Fly-by-Feel (FBF) Control

NASA Aeronautics Research Institute

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Aeroservoelastic sensor-based control certified-by-design with performance and stability guarantees

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Outline

Motivation and background

FBF: Testing history and results

FBF-Seedling: Recent testing and results

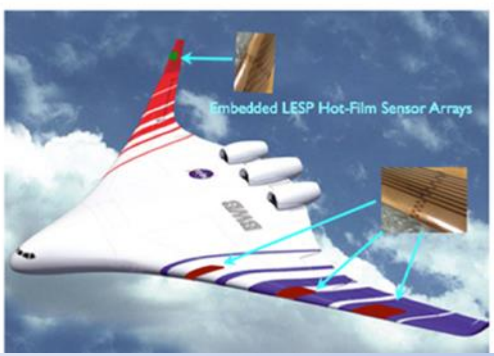
ARMD (FAP) / X-56A / F18 / etc.

Distributed sensing/controls

***Applications* and partnership**

Potential Flight-Test R&D Application of Sensors

- Flight Estimation of Section Aerodynamic Coefficients
- Local Angle of Attack, Side Slip (from Winglet Sensors)
- Spanwise Aerodynamic Load Distribution



LEADING EDGE

BY GUY NORRIS

Southern California Bureau Chief Guy Norris blogs at: AviationWeek.com

COMMENTARY

Fly-by-Feel

Lightweight, flexible-structures project could bridge gap to practical adaptive aircraft

Since the advent of powered flight, aircraft designers have sought to escape the bondage of heavy rigid structures by moving to lighter, bird-like adaptive shaping and sensing technology.

Such advances potentially offer dramatic improvements in performance and safety, allowing designers to reduce load margins and enabling the aircraft to react swiftly to changes. While the theoretical benefits of adaptive aircraft have long been known, and dramatic damage tolerance demonstrations using sub-scale F-18 models have proven the concept's viability, more needs to be done to make it a practical prospect. With this in mind, NASA is planning a lightweight, flexible-structures research program that could build on previous basic research efforts to demonstrate "fly-by-feel" sensing and control technology on a modified F-18. Researchers believe the demonstration will boost technology readiness levels toward real-world applications of lighter commercial and military designs.

As part of the continuing development of lightweight structures, the U.S. Air Force Research Laboratory is also discussing joining the initiative. "We've been talking to them and they're very interested in trying to pull together some collaborative effort in the future," says Mark Dickerson, program manager for Model Reference Adaptive Control (MRAC) at NASA Dryden Flight Research Center.

The MRAC F-18 is fitted with a simplified adaptive controller that compensates for simulated failures of flight control surfaces. Using MRAC as a springboard, NASA believes it could take the concept much further. "The ultimate idea is to put a system in service on an aircraft that can sense the structure and things that are happening to the aircraft, and use that information and force it into a shape that it would like it to be," says Dickerson. "The side benefit is that if it can sense shape, it can also control it in case of a failure. Load-sensing can help you cut back on load margins, so you can have a lightweight structure that is active."

A subset of NASA's Aviation Safety Program's Vehicle Safety System effort, MRAC builds on earlier attempts including the F-15 Intelligent Flight Control System (IFCS), and the follow-on F-18 Full-Scale Advanced Systems Technology (FAST). "The current adaptive control comprises less complex systems and algorithms that could be more easily certificated for commercial use in the future, when new technologies are fully validated and verified," says Dickerson.

"We're using much simpler algorithms than in the IFCS. We sort of dumbed it down if you will," says Jim Lee, MRAC project chief engineer. "The system does not have all the feedbacks in it this time. It is simplified to something that will enable conventional processors to be used, and that can be shown to be safe in a commercial application."

Earlier projects included a Rockwell Collins and Defense Advanced Research Projects Agency system, which proved that a catastrophically damaged unmanned F-18 subscale model air vehicle with an adaptive control system could safely land. "That program showed you can design the algorithms to control a severely damaged aircraft, but the problem is getting it certified in the real world. We feel like NASA has the dollars to work on a full-scale vehicle to help this process," says former IFCS chief engineer John Bosworth.

Following the end of MRAC flights and a maintenance layup, the F-18 will be fitted with fiber-optic wing shape sensors to provide real-time measurement and feedback to the flight-control system. This comprises the baseline F-18 system, a quad-redundant research flight control system developed for the FAST effort, as well as a dual-redundant airborne research test system—ARTS IV—which provides a way of rapidly testing new concepts. In addition, the system will be linked to 200 strain gauges that remain on the flight-control surfaces from the Active Aeroelastic Wing research program, which tested the concept of using lighter-weight wings and wing twist for enhanced aircraft roll control.

Although fiber-optic sensors have flown on composite-built unmanned air vehicles, none have so far been tested in a rigid, conventional airframe. "The F-18 has a stiff wing, with a complex structure. This is a 'real' aircraft with lots of panels," says lead controls engineer Ryan Dibley. Initial flight tests of the modified F-18 are set to begin in December 2011.

Precise sensing technology, along with detecting flow stagnation, paves the way for active control, says Bosworth. "Rather than controlling it by angle of attack, the next step is novel ways of controlling flow across the wing via nano devices and active flow."

Distributed Fly-by-Feel Aerodynamic Sensing

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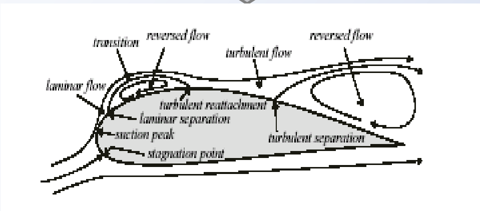
STATUS QUO

Lightweight configurations => inherently flexible

Current limitations:

- *Complex aerostructural control*
- *Limited aerodynamic observables*
- *Measurement/inertial uncertainty/lags*
- *Cost-ineffectiveness / hi-maintenance*



NEW INSIGHTS

Flow bifurcation point (FBP) model captures stagnation point, stall, separation, SBL flow dynamics

***Aerobservable*-based analytic codes**

Distributed sensing/control apps with spatio-temporal feedback

V&V of CFD/CSD for unsteady ASE

Aero coefficient estimation

Force-feedback framework

GLA/LCO control; flutter prevention

MAIN ACHIEVEMENT:

Relevant Sensor Information-based Distributed Aeroservoelastic Control for Reliability, Effective Performance and Robustness

Challenges:

Physics-based architecture

Distributed control with alternative sensors

Information-based sensing for efficient mission adaptivity with aerostructural control

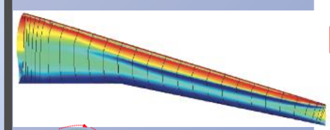
Development of physics-based analytical aerostructural feedback mechanism

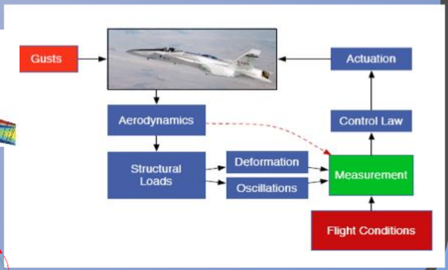
HOW IT WORKS:

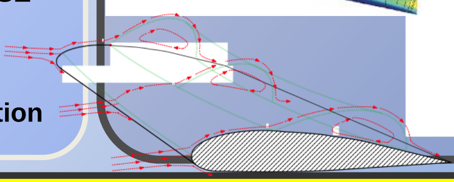
Real-time aerodynamic force measurement improves aerostructural performance and efficiency across all flight regimes (sub/tran/sup/hyper)

Redundancy with analytical sensing critical to reduce aerostructural uncertainty

Decouples the aerodynamics (forces) from the structural dynamics (responses)







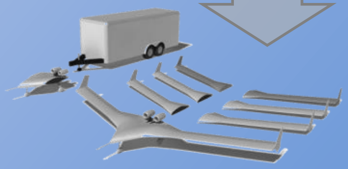
QUANTITATIVE IMPACT

[FAP] Reduce drag & weight; Increase performance & energy efficiency; Improve CFD-CSD and experimental tools & processes with reduced uncertainty; Develop/test/analyze advanced multi-disciplinary concepts & technologies;

[AvSP] LOC prevention, mitigation, and recovery in hazardous flight conditions

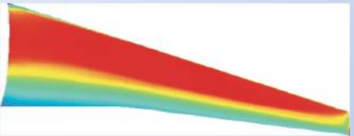
AFRL/LMCO (MUTT), NASA-OCT

Partners: IIT, TAMU, Caltech, UMN, SBC (sensing)



PROGRAM GOALS

- Design and simulate robust control laws (UMN, SBC, DFRC) augmented with the aerodynamic observables
- Conduct wind tunnel tests (TAMU) and flight test (DFRC) to validate the controls
- **Ultimate objective is to determine the extent of performance improvement in comparison to conventional systems with multi-functional spatially distributed sensor-based flight control**



Flight systems operating near performance and stability limits require continuous, robust autonomy through real-time performance-based measurements

Enabling Fly-by-Feel Control

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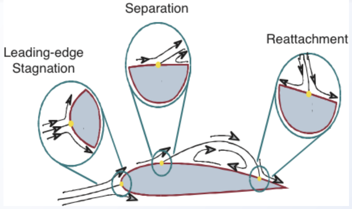


Theoretical/experimental tools to validate stability and performance of robust control with Fly-by-Feel sensing

Lightweight structures => inherently flexible

Current limitations:

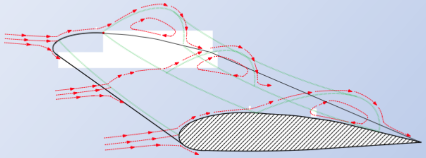
- Aerostructural model uncertainty
- Limited aerodynamic observables
- No flow separation or shock info
- Measurement/inertial uncertainty/lags
- Actuator uncertainty/lags

Flow bifurcation point (FBP) model maps surface flow topology to aerodynamic coefficients (CL, CM, CD)

Distributed sensing/control enabled with spatiotemporal aerodynamic feedback

Force feedback enabled by sensing FBPs, *aerobservables*

Robust control enables stability under sensor, actuator & model uncertainty



Validate robust control laws augmented with aerodynamic observables in aerostructural wind tunnel (WT) / flight test (FT)

Challenges:

- Development of analytical codes for nonlinear aerodynamics with compressibility effects
- Developing aeroservoelastic (ASE) sim with unsteady aerodynamics for developing robust control laws
- Developing low-power sensor technology robust in operational environments

Critical Technologies:

- FBP model for CL/CD/CM for subsonic/transonic flows
- Low power/noise instrumentation and DSP techniques
- Sensor, actuator & ASE model including uncertainties
- Robust control for sensor/actuator/model uncertainties

Approach:

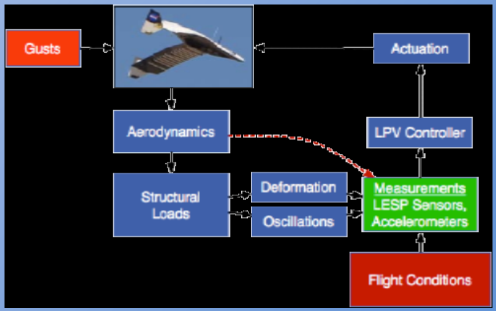
- Design/validate robust control laws for ASE WT/FT
- Develop FBP-based model including compressibility
- Develop low-power FBP sensor array

Operating near performance and stability limits requires real-time force feedback

Improved worst-case performance under uncertainty

- Gust load alleviation
- Flutter prevention envelope
- Suppression of limit cycle

Feedback control performance is limited by time-delay



- **Provide technology foundation for an autonomous Fly-by-Feel platform demonstrating:**
  - Aerodynamic / structural efficiency for range /endurance
  - Mission-adaptive capability
  - Maneuverability

Previous Analytical Approaches

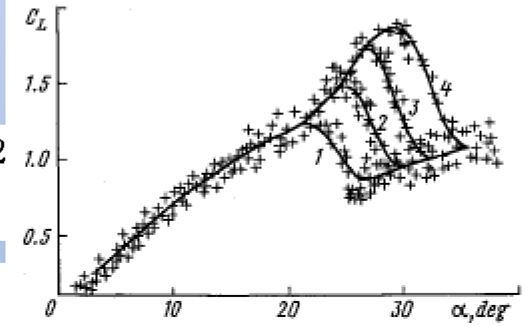
LE stagnation point (LESP, xl); Flow separation point (FSP, xs)

