Review of IEA Smart Structures Meeting & Review of Sandia Active Aerodynamic Flow Control Efforts

Dale E. Berg
Sandia National Laboratories
Albuquerque, NM USA

May 12-14, 2008

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

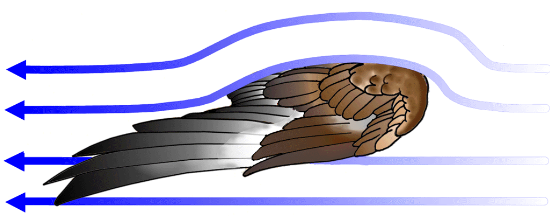
- Brief Review of IEA Expert Meeting on Smart Structures
  - objectives
  - why investigate local load control
  - areas of concern
  - trailing edge flap results
  - blade integration issues
  - sensor investigation efforts
- Sandia Active Aero Control Efforts
  - microtab concept
  - system modeling
  - cooperative efforts

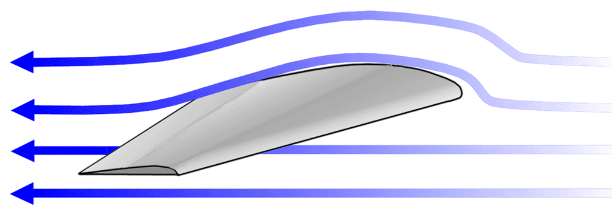
Objectives of Smart Structure Concept

- **Significantly reduce blade loads**
  - vary with position on blade
  - vary with time scale of a few seconds
- **Increase energy capture**
- **Flow control utilizing distributed**
  - sensors
  - intelligence
  - small, fast-acting control devices
- **Modify local aerodynamics of the blade**
- **Maintain reliability**
- **Minimize additional cost**

Why Look at Local Control?

RISØ





Sandia National Laboratories

Why Local Load Control?

- Large size means loads vary quickly & dramatically along blade
- Active pitch control can only control “average” load on blade
- Passive load control cannot respond to local load variations
- Fatigue loads can drive the lifetime of all turbine components

What Benefits do We Expect to Gain?

- **Lower fatigue loads**
- **Increased energy capture**
- **Actively suppress vibration (certain modes)**
- **Control noise?**
- **To fully realize the potential benefits, may need to design a machine from scratch that integrates local flow control**

Key Areas of Concern

- **Aerodynamics of airfoils with distributed control elements**
  - **Multiple devices available to adjust lift & drag**
  - **Need CFD(?) tools to determine device performance characteristics**
  - **Need aero/CFD(?) tools to determine control effects on entire system**
- **Actuators**
  - **Control device must be deployed, retracted, moved**
  - **Bi-stable or multi-stable devices are interesting**
- **Sensors**
  - **Many types are available today**
  - **What do we need to measure?**
    - loads
    - state of flow
    - deflection
    - acceleration
    - ????

Key Areas of Concern

- **Controls**
  - **Major development required**
  - **Needs:**
    - fast
    - real-time load identification
    - fault tolerant
    - improved energy capture
    - site and condition adaptive (self learning)
    - failsafe
    - predictive?
    - multiple time scales, multiple impact levels

Key Areas of Concern

- **Communications and power supply**
  - **Not usually considered high tech problem**
  - **immune to lightning**
- **New blade materials and construction**
  - **Incorporate control devices/actuators/sensors**
  - **Preserve integrity of blade interior**
  - **Replaceable control elements**
- **Blade design and analysis tools**
  - **Increase capability**
  - **Accommodate**
    - innovative blade construction
    - distributed control

Sandia National Laboratories

Why Focus on Trailing Edge Devices?

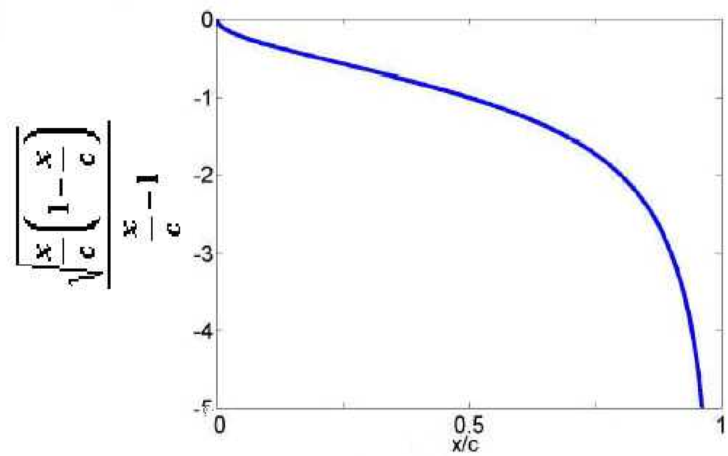
- **From Thin Airfoil Theory**

$C_l = C_{l\alpha} + C_{lc}$

Where

$C_{l\alpha} = 2\pi\alpha$ *is lift due to airfoil angle of attack*

$$C_{lc} = 4\int_{x/c=0}^{1} \frac{d(y_c/c)}{d(x/c)} \frac{\sqrt{\frac{x}{c}\left(1-\frac{x}{c}\right)}}{\frac{x}{c}-1}\, d(x/c)$$ *is lift due to airfoil camber*

