuration files:

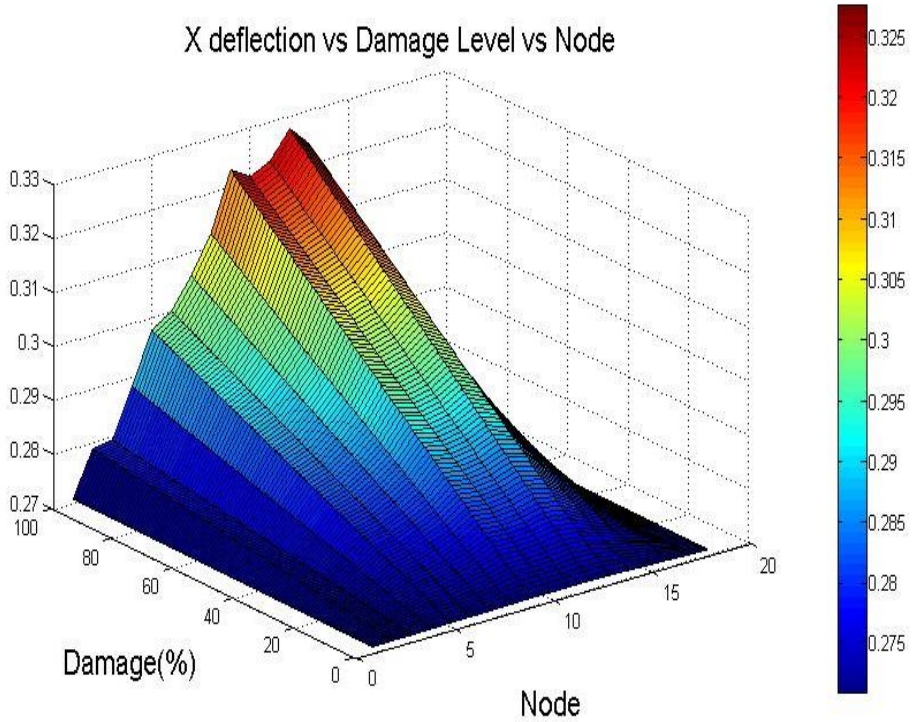
- Edgewise and flapwise stiffness are varied at a blade station
- Blade bending mode shapes are recomputed
- Structural damping and other parameters were left unchanged

Blade Node Sensitivity to Stiffness Changes

Full factorial study performed to determine node sensitivity:

- Parameters: blade damage, wind speed, blade pitch
- Levels: 8 for damage, 7 for wind, 10 for blade pitch