L.C. Woods: any two of the three (AoA, FSP, LESP)

fully determines the system

$$C_L(\alpha, x) = \frac{\pi}{2}\sin(\alpha)\left(1+\sqrt{x}\right)^2$$

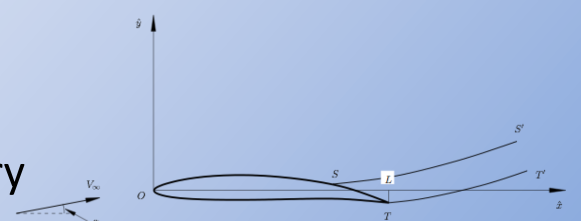
$$\tau_1 \frac{dx}{dt} + x = x_0(\alpha - \tau_2 \dot{\alpha})$$



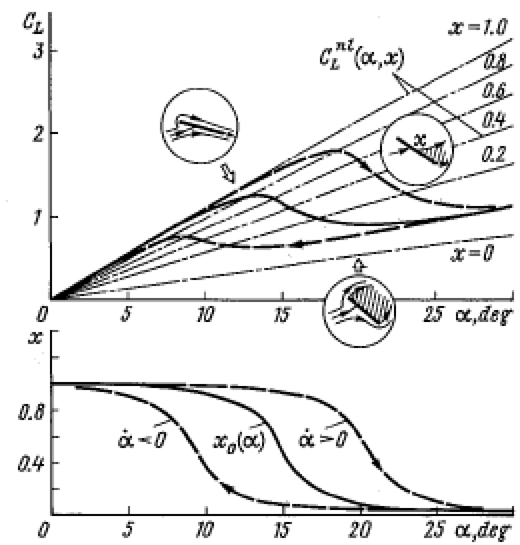
Goman & Khrabrov

– AoA & FSP => aero coeffs
– Unsteady experiments
  for τ1, τ2 time constants
– Based on thin airfoil theory

What is AoA in unsteady flows?



$$x_l = \sqrt{2}x_s^{1/4}\left\{\alpha_* - \frac{1}{\pi}\int_{-1}^{\sqrt{x_s}} \frac{G(\zeta')}{\zeta'}d\zeta'\right\}$$



FBP: Experiments / Validation

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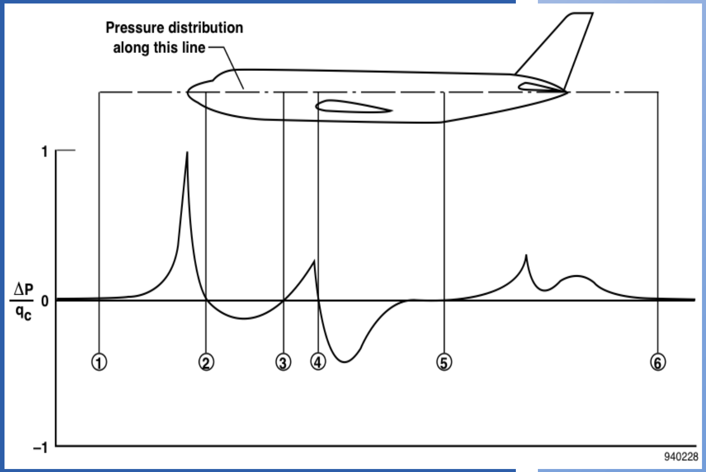
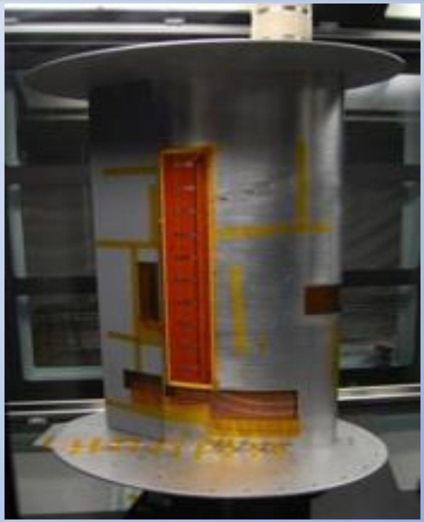
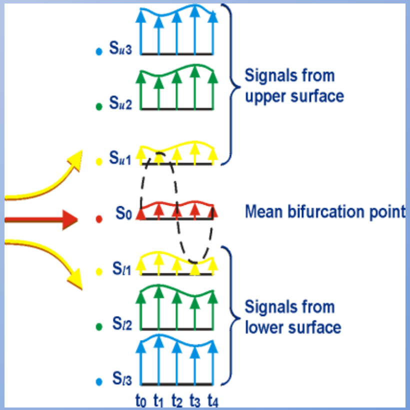
- AFRL/NASA TDT [aeroservoelastic control]
- NASA ATW [flutter]
- Sandia National Lab [smart blade]
- AFRL SARL [flow control]
- AFRL/NASA OSU [transonic shock]
- AFRL/NASA/LM BFF [flutter suppression]
- AFRL X-HALE [aeroservoelastic modeling/ground test/flight test]
- Relevant Past Experiments
  - NASA F-15B tail
  - NASA F-15B: shock location



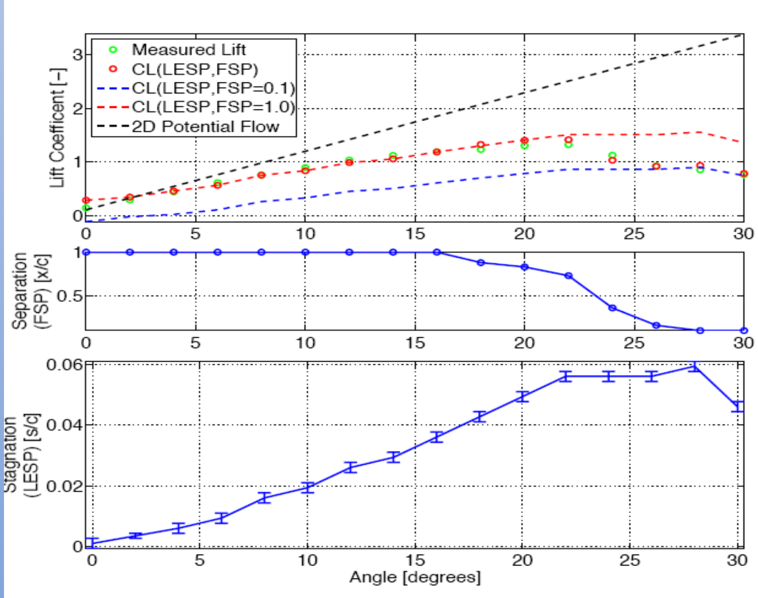
FBP Model Validation: Subsonic Aeronautics Research Lab

- Cambered airfoil w/ Flexsys conformal flap
- Low aspect ratio => significant 3D flow
- Pressure taps to obtain pressure distribution & lift / moments
- Hot-film sensors
  - Leading-edge => stagnation point
  - Upper surface => flow separation
  - Phase reversal signature





- Effect of plasma on circulation
- Trigger control on FBP characteristics



FBP Model Validation: SARL

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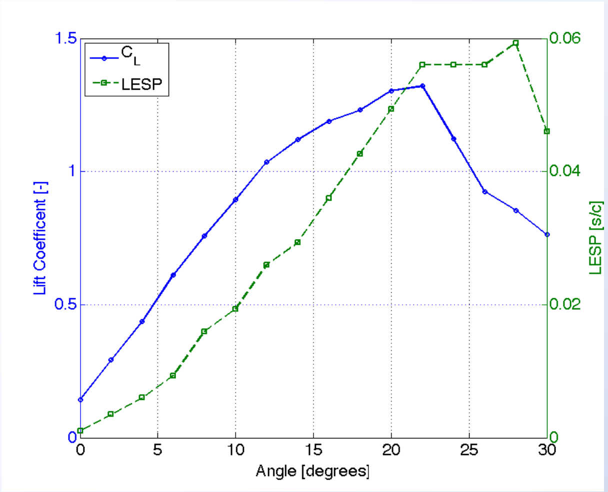
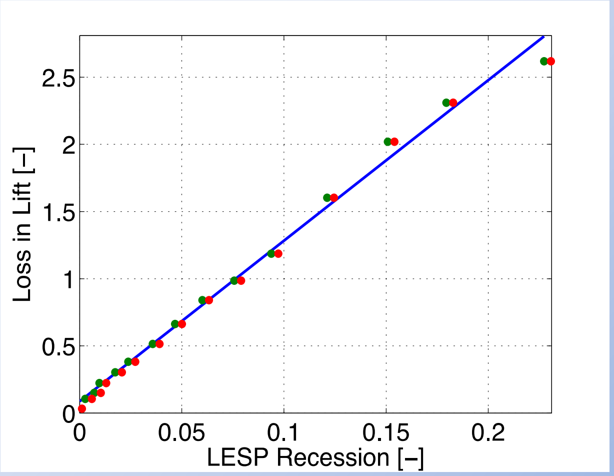
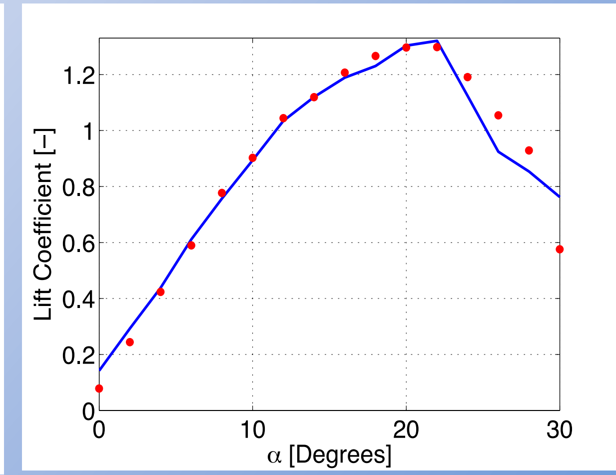




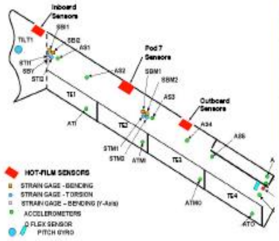


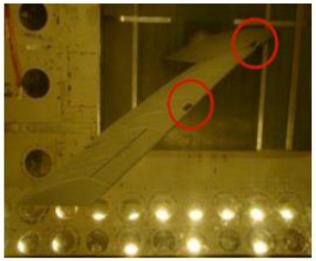
- Low aspect ratio wing stalls ~22 degrees
- LESP location does not decrease until 28 degrees
- Loss in lift obtained from Kutta condition minus the actual measured lift
- LESP recession
  - LESP location associated w/ Kutta condition lift minus actual LESP
  - Monotonic (one-to-one mapping) & mostly linear with loss in lift
  - LESP & AoA used to obtain lift coefficient through stall

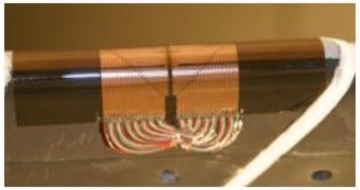
LESP location is monotonically related to AoA and circulation/lift