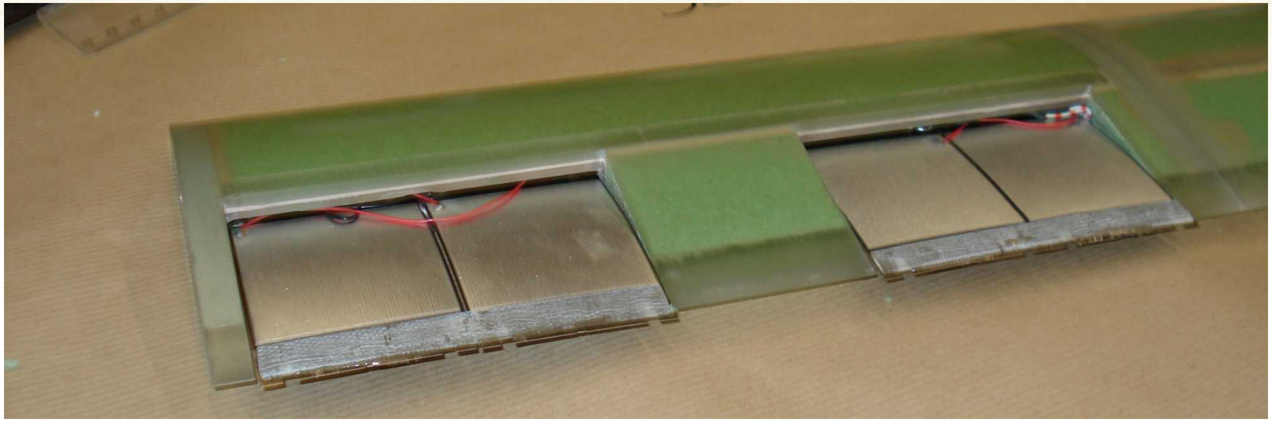


– **effect of camber is greatest at trailing edge**

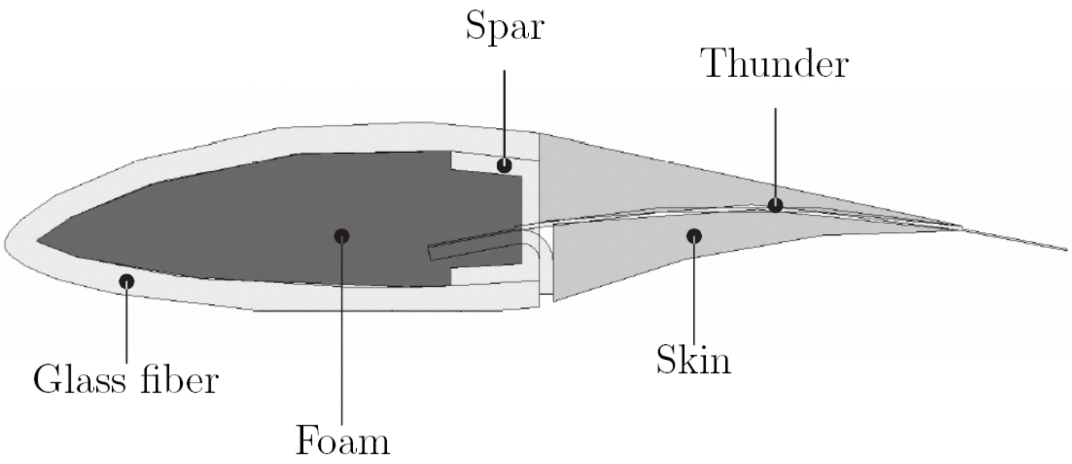
- **Aerodynamic Loads are Low at Trailing Edge**

Experimental Design

- Wind tunnel
- Blade
- Pitch system
- Trailing edge flap
- Sensors
- Real-time system



- Flexible trailing edge flap
- Piezo bender (Thunder)
- High voltage requirements



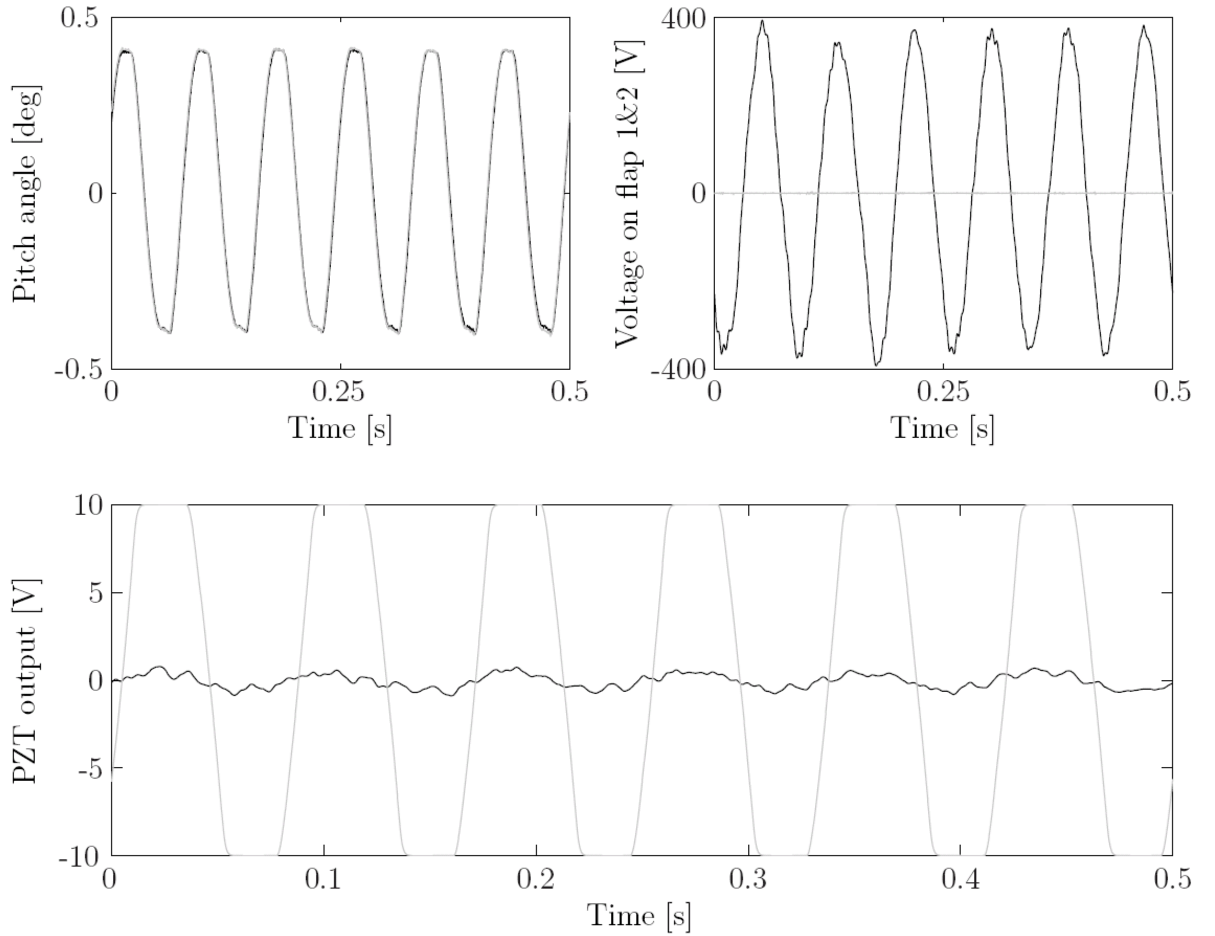
Experimental Results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees

Eigenfrequency

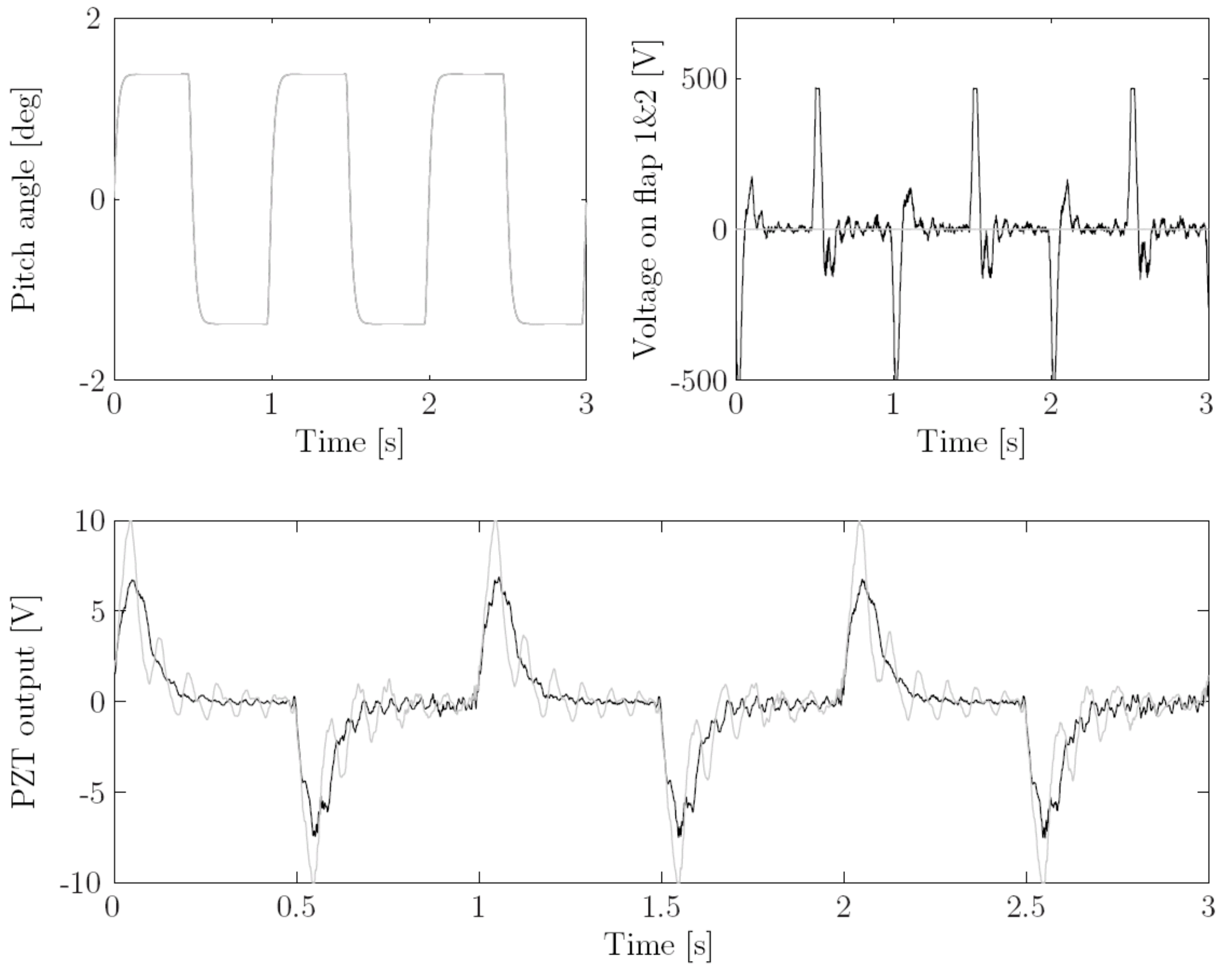


Experimental Results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

V= 30 m/s

α= 6 degrees



Sandia National Laboratories

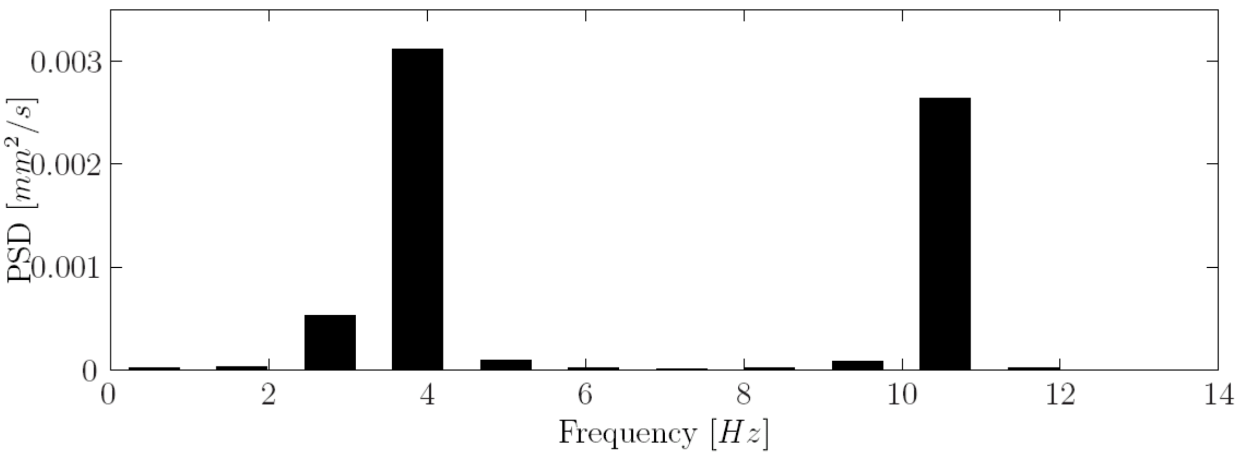
Experimental Results

- Feedforward control
- Feedback control
  - Periodic disturbance
  - Step disturbance (gust)
  - Random disturbance (turbulence)