Loads on blades are primarily due to aerodynamic forces

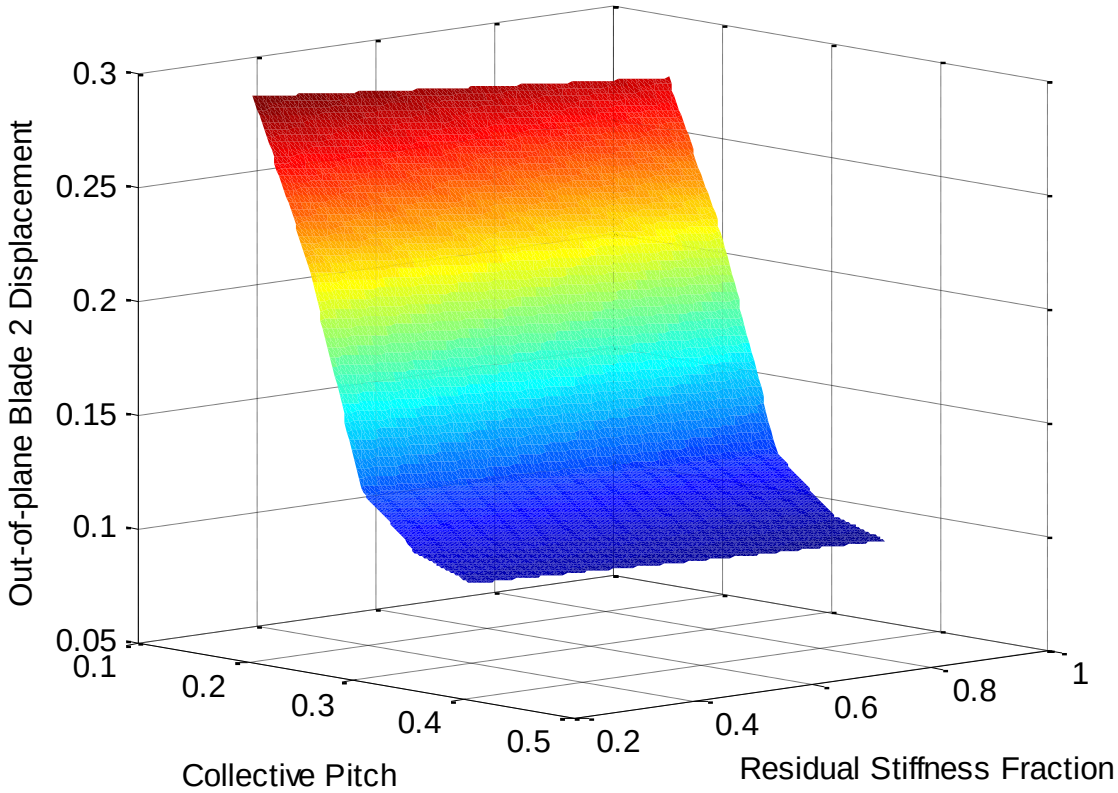


Study of Turbine Response to Blade Damage

Preliminary study of effects of blade stiffness reduction

- Damage located on one blade at station 7, 30% from blade root
- Study run in open-loop with no generator speed tracking
- Generator torque held fixed at rated torque
- Simulation run with steady wind speeds from 12-24 mps
- Collective pitch varied from 0.1-0.45 radians
- Blade tip displacement was measured