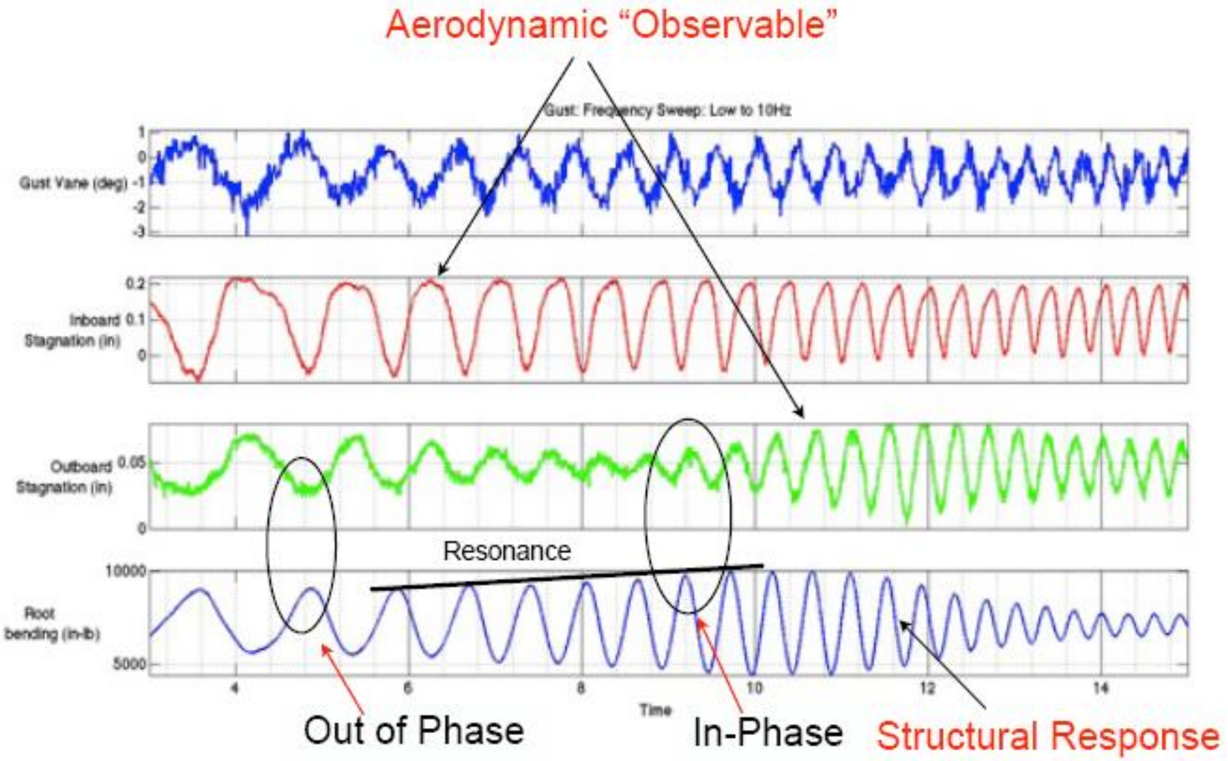
FBP Low-speed ASE Control: NASA-TDT, NGC/LMCO

NASA LaRC TDT Test : NGC / LMCO





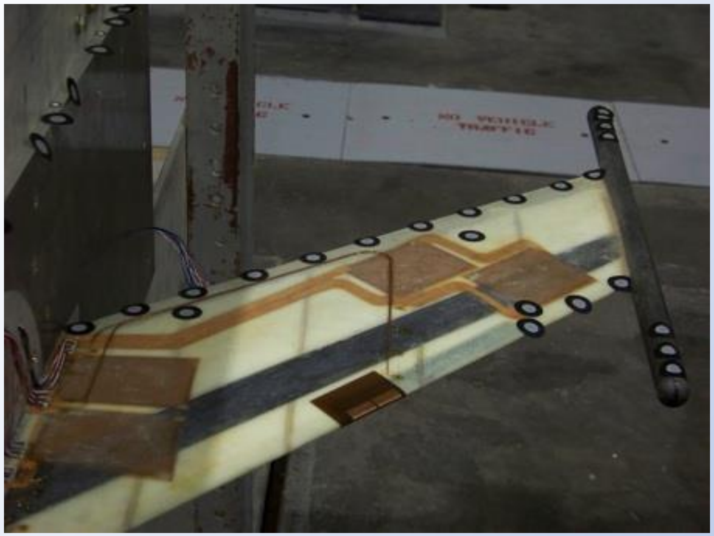


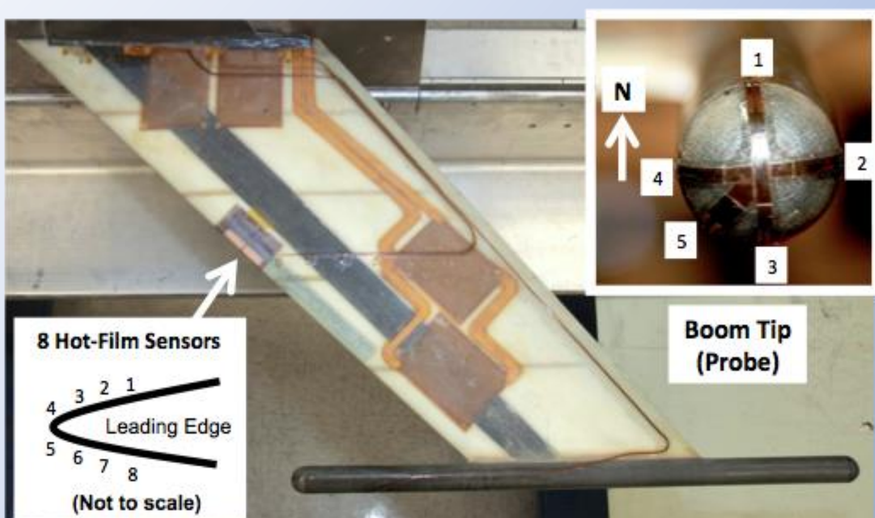


ASE control techniques
- Effect of delay in ASE control
- Adaptive control: requires bounded uncertainty in physics
-Bounds particularly important for aeroelastic applications (3D)

FBP-based control
- Exploit passivity of aeroelastic system by shaping lift/moment
- Reduce uncertainty of flow physics through direct estimation of parameter intrinsically related to lift

NASA ATW Flight Test





- Aerostructures Test Wing
- On F-15 test fixture
- Onset of flutter
- Instrumentation
- Hot-film sensors
    - Leading-edge
    - Angularity probe
- Accelerometers
- Strain gages
- Air data

ATW_MOVIE.AVI

ATW_MOVIE.AVI

ATW Test Data

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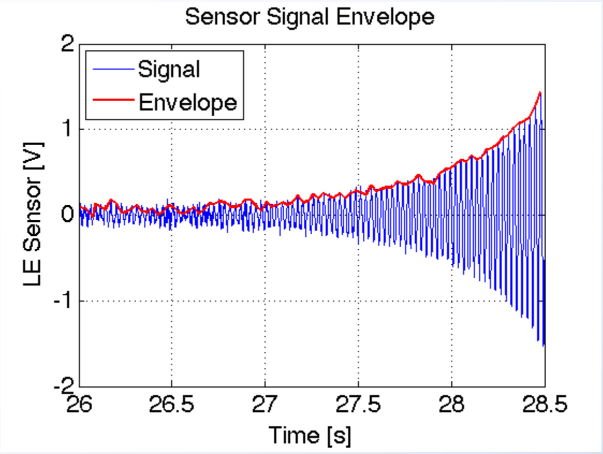

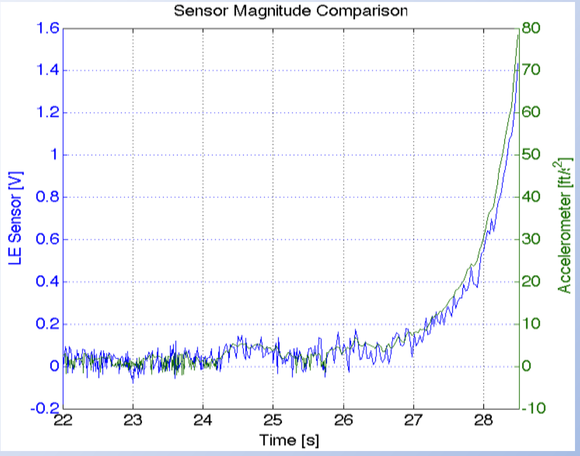

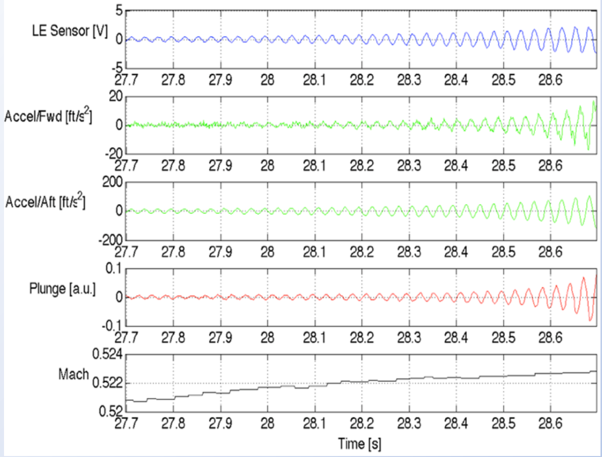

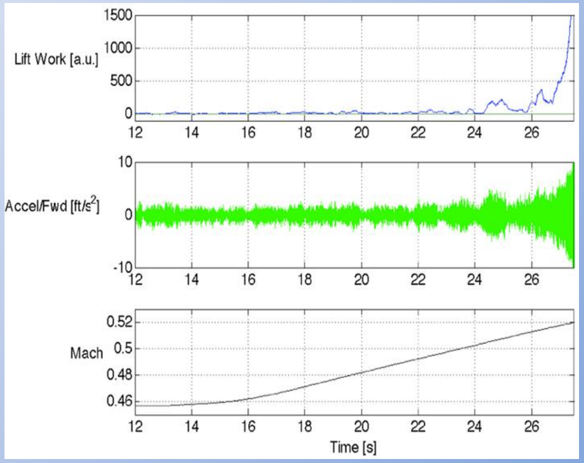

LESP amplitude increases like force measurement

$$W_L = \oint (L - \overline{L})\dot{h}dt$$

Estimate plunge from co-located fore/aft accels =>

Work done by fluid on the structure

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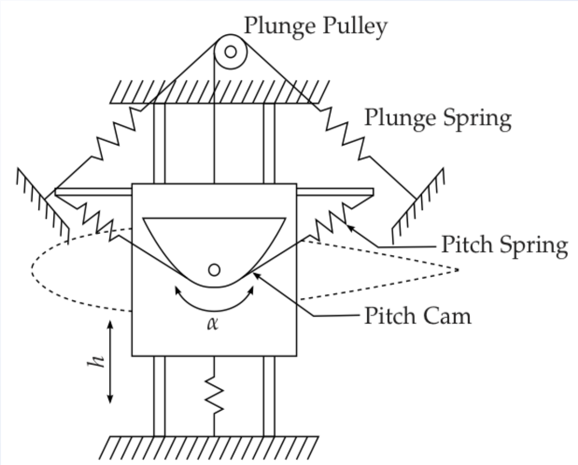
FBP / ATW Summary

- Developed flow bifurcation point (FBP)-based aerodynamic model
  - Validated model for subsonic flows (SARL)
  - Demonstrated LESP & FSP => CL
    - Consequence: no air data parameters required for aerodynamic coefficients
    - Curve-fitting may not be required
- Flutter test: ATW2 (NASA Dryden)
  - Significant flow separation at low angles of attack during onset of flutter
  - LESP magnitude similar to a force-type measurement
  - Use of accelerometers + LESP to estimate aerodynamic work
  - Potential for passivity-based control

FBP Model Validation: TAMU



Does FBP relationship with aero coeffs. hold for unsteady cases?