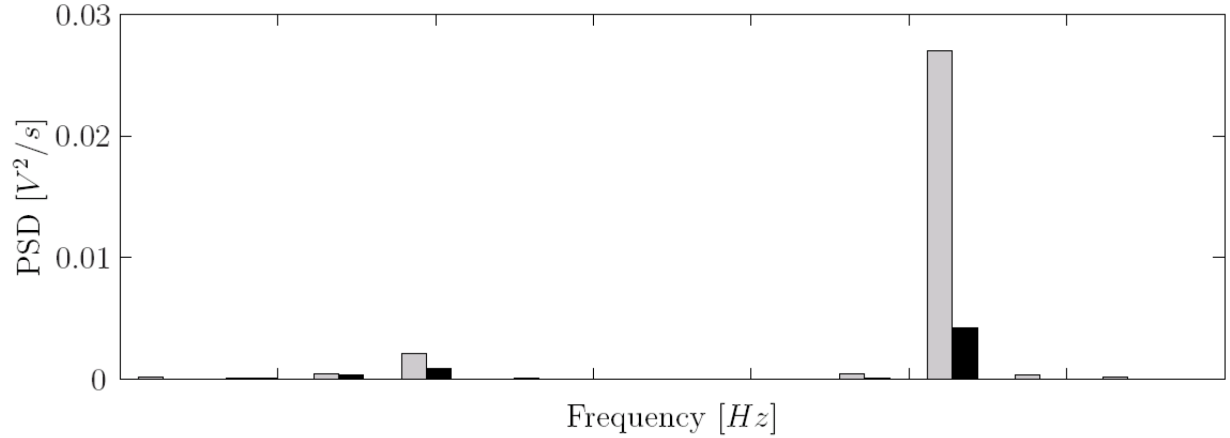
V= 30 m/s

α= 6 degrees

Input spectrum



Output spectrum

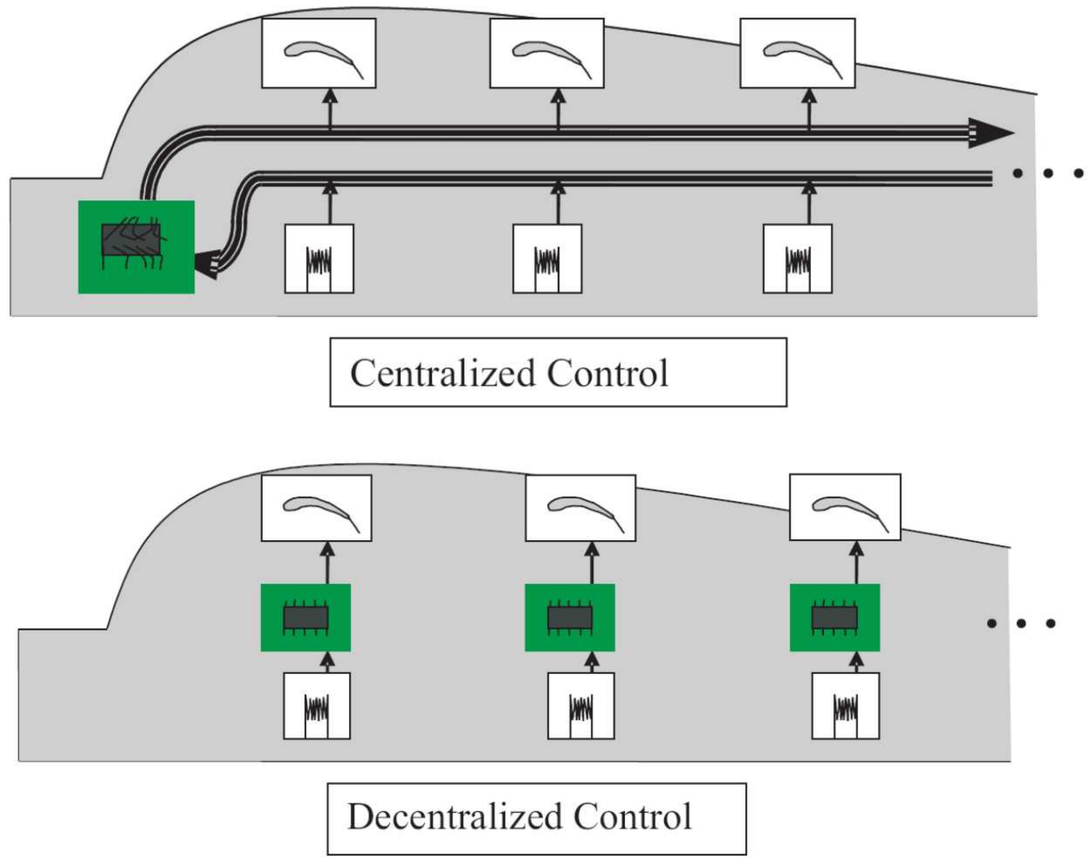


Sandia National Laboratories

Challenges: Distributed Control

Control for distributed systems

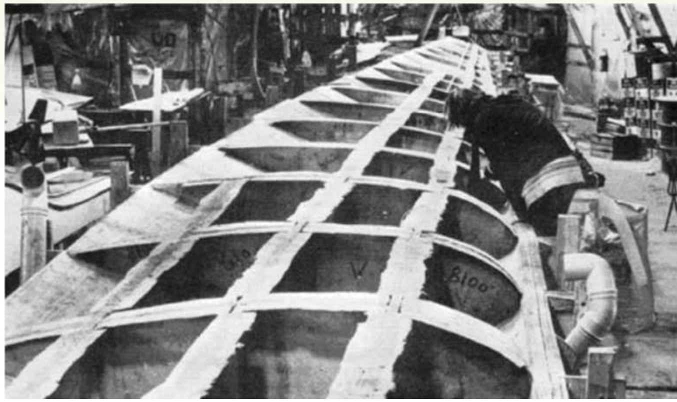
- Large number of actuators and sensors
- Centralized vs Decentralized control
- Or....



Rice

Sandia National Laboratories

Device Integration

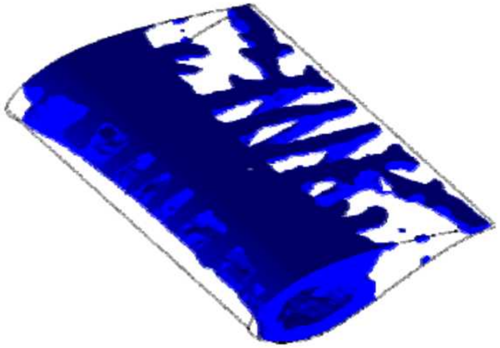


Utilize Thermoplastic Material

Adding elements

↓

Adding ribs



↓

Rib-spar design,

in combination with TPC material system

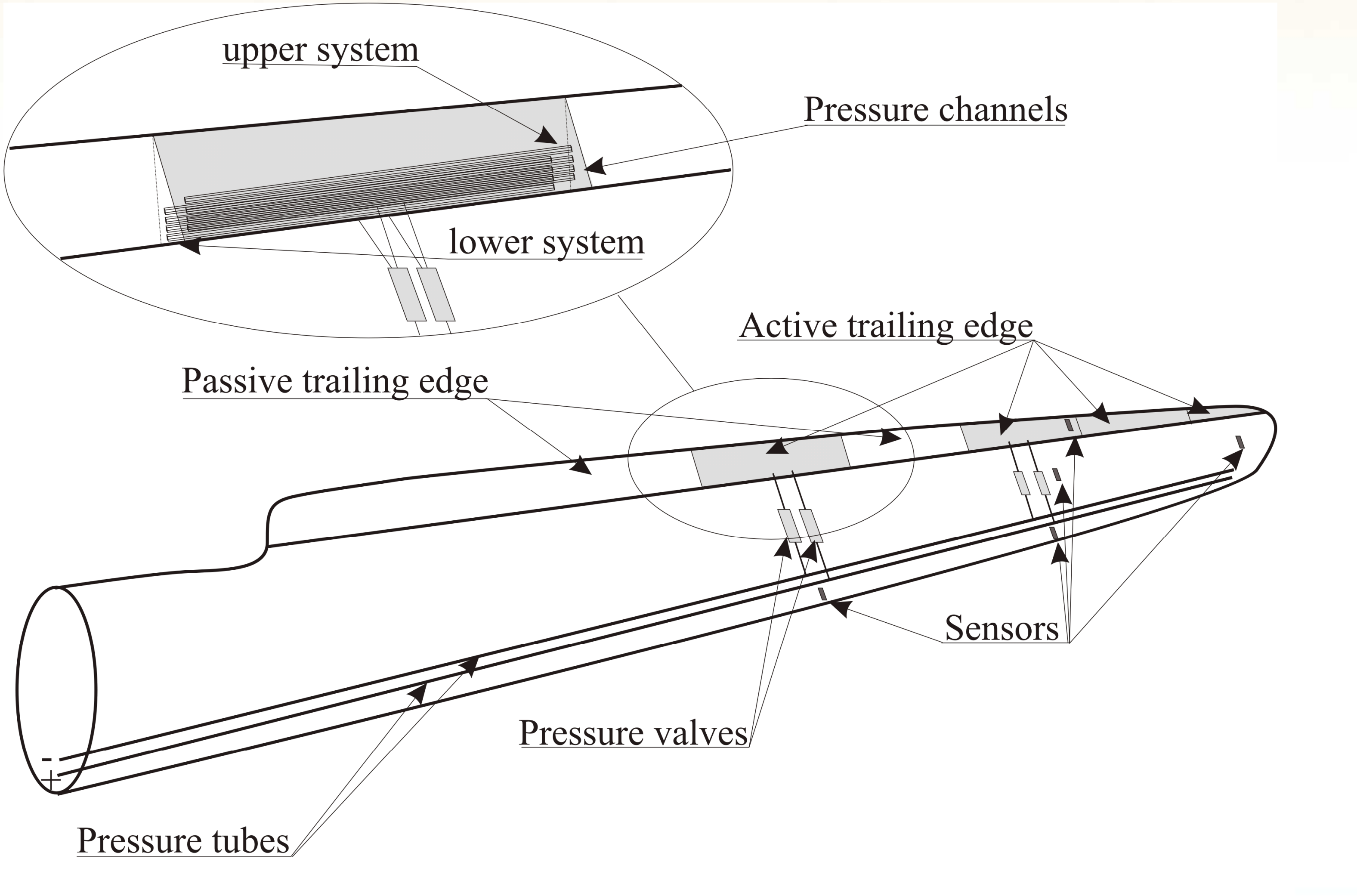
Through-out the whole blade: structurally more feasible??