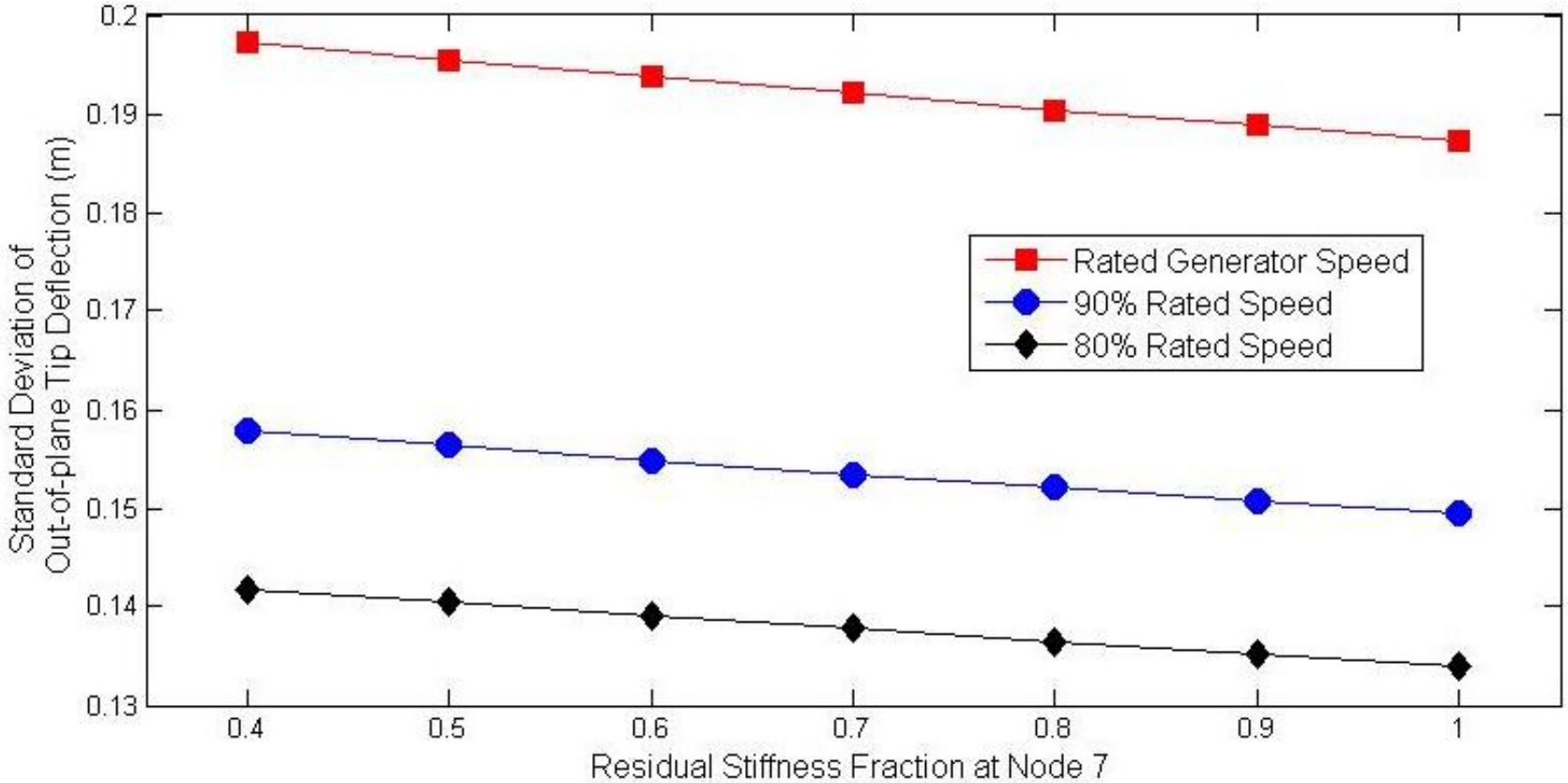
Tip Displacement vs Pitch vs Damage



- Pitch & wind speed dominate change in stiffness
- Damage detection tool needs to factor out impact of pitch and wind speed to use deflection

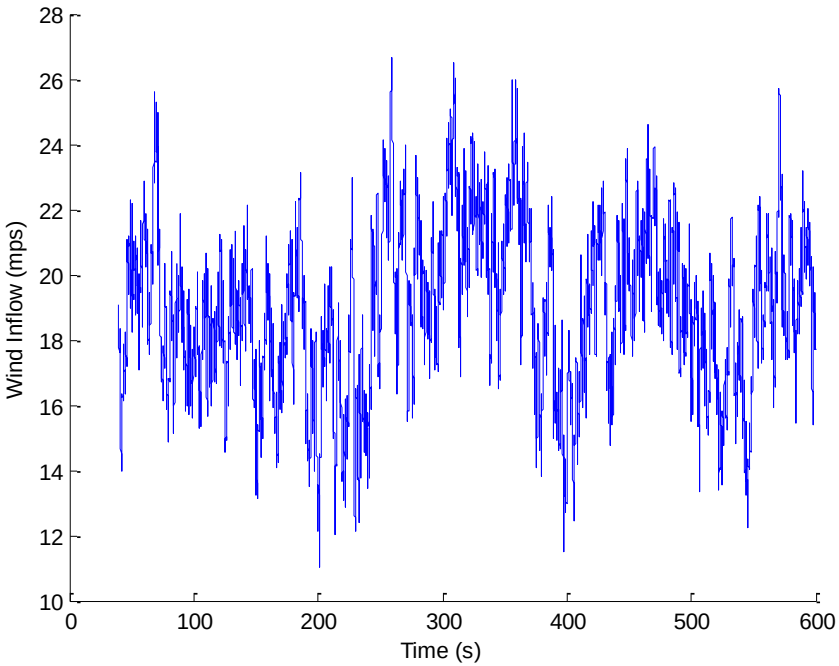
Change in Tip Deflection with Power Output

Hypothesis: Reducing power output through generator set-point reduction will reduce loads on turbine blades