Texas A&M (TAMU) Pitch-and-Plunge Apparatus (PAPA)

- Free PAPA: LCOs / flutter and robust control law development
- Forced PAPA: pitch/plunge dwell/sweep with pitch/plunge dwell
- Wings with control surfaces and instrumented w/ load balance, accels, optical encoders, etc. for developing relationship between FBPs, pitch/plunge rates, control surface deflection and aero coeffs

Fly-by-Feel Ground Testing:

FBP Model for Steady Lift Estimation

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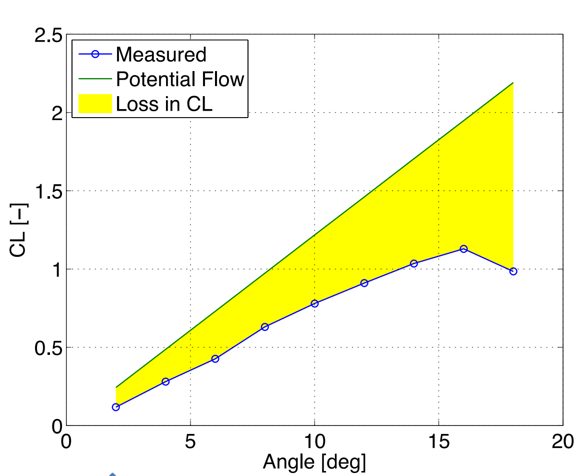
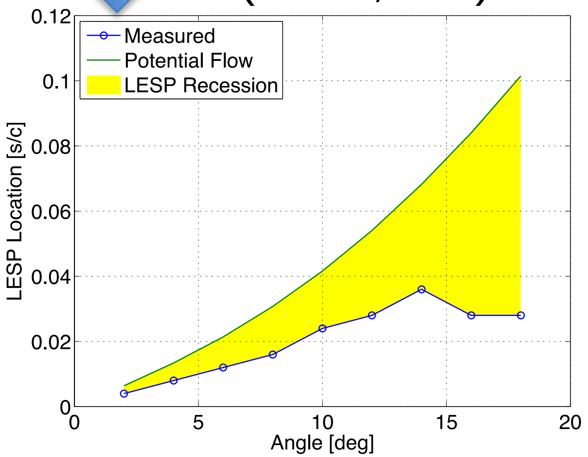
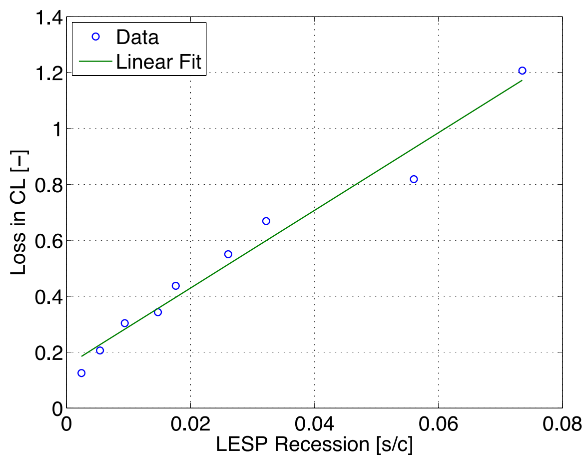


(CL,AoA) & (LESP,AoA)

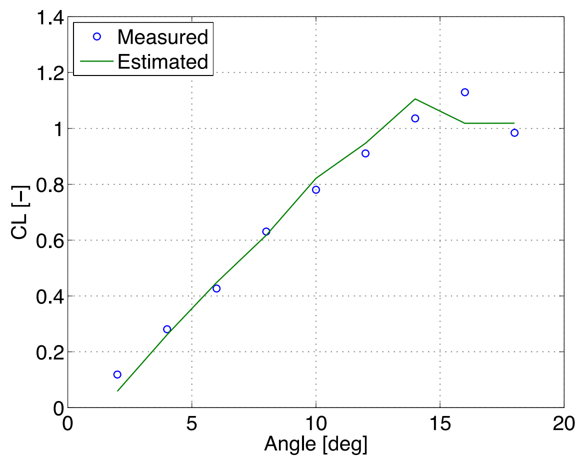


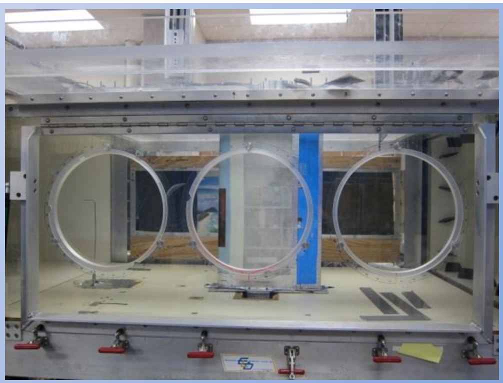
CL non-monotonic, non-unique function of AoA through stall (conventional)
- Loss in CL is monotonic function of LESP recession through stall (new)

Calibration: CL(LESP,AoA)



Lift Estimation Through Stall





Next Steps

- Development and validation of closed-loop ASE controller for suppressing limit cycle oscillation in TAMU wind tunnel
- Extend FBP model to transonic and supersonic flows including effect of shock wave boundary layer interaction

Fly-by-Feel Ground Testing:

FBP Model for Unsteady Lift Estimation

Next tests - forced PAPA

Objective of this test is to relate the movement of flow bifurcation points, e.g. LESP, and flow separation point to the aerodynamic forces under increasing pitch rates

Enable calibration of the wing for unsteady response and closed-loop free PAPA tests

MUTT-like wing instrumented at three span stations

Parallel-related ARMD Seedling Work

Develop open-loop / closed-loop test procedures for upcoming tests on F-18 with AFRL

NASA work in distributed aeroservoelastic control on X-56A vehicle – low power, small volume, robust sensing

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FBF Seedling: Innovation Elements

Essential Elements

- integral approach to flight control, structural mode and load attenuation, and flow control by **utilizing aero-observables in a robust control framework**
- advantage of the proposed approach is that the job of integration is done by the fluid itself: ***LESP represents an integrated effect of the section aerodynamics indicated at a single point (singularity, FBP)***
- investigation of the effectiveness of the FBF approach in **suppressing aeroelastic instabilities** with nonlinear ASE wind tunnel test model
- ultimate goals of **improving aerostuctural performance** (lift/drag/moment/load) with distributed FBF sensor-based flight control
- provides comprehensive validation of the closed-loop control with resulting ***architecture scalable to flight***
- physics-based embedded distributed sensor architecture ***certifiable-by-design***

FBF Seedling: Objectives/Approach

Technical Objectives/Approach

– **determine the relationship between aerodynamic observables and aeroelastic performance, loads/moments, and control surface actuation** with a nonlinear unconstrained pitch-and-plunge apparatus (PAPA) using representative wing with regard to aeroelastic instabilities

– **validate computational models** predicting aerodynamic coefficients based on pitch/plunge/actuator state and aerodynamic observables

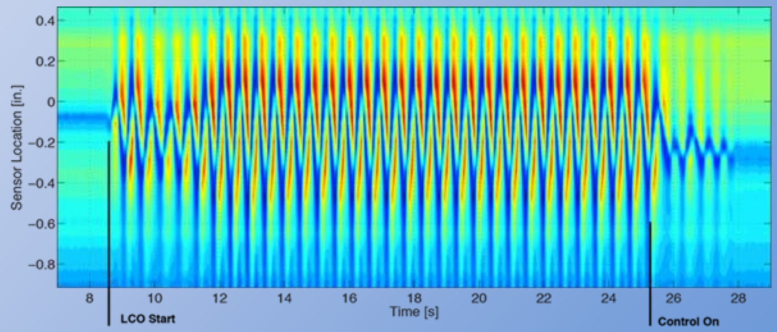
– determine the **accuracy/robustness of system identification techniques** in capturing the nonlinear system parameters

– characterize performance of conventional / robust / adaptive control laws using a **variety of aerostructural sensors for feedback** including aerodynamic observables in unsteady flows

TAMU PAPA Tests

First test was an open-loop test in a free-free PAPA to determine the relationship between the LESP location and aerodynamic forces (lift) for various angles of attack and control surface deflections

Second test was unsteady test of wing undergoing pitch at increasing frequencies (forced PAPA). Objective is to **provide data to relate the LESP movement with the pitch angle and angular rate with the aerodynamic forces**



LESP visible as the oscillating minimum shear stress (blue)

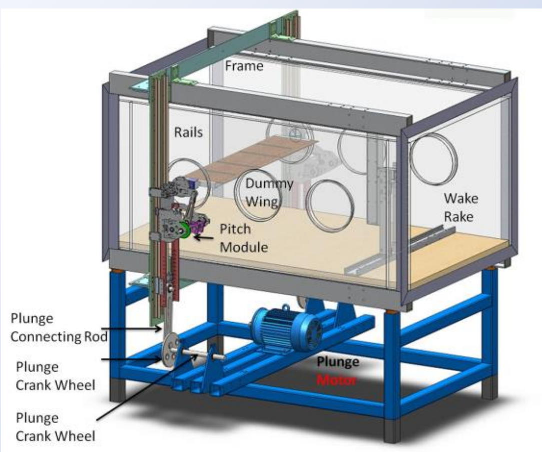
PPFDS / NATA II Facility

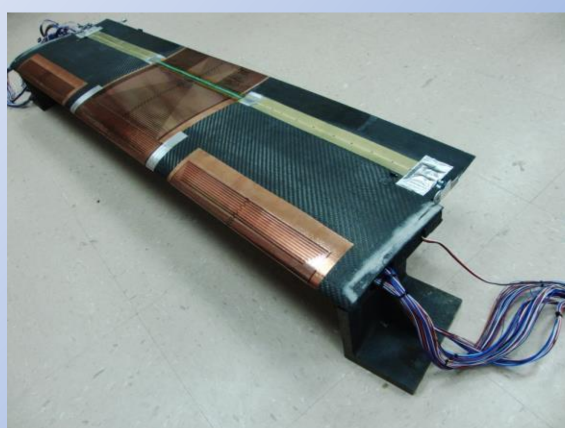
Statically **calibrated LESP sensors with aerodynamic lift** and use the constituent aeroelastic equations to develop an ASE controller to suppress the LCOs

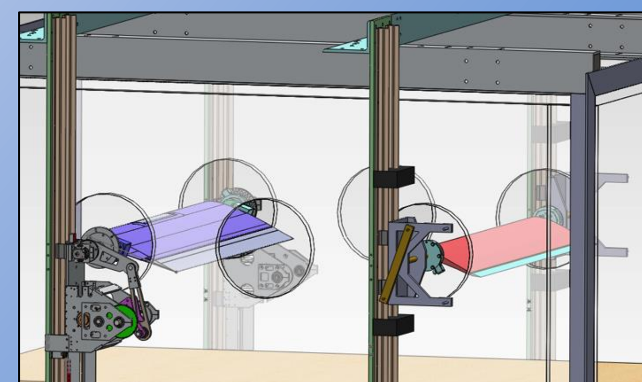
{videos 1-2 xxxyyyzzz.mp4}

Second test relates movement of flow bifurcation points, e.g. LESP, and flow separation point to the aerodynamic forces under increasing pitch rates

Enables **calibration of the wing for unsteady response** providing basis for flight testing the actual MAD/MUTT wing with a model for the sensor dynamics







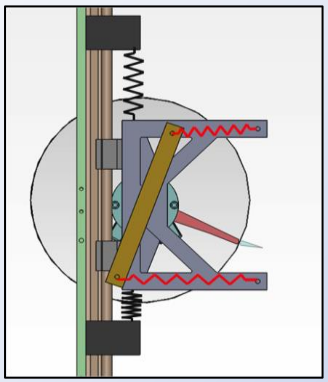
Pitch-Plunge-Flap Drive System (PPFDS) in Nonlinear Aeroelastic Test Apparatus (NATA II)

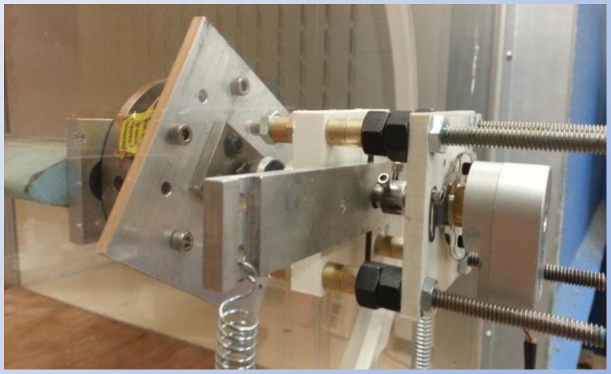
PPFDS / NATA II Tests

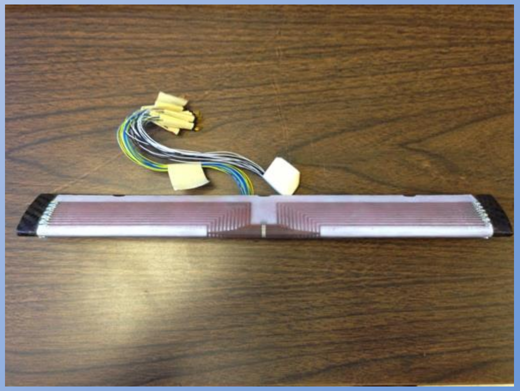
Flow sensors embedded directly onto the leading-edge using **direct-write techniques**

- process to embed metal onto surfaces to fabricate rugged sensors

Plan to transition this technology from **wind tunnel tests to operational aircraft**







Babbar Y., Suryakumar V.S, Mangalam A., Strganac T.W., "An Approach for Prescribed Experiments for Aerodynamic-Structural Dynamic Interaction", 51st AIAA Aerospace Sciences Meeting, 2013.