Device Integration

Rib-spar, TPC design through-out the whole blade: structurally more feasible?

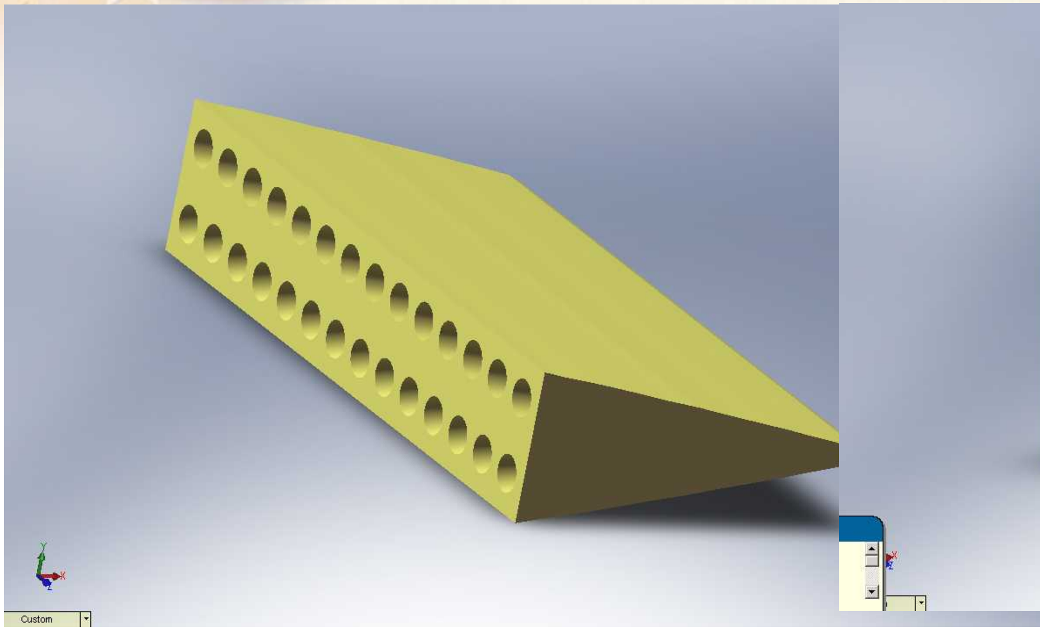
1. (100%?) reduction in foam/balsa,
2. Ease assembling through welding,
3. Load paths,
4. Possibly added value for sectional blades.

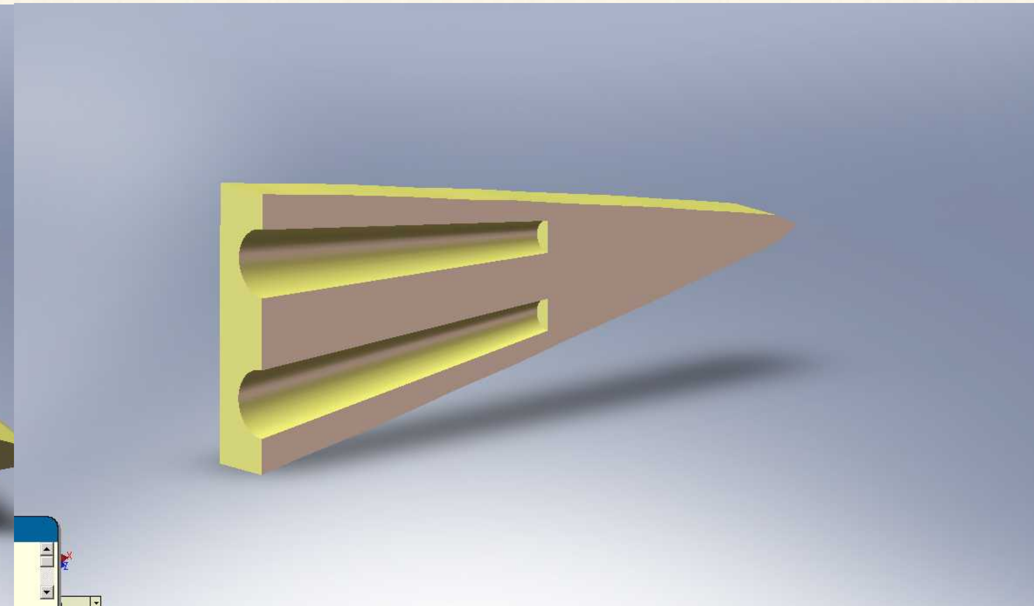
New concepts

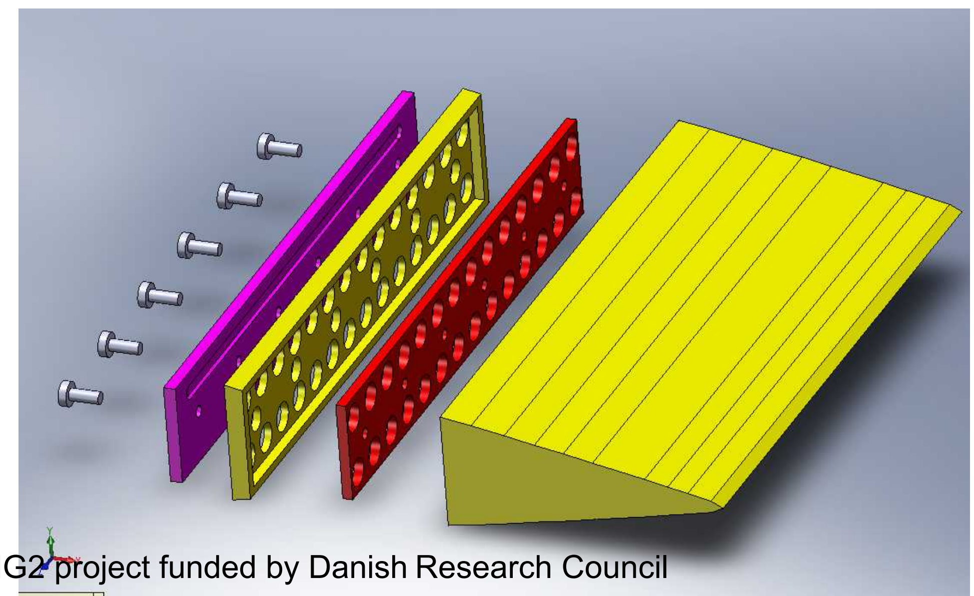


From the ADAPWING2 project funded by Danish Research Council

New concepts







From the ADAPWING2 project funded by Danish Research Council

Development Process Stages

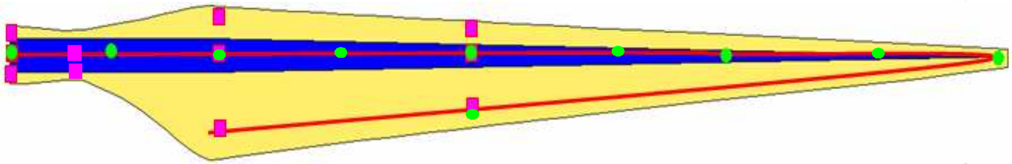
- Research
  - analysis
  - laboratory testing
- Proof of Concept
  - small/medium scale prototype testing
- Commercial Viability
  - large scale prototype field testing
- Commercial application