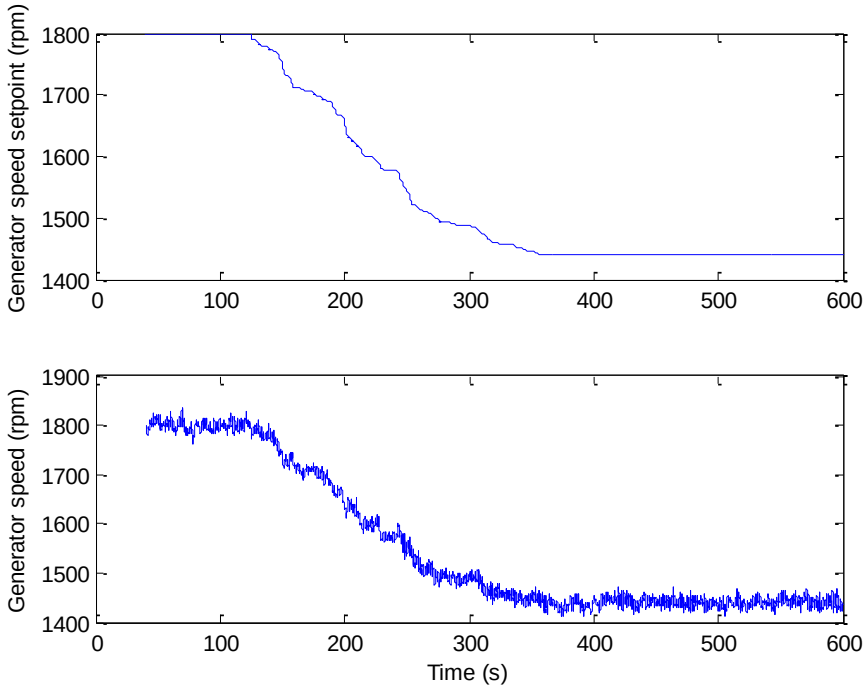


Out-of-plane tip deflection std. dev. for 3 generator set-points & 7 damage levels.

De-rating Generator for Reduced Loads



Simulation Wind Input

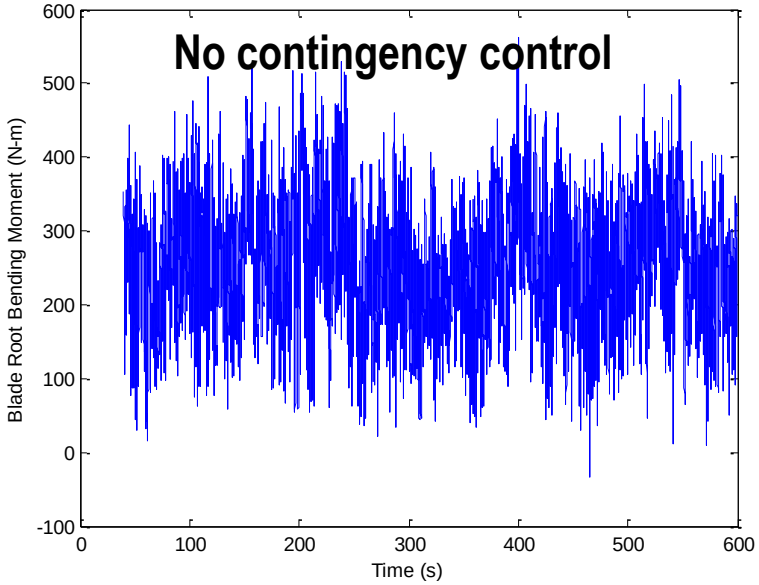


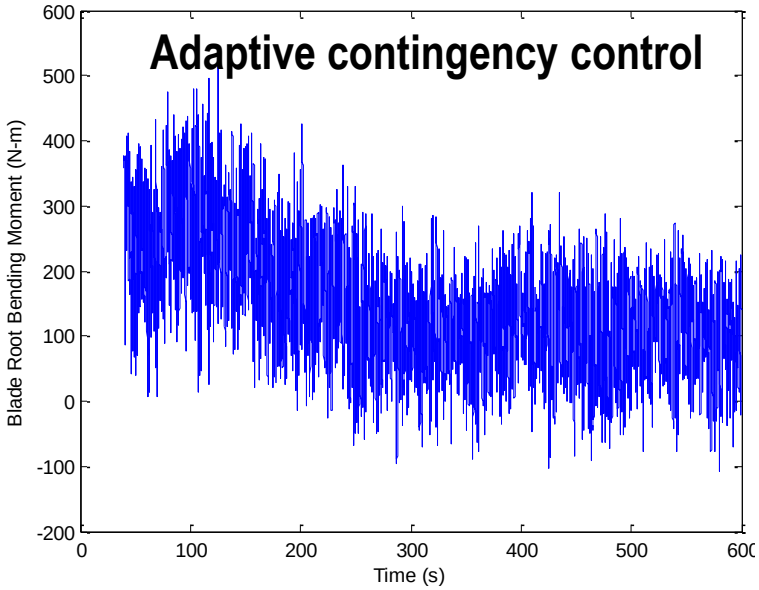
Top: Generator set-point
Bottom: Generator speed

Control Integrated with Condition Monitoring

- Simulation demonstrating contingency controller lowering generator set-point for turbine with blade damage when winds are turbulent & above rated speed
- Resulting decrease in blade root bending could extend service life

Blade root bending moment





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