Babbar Y., Suryakumar V.S, Strganac T.W., "Experiments in Free and Forced Aeroelastic Response", 51st AIAA Aerospace Sciences Meeting, 2013.

Babbar Y., Suryakumar V.S, Strganac T.W., "Experiments in Aeroelastic Response and Control under Gust", 54th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2013.

PPFDS / NATA II Gust Modeling/Control Tests

NASA Aeronautics Research Institute

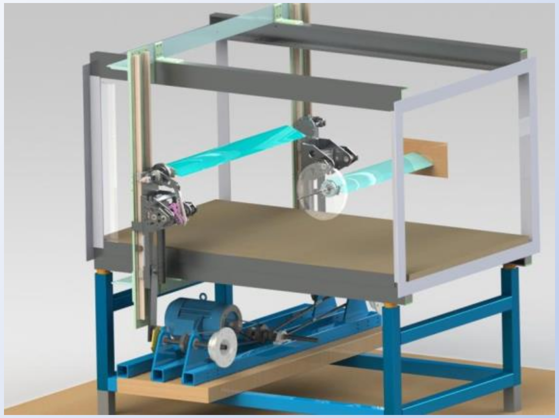
Characterize **flow field in the wake of gust generator** using probes

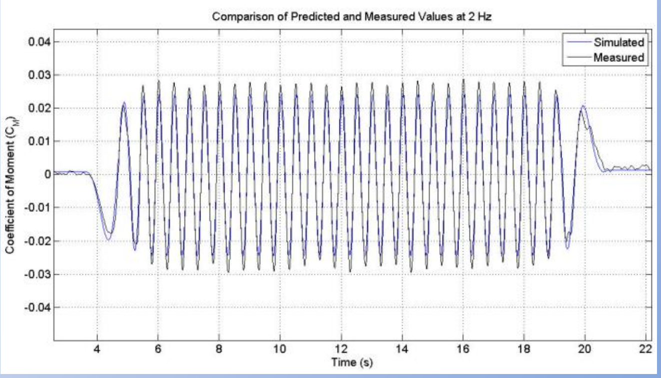
- PPFDS oscillates wing in pitch/plunge motion 0-5 Hz

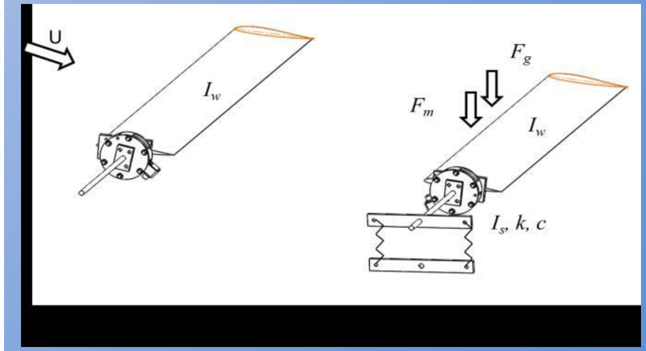
Conduct system ID tests to **determine gust response parameters** to aid in development of gust response prediction

$$F_g = -K_1\alpha(t+d_2) + K_2\dot{\alpha}(t+d_2) \qquad = C_{M,g}$$

Develop and test **control strategies using wing actuated control surface** to suppress LCO and possibly exploit flexibility to improve performance under gusts







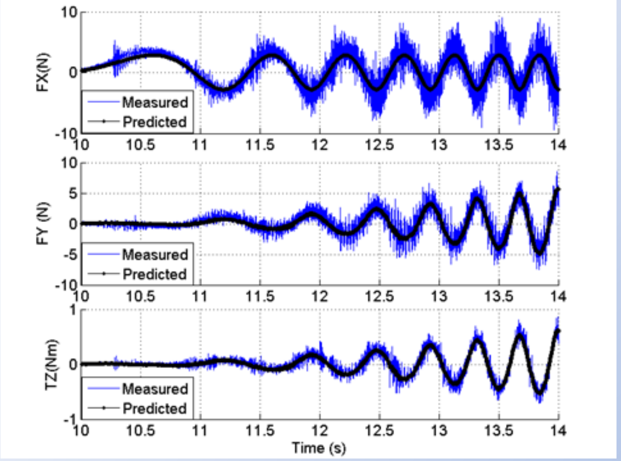
{video 5 xxxyyyzzz.mp4}

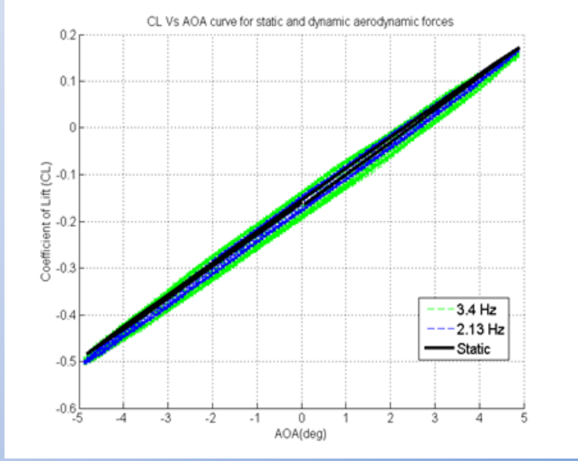
PPFDS Calibration

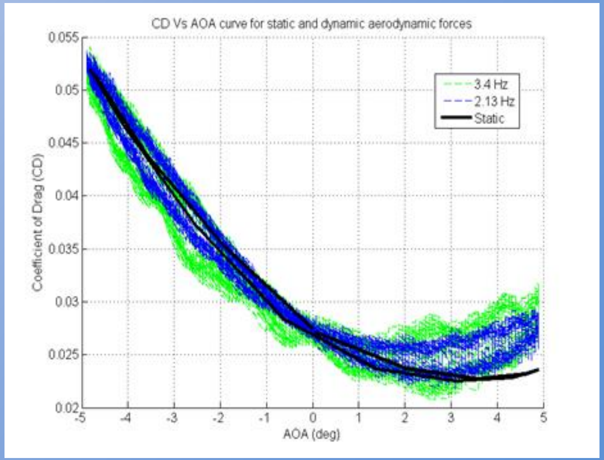
Aerodynamic forces and moments are calculated through the dual load balances mounted on either side of the wing

PPFDS significantly modified to **correct mechanical design issues for accurate aero forces wrt inertial pitch/plunge loads**

Enables more persistent LCO by changing the pitch/plunge stiffness coefficients for better environment to compare ASE controllers with consistent modeling and verifiable test conditions







PPFDS validation of inertial loads and unsteady aero coeffs

Pre-Stall & Post-Stall Behavior

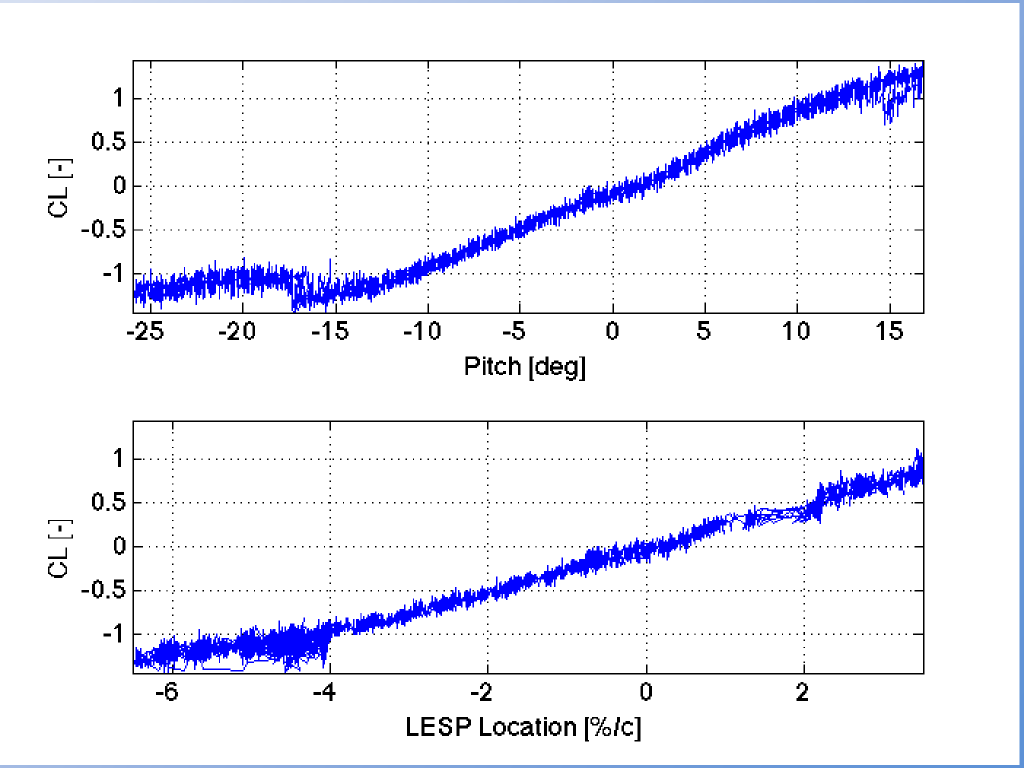
Free Pitch-and-Plunge Facility
- Structural nonlinearity
  - Nonlinear pitch stiffness
- Control surface nonlinearity
  - Free-play
- Aerodynamic nonlinearity
  - Stall (around ~14 deg)

Correlation with lift coefficient
- Pseudo-steady pitch sweep

- Pitch angle
  - Nonlinear, Non-monotonic

- **LESP**
  - **Nonlinear, Monotonic**

Pseudo-steady Pitch Sweep



LCO Behavior of LESP, Pitch/Plunge

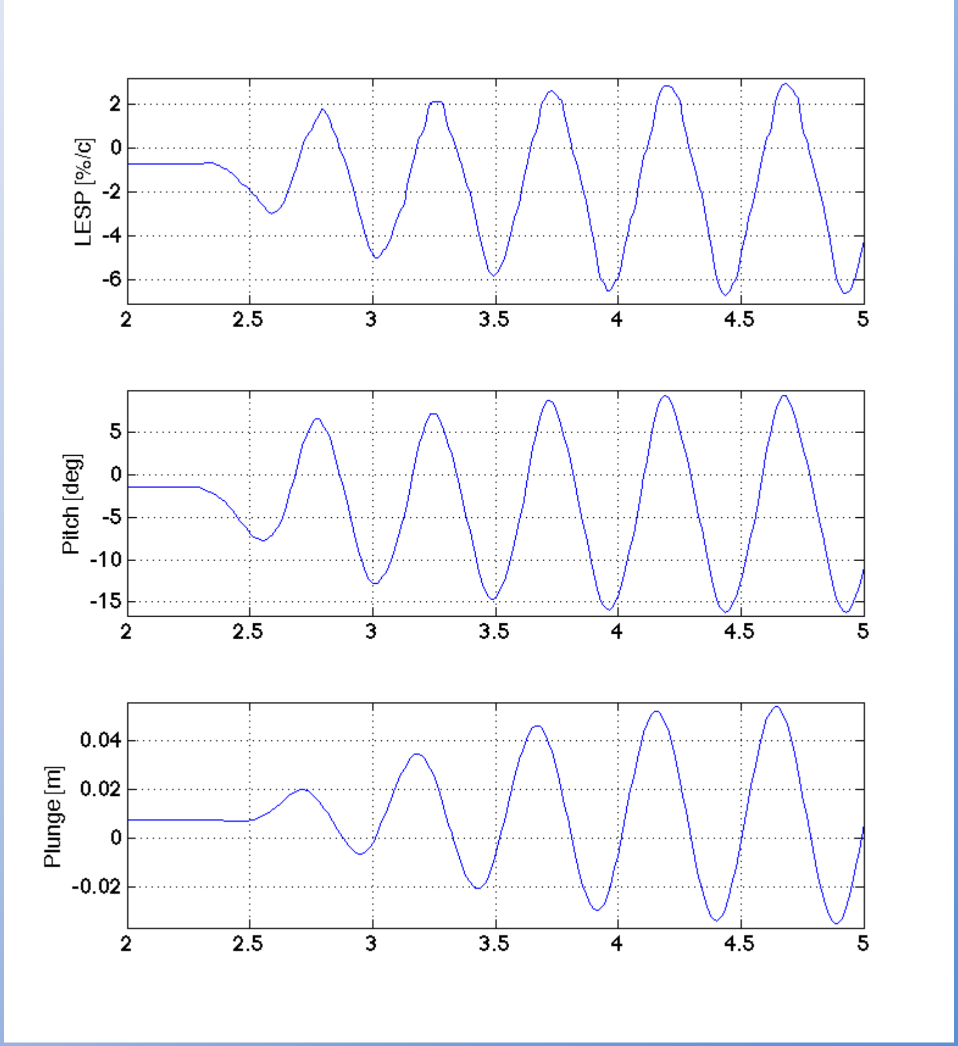
NASA Aeronautics Research Institute

Free Pitch-and-Plunge Facility

- Structural nonlinearity
  - Nonlinear pitch stiffness
- Control surface nonlinearity
  - Free-play
- Aerodynamic nonlinearity
  - Stall (around ~14 deg)