Sensor Tasks at Sandia Labs

- **Fully anticipate advanced control strategies**

- **Address Sensor-in-Blade Issues**
  - **Incorporation** (material compatibility, egress/ingress, surface-mount/embed, manufacturing, maintenance accessibility, costs)
  - **Reliability** (long-term aging, robustness)

- **Sensor Blade (SBlade) Project**



- **Sensor and Active Flow/Load Control Lab**
  - **Model and validate sensor/actuation performance**
  - **Determine sensor requirements** (accuracy, reliability, cost)
  - **Evaluate various sensing technologies**
  - **Build and test subscale structures**

Sandia National Laboratories

Sensor Blade (SBlade) Project

- **Build a Sensor Blade**
  - **Incorporate sensors in a blade during blade manufacture**
  - **Sensor list:**
    - Embedded FBG sensors (strain and temperature, blade shape)
    - Inner-surface mounted FBG sensors (strain and temperature, loads)
    - Inner-surface mounted accelerometers (blade shape, loads, SHM)
    - Metal foil strain gages (strain, loads)
    - RTD temperature
    - Streaming video on rotor (blade shape)

- **Field Test Sensor Blade**
  - **On-the-ground checkouts and calibrations**
  - **In-the-air checkouts and calibrations**
  - **Measure loads and blade deflections during turbine operation**
  - **Real-time video monitoring**

- **Static and Fatigue Test Sensor Blade)**
  - **Static Proof Test**
  - **Fatigue test to SBlade failure**
  - **AE NDT, SHM (Impedance-based, Virtual Forces, Residual Force, …)**

- **Analyze datasets and report results**

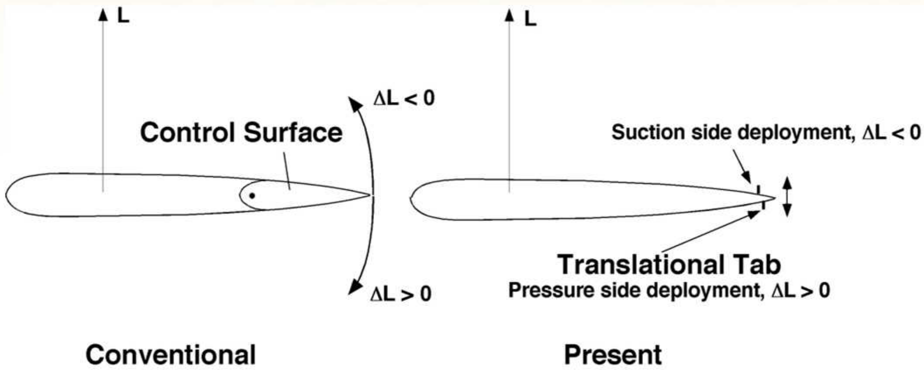
Sandia National Laboratories

Sandia Active Load Control Effort

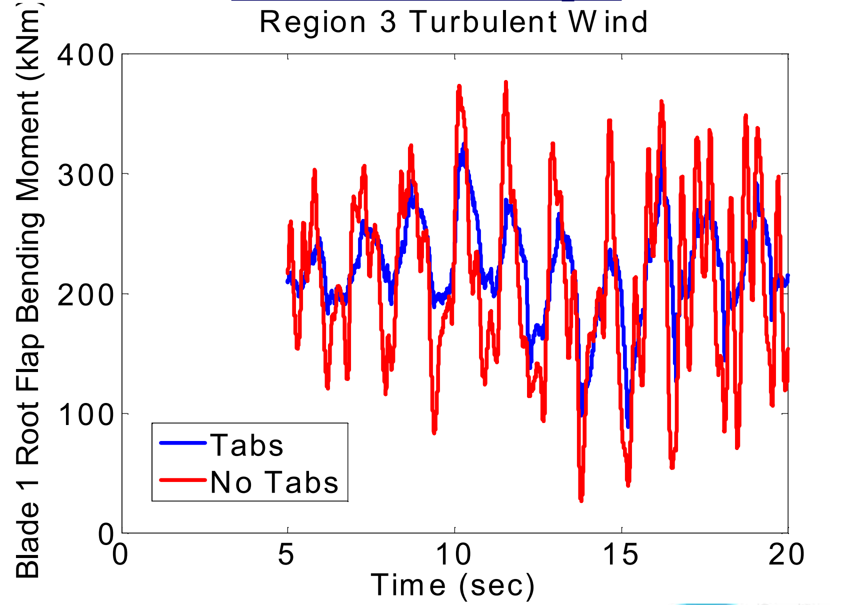
- **Effort will investigate the use of active load control for turbine blades and evaluate its impact on cost of energy**
- **Aerodynamic loading on blade can be modified through:**
  - **Blade incidence angle**
  - **Flow velocity**
  - **Blade size**
  - **Blade aerodynamic characteristics**
- **Focus is on small fast-acting systems that change sectional aerodynamic characteristics to alleviate load spikes due to gusts and to reduce blade tip deflections during high load conditions**

Innovative Concepts Goal & Impact

- **Goal:**
  - Develop small, light-weight control devices & systems to attenuate fatigue loads on turbine blades and enable increased energy capture
- **Current Status:**
  - Devices
    - Investigating micro tabs, morphing trailing edge, and micro flaps
    - Building wind-tunnel model with integrated devices and actuators
  - Actuators
    - Researching durable/low-power, simple designs
  - Controls
    - Developing appropriate control algorithms
- **Industry Impact:**
  - Weight reductions
  - Lower cost of energy



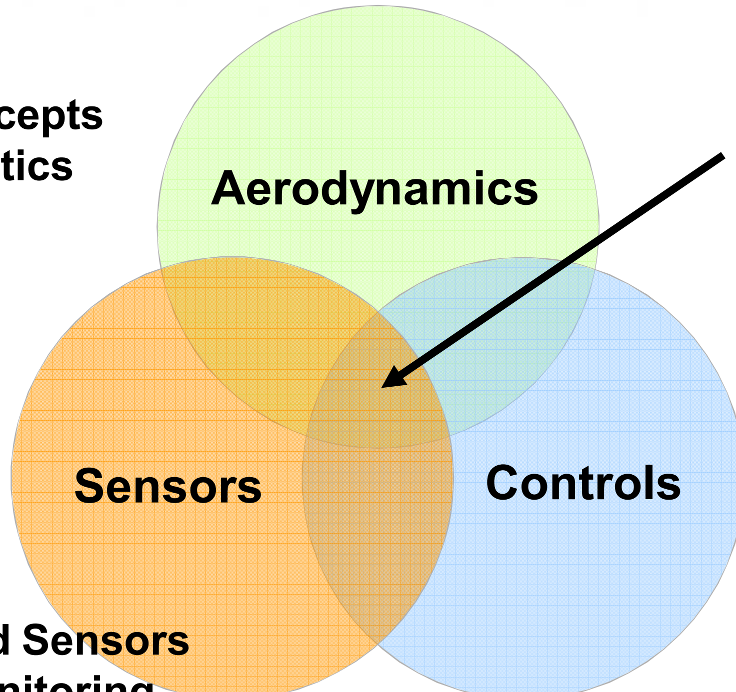
Microtab Concepts



Enabling Smart Blades

Future Design Needs

- Novel Concepts
- Aeroacoustics



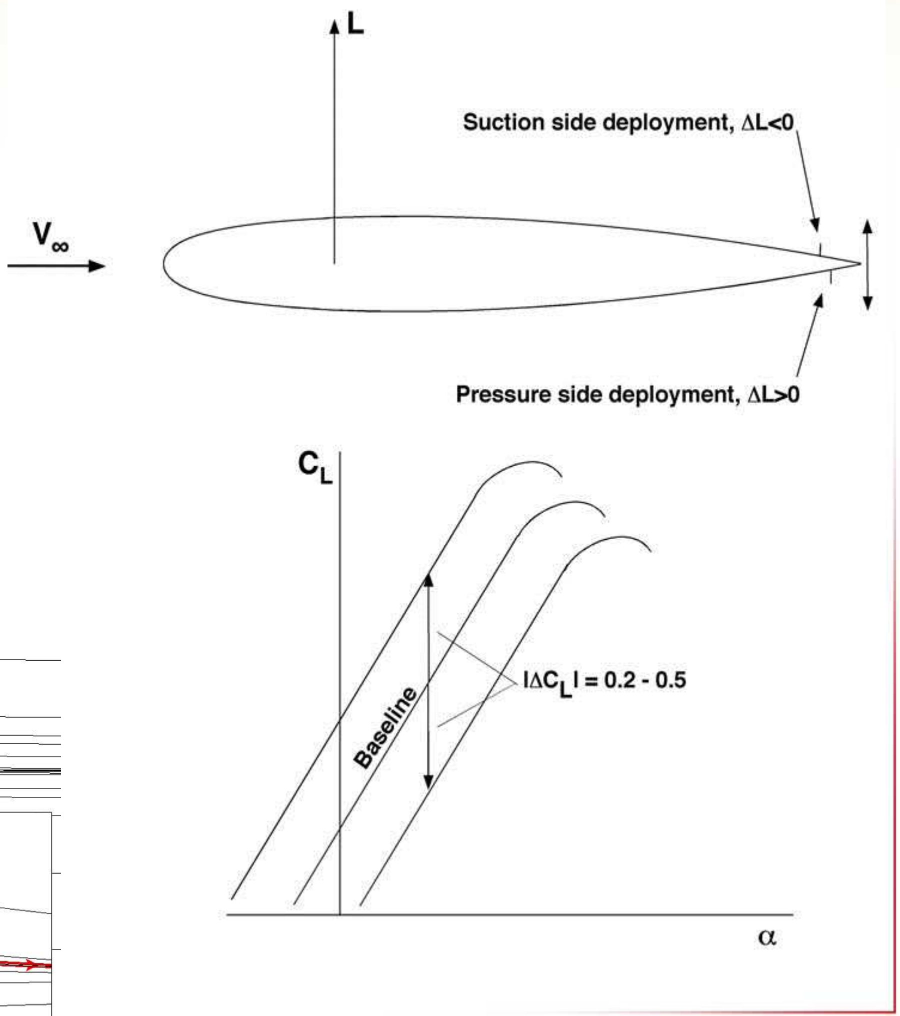
Enabling New Technology
To develop small, light-weight control devices & systems to attenuate fatigue loads on turbine blades and increase turbine efficiency

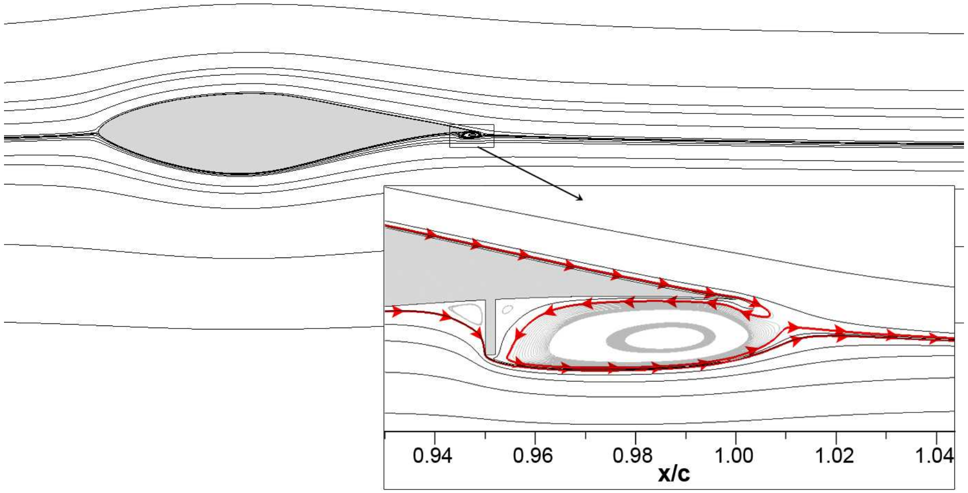
- Advanced Embedded Sensors
- Structural Health Monitoring

- Advanced Control Strategies

Microtab Concept

- Conceptualized in 1998
- Tabs deploy (near-)normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hinge-less device
  - Small actuation forces
- h_{tab} ~ boundary layer thickness
- Trailing-edge flow condition is altered