Overall behavior

- LESP travel: ~ 10% chord
  - 0.3m chord
  - 0.03m (30 mm) travel
- Pitch: -16 to 10 degrees
- Plunge: -0.04 to 0.06 m
- Change in phase

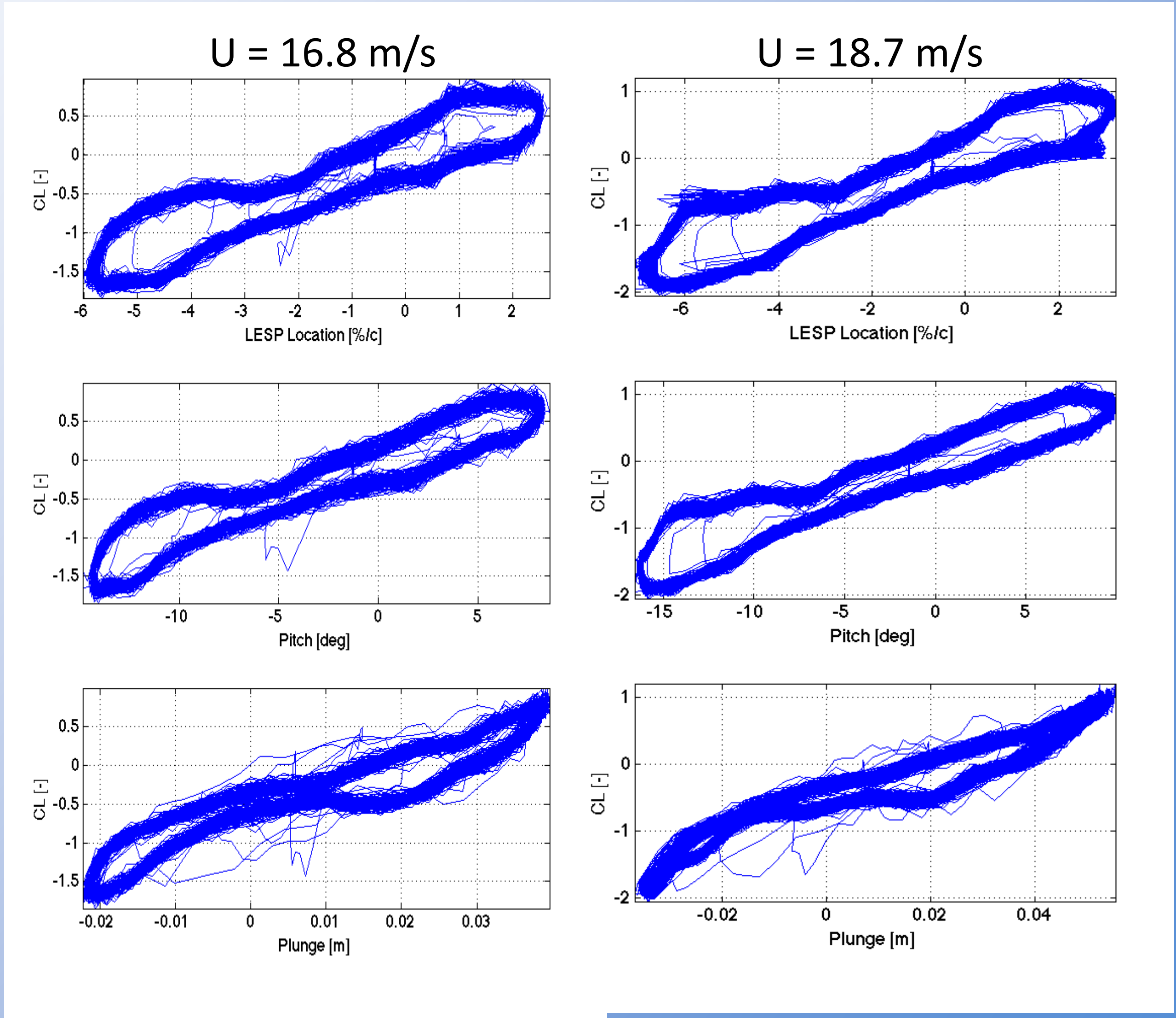


LCO Behavior of LESP, Pitch/Plunge

NASA Aeronautics Research Institute

Static stall: ~14 deg
Lift Hysteresis
Speed increase
- Plunge increase
- Pitch increase
- CL increase
- LESP increase

LESP-based unsteady aero model
Validation in tunnel
Closed-loop control to suppress LCOs



FBF-related Future Objectives/Plans/Goals

Address delays and nonlinearities such as actuator free-play in uncertainty

Developing aero model that represents the unsteady aerodynamic response of the LESP sensor and ***model the absolute uncertainty in load estimation***

LESP measurement allows ***bounding the aerodynamic forces*** in absolute sense

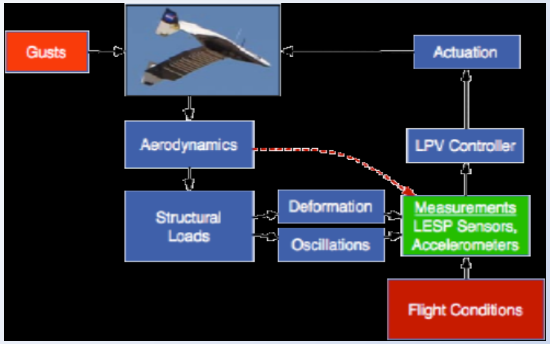
Effectiveness of **energy-based control** depends on assumptions underlying measured aerodynamics forces/moments and accelerations, therefore uncertainty in those measurements are critical

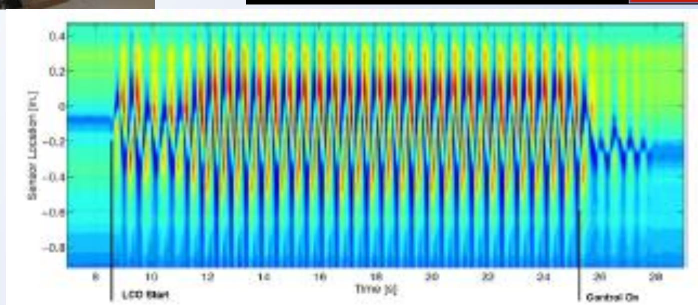
Provide foundational systematic approach to fully understand the mechanism underlying free-play response and stability using novel sensing and control

Extend energy-based controller to the X-56A flying-wing configuration with wing sections structurally and aerodynamically cross-coupled in PPFDS-NATA tests

Fly-by-Feel Aerodynamic Sensing

NASA Aeronautics Research Institute





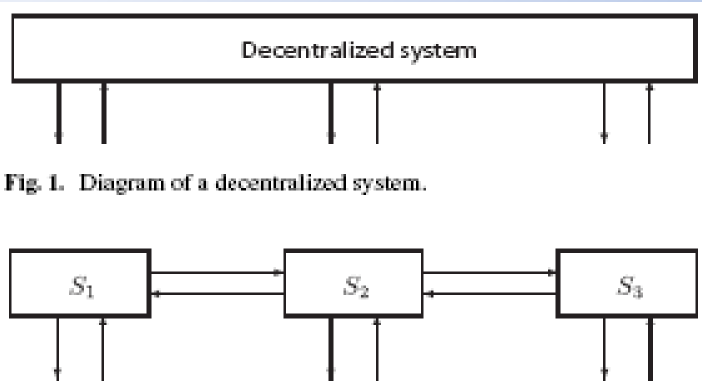


Fig. 1. Diagram of a decentralized system.

Fig. 2. Diagram of a distributed system.

- **Extension of physics-based FBP analytical model to generalized vortex state (low-order fluids model)**
  - **Applicable to unsteady flows (high reduced frequencies & near-/post-stall pitch angles)**
  - **Capture vortex dynamics for flow control**
  - **Consistent with higher-order CFD models**
  - **Enables near-term flight test flow control demos**
- **Extension of physics-based FBP analytical model to compressible flows**
  - **Applicable to characterizing shock wave turbulent boundary layer interactions (SBLI) as it relates to performance and aeroelastic stability**
  - **Reduction of noise & emissions**
  - **Flight test opportunities at relevant conditions**
- **Development of distributed ASE control architecture with "calibration-less" or self-calibrating sensors**
  - **New formulation of ASE eqns may reduce the requirement for calibration provided that flow and structural sensors are both available**
  - **Distributed control architecture may reduce requirements for structural & aerodynamic model accuracy by proving that local control approaches stable, globally optimal control**
  - **Provably robust adaptive control**
- **Partners: UMN, IIT, CalTech, SBCs, TAMU, AFRL, etc.**

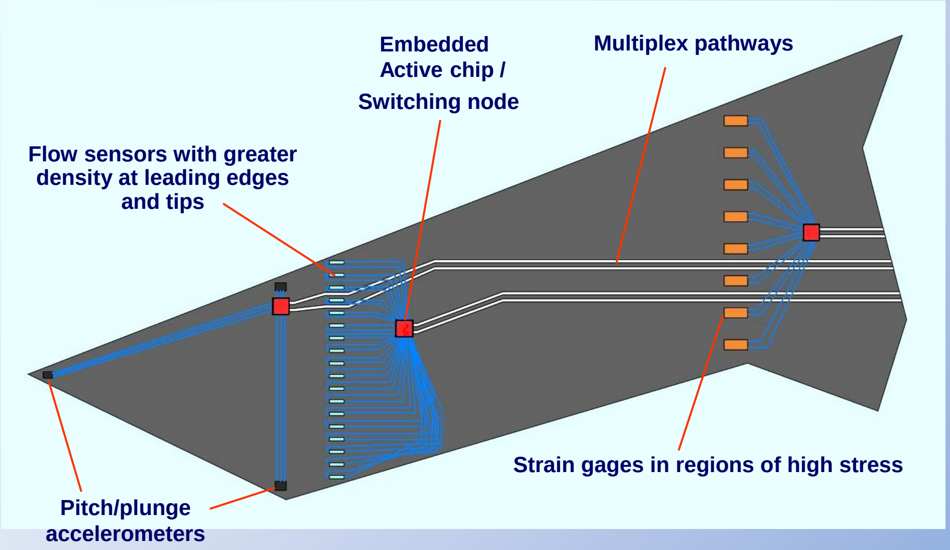
Real-time Aero-Structural Sensing for Controlling Aeroelastic Loads (RASSCAL)

NASA Aeronautics Research Institute

"Fly-by-Feel" is an expansion of ISHM through active sensing of the flight environment.

Why do we want fly-by-feel?

- Vastly improved empirical models for control and analytical modeling for design
- Exploitation of phenomena that can't be analyzed accurately (such as stall for perching)
- Aerodynamic, structural, and control efficiency increase
- Reduction in factors of safety (due to load uncertainty)
- Reduction in air vehicle certification time and cost

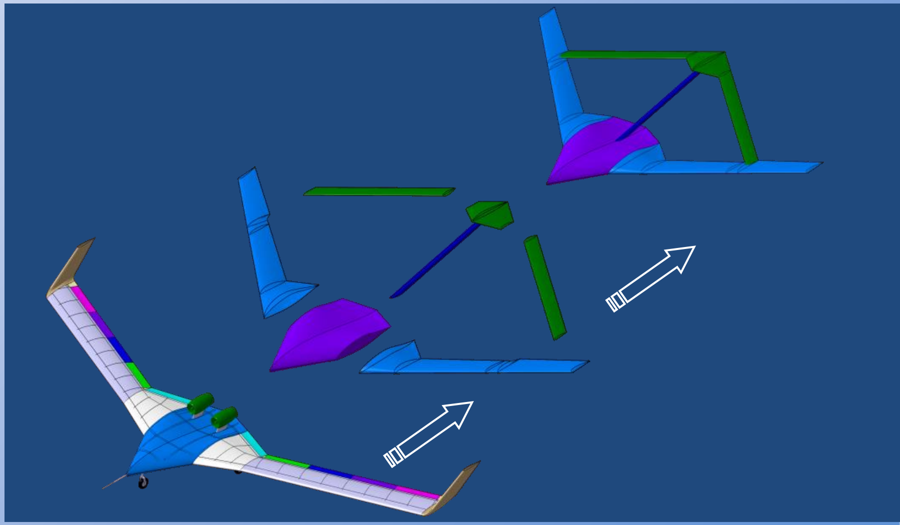


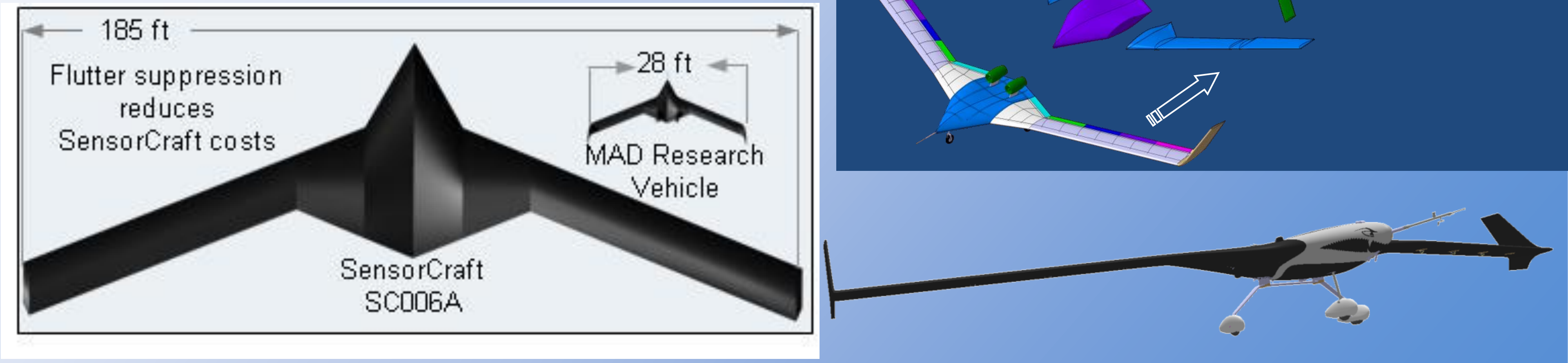
What is needed to enable fly-by-feel?

- Structurally embedded sensors, traces, and active chips
  - Minimize sensor protrusion into air flow
  - Minimize impact on structural performance
  - Improve reliability of sensors and associated electronics
  - Minimize trace count, length, weight, and power requirements
  - Minimize ingress/egress issues
- Efficient processing of aeroelastic sensor data
  - Identification of "critical points" for characterization of aero / airframe response
  - Switching and multiplexing algorithms
  - Understanding how to use new sensors and parameters in controllers
- Efficient manufacturing of multifunctional structures
  - Direct Write, Laser Transfer, flexible membranes
  - Thin-Film Transistor (TFT) Nanomembranes

ASE Sensor Applications: X-56A

NASA Aeronautics Research Institute



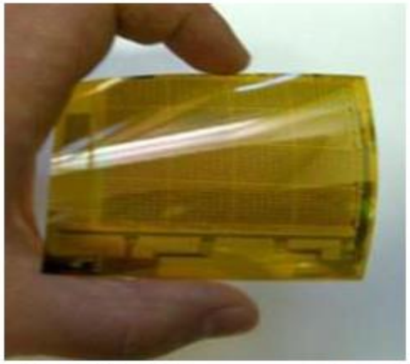


Real-time Aero-Structural Sensing – Flex Arrays

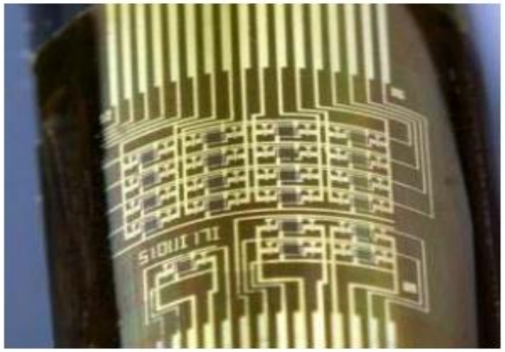
NASA Aeronautics Research Institute

Current status of flexible arrays

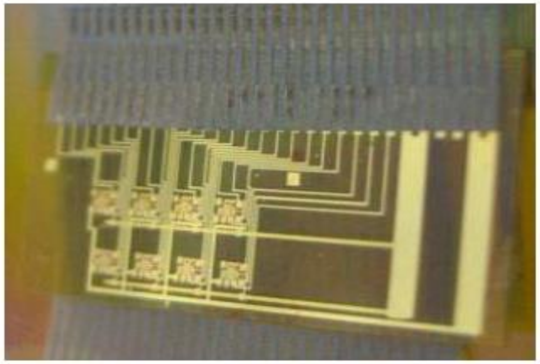
NextGen Aeronautics



μC-Si 32x 32 array on polyimide



Single-C-Si 4x4 arrays



Integration of dissimilar devices

Metric	Target Value	Actual Value
(1) Strain range	4000με – 6000με	Discretes linear 7000με; 4x4 arrays shown repeatedly to at least 2000με.
(2) Operational temperature	-54°C to 190°C (-65°F to 375°F) (Typical fighter class aircraft, top level structural requirements include -54°C to 121°C (-65°F to 250°F) skin temperature[†]	Strain sensors have demonstrated in excess of skin temperature range (-65 to 160°C); Differential amplifiers demonstrated to 80°C but failed at 90 °C.
(3) Gage factor	Minimum 24	Gage factors range from 20 to 65, significantly dependent on processing.
(4) Response	Frequency response in millisecond range	Average 0.6ms time constant, -3dB cutoff frequency: 270Hz
(5) Gage dimensions	<1 mm in area	Tested discrete sensors with gage area from 0.11mm^2 to 7.2mm^2; sensors in arrays have 0.11mm^2 area.
(6) Fatigue life	1 lifetime (i.e., 6000 hours) for fighter aircraft applications[††]	Demonstrated functionality exceeding 132,000 tension/compression cycles for discrete sensors. Surpassed 126,000 as in S^3TD F-18 case.

9th Annual Flexible Electronics and Displays Conference, February 3, 2010, Phoenix

35

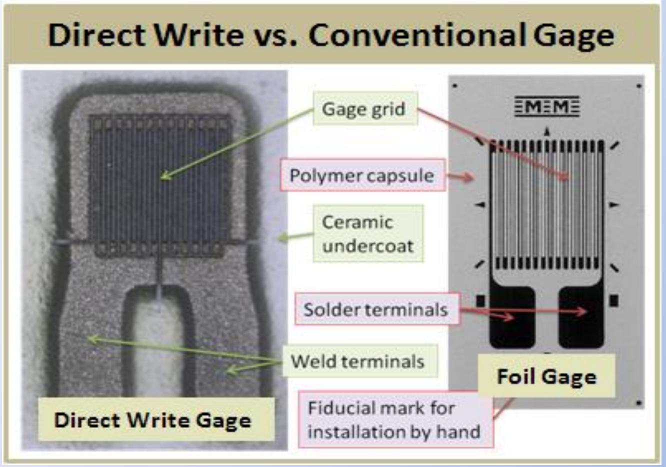
Cleared for Publc Release 23 Oct 2009, Case # 88ABW-2008-4483

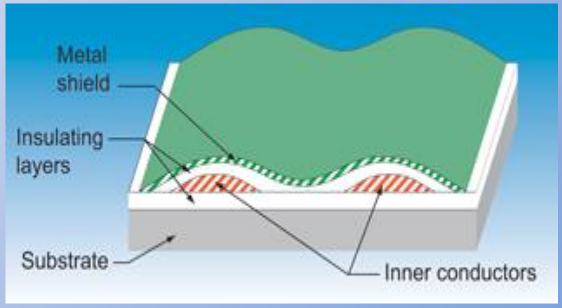
Real-time Aero-Structural Sensing – Direct Write (http://www.mesoscribe.com/)

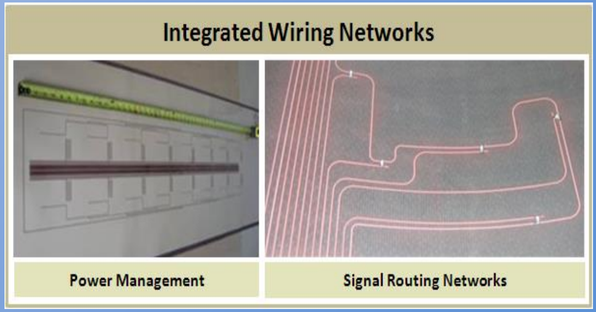
Direct Write strain gages enable structural state sensing of components operating at high temperatures, and in abrasive, corrosive, and other harsh environments. Gage properties optimized for static and dynamic applications as well as integration with conventional conditioners and DAQ systems.

Direct Write strain gages are analogous to conventional resistive gages, albeit fabricated directly and conformally onto surfaces for integrated health monitoring.

No adhesives or polymer films are required, enabling deployment in high temperature harsh environments. Gages can also be embedded within composite laminates, thus providing robust structural state sensing and integrated component diagnostics. Sensor alloys and patterns are selected to meet application requirements.





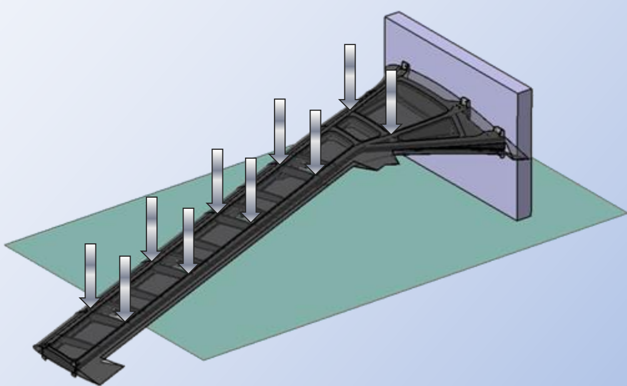


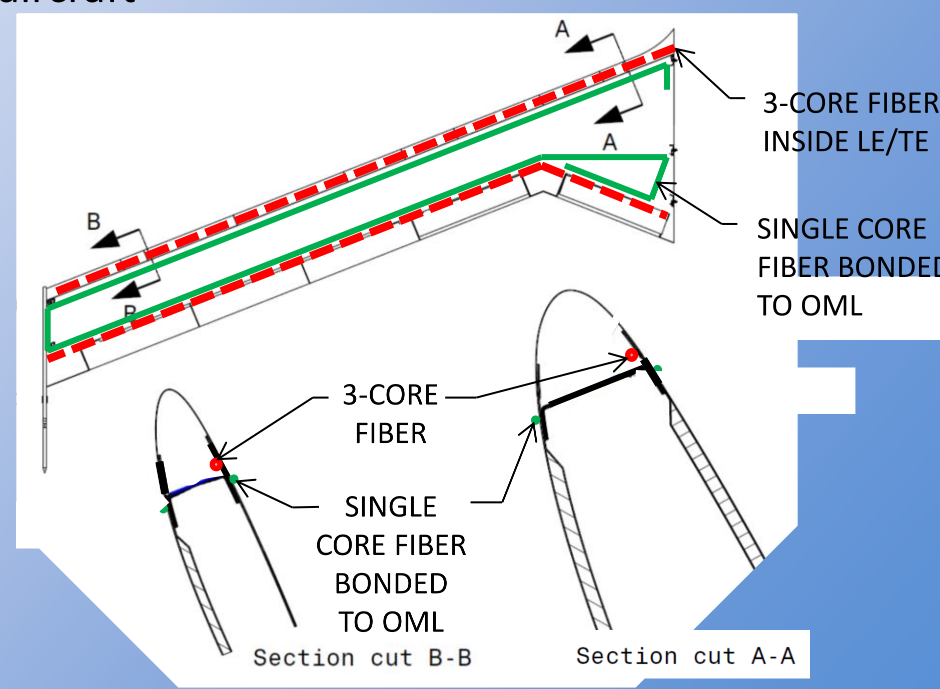
Fiber-Optic Sensor Technology (FOSS) Technology Development

NASA Aeronautics Research Institute

Goal: robust data, model-independent AE control applications

- Control of flexible structures is critical (FW, HS, AS, etc)
- Available for ground and flight testing with detailed models
- Interchangeable wings and low operating costs
- Structure representative of larger aircraft
- Risk-tolerant step towards larger aircraft





Skin Friction Measurement Opportunities

The direct measurement and mapping of distributed skin friction are needed on the surfaces of flight-test vehicles and wind tunnel models

Local skin friction values are central to all correlating techniques for turbulent flows through the ***friction velocity*** **$u^* \equiv (\tau w/\rho)1/2$**

Measurement of skin friction is critical

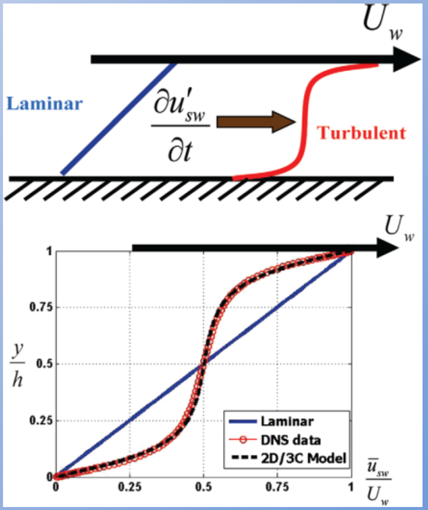
current computational methods do not provide sufficiently accurate skin friction results for complex flows

Skin friction drag accounts for about **45 % of the drag** on aircraft in cruise

Robust Physics-based Distributed Control

Lack of stability robustness plays fundamental role in wall turbulence

- Energy amplification (high gain feedback) and increased velocity gradient at the wall associated with the turbulent profile appears to have important implications for flow control techniques that **target skin friction or the mean profile** (2*D/3C model)*
- As Re increases, robustness (laminar-to-turbulent) decreases
- Tradeoff between linear amplification and non-linear blunting



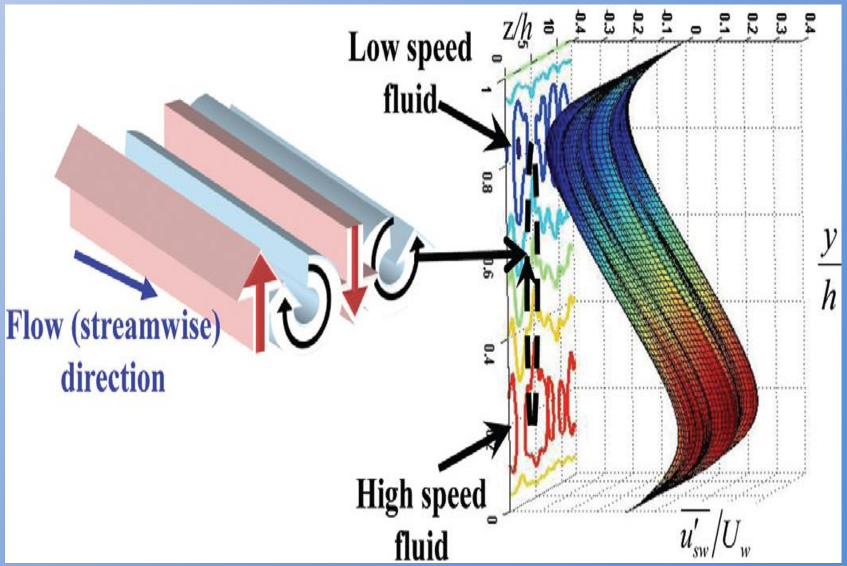
Turbulence in robust control framework

Reveals important tradeoff between

linear / non-linear phenomena

Provides insight into mechanisms associated

with both transition and fully turbulent flow

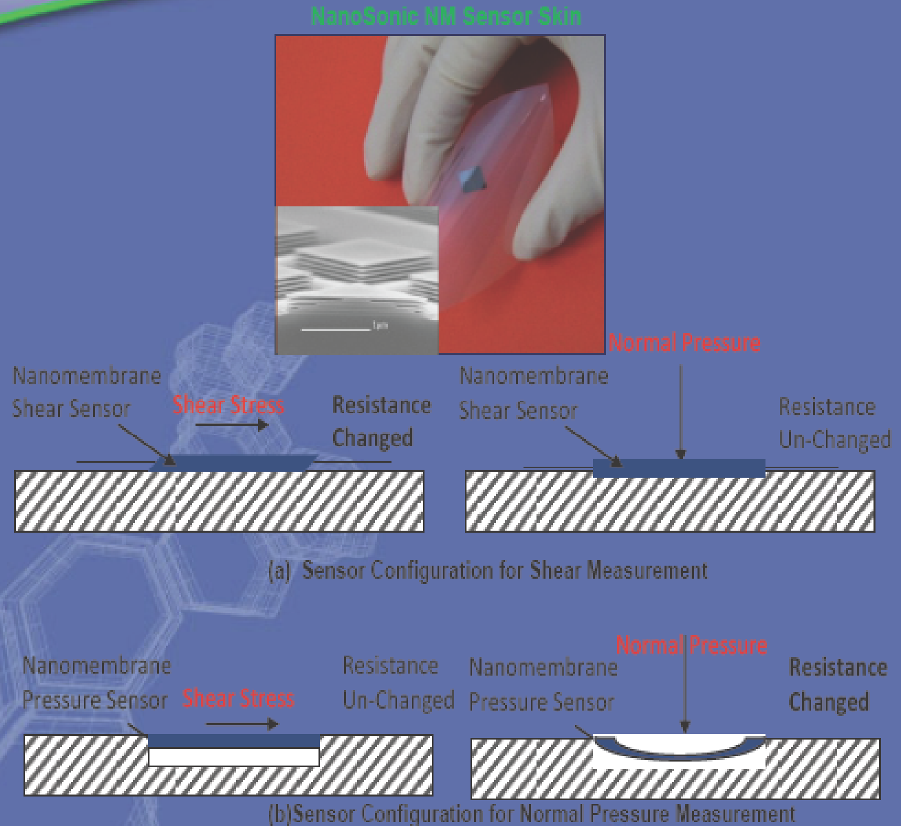


Skin Friction / Pressure Measurement Techniques

NanoSonic, Inc.

Virginia Tech
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

NM Sensor Configuration



- ❑**Ultrafast Response:** Frequency response ranges from DC to 100KHz due to high mobility from inorganic NMs, able to detect the high speed unsteady flow situations.
- ❑**Ultralightweight:** The thickness of the membrane can be as thin as 50nm, the disturbance to the measured parameter can be minimized.
- ❑**Ultraflexibility:** Conformal to the test model due to the low rigidities and energy release rates, less invasive and fewer holes for installation.
- ❑**Array Configuration:** Compatible with current CMOS fabrication technique, so that "Row-Column" transistor structure can be added.

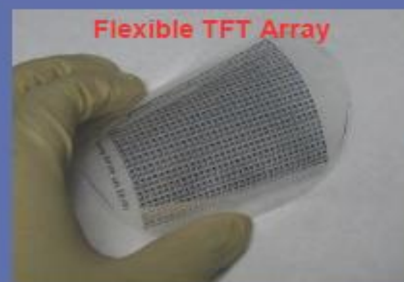
Thin Film Multi-Sensor Transistor Arrays

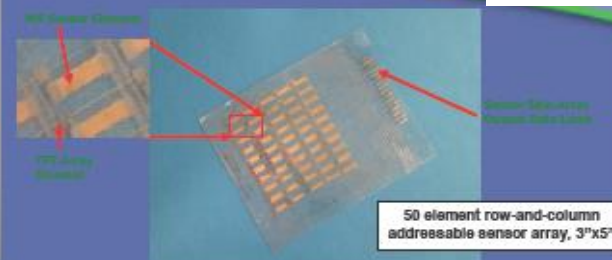
NASA Aeronautics Research Institute

Integration with Thin Film Transistor Array

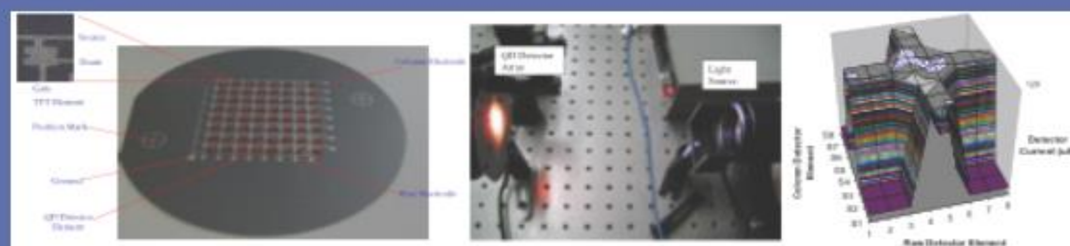
NanoSonic, Inc.

Row-and-Column
Self-Assembled
"Addressable"
Flexible
TFT
Appliqué

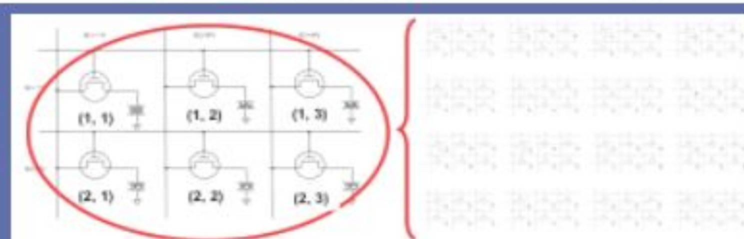




TFT Array with
Visible Detector
Sensor Elements



TFT Array with
Other Sensor
Elements –
"Fly-by-Feel"
Skin Friction
Sensors



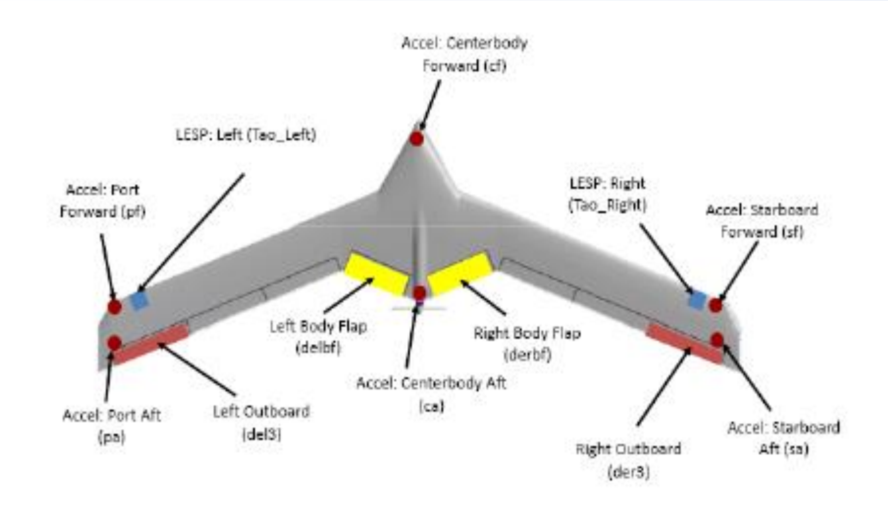
Flexible TFT + Sensor Array

2D Sensor Mapping Array

Virginia Tech
Virginia Polytechnic Institute and State University

BFF GLA/Flutter Control Demo: LMCO / AFRL

NASA Aeronautics Research Institute



{BFF.mp4, BFF_Open_Closed.wmv}

X-56A Body-Freedom with Classical W/T Flutter Control

{MUTT_Flt2_90SecHilite_9-6-13.mov} {MUTT_FirstFlight_7-26-2013.mov, ??}

Full-Scale Advanced System Testbed (FAST) F18 Flight Research
LESP and SBLI Aero Sensing

Aero Sensing LESP / SBLI Flight