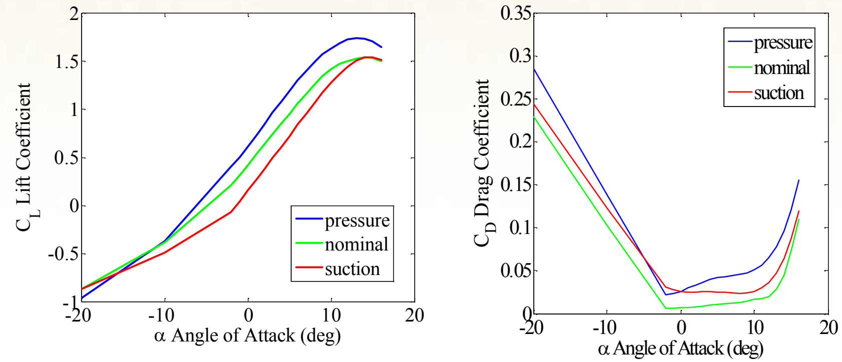




Sandia National Laboratories

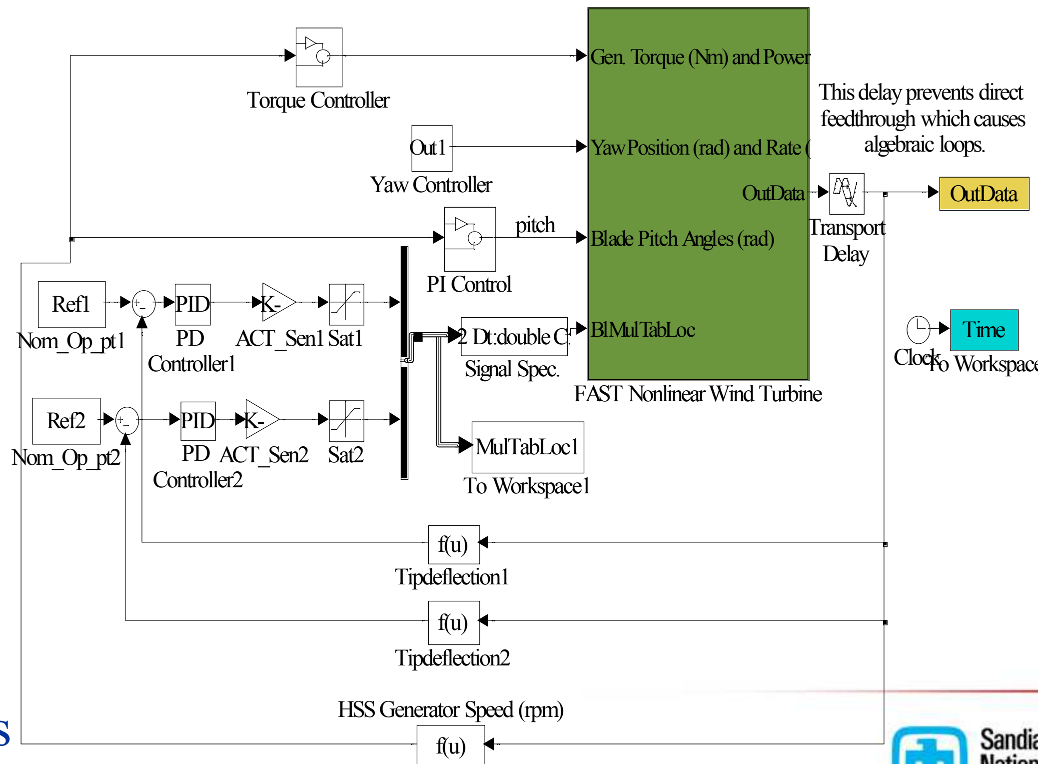
System Modeling - Analysis

- **Controls Advanced Research Turbine (CART):** utilized as simulation testbed with 600kW rated power @ 42 RPM
- **Dynamic Simulation Environment:** FAST (Fatigue, Aerodynamics, Structures, and Turbulence) run within Matlab/Simulink
- **Hybrid Controller:** Proportional-Integral (PI) Blade Pitch Control with Proportional-Derivative (PD) Microtab Control for above rated wind speed conditions, Region III
- **Microtab PD Control:** Uses tip deflection feedback and nominal reference tip deflection as set point

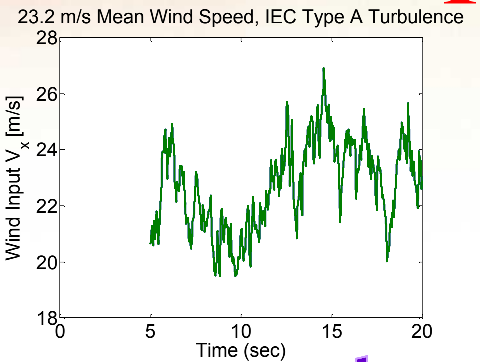


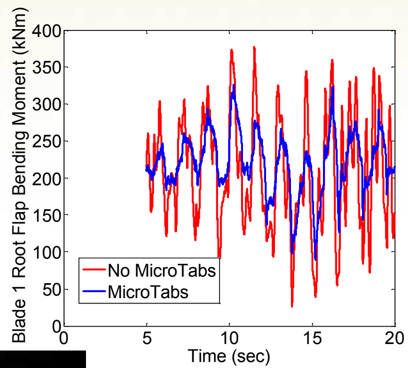
AeroDyn Inputs

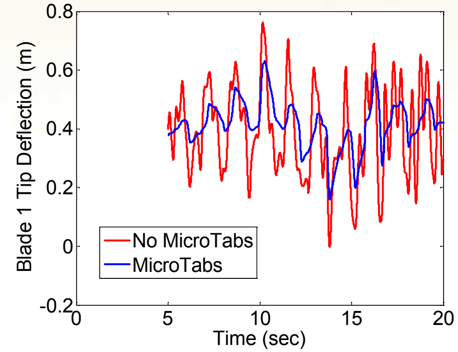
Microtab Profiles

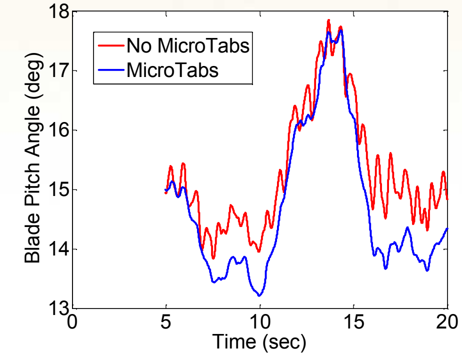


Microtab Active Aero Blade Control Performance Visualization

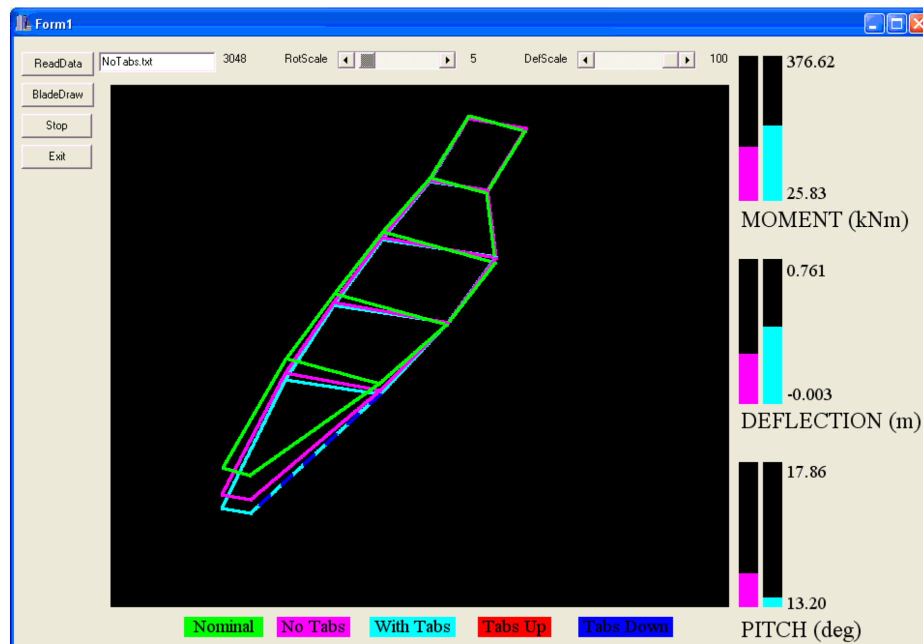








Wind Input



Active Controls

Region III

Sandia is also Working with Other Organizations

- **Memorandum of Understanding with TU Delft**
  - active aero device
  - material development
  - reliability
  - controls

- **CRADA with FlexSys**
  - evaluation of morphing trailing edge

Summary

- **IEA Expert Meeting**
  - lots of activity in past 17 months
  - still very much a research effort
  - need considerable work in sensor area
  - continue to hold Expert Meetings for now
- **Sandia Effort**
  - goal is to decrease fatigue loads and increase energy capture
  - focusing on microtabs, but also looking at morphing TE
  - full system modeling, including control system
  - cooperative efforts with TUDelft and FlexSys

Thank You!

Questions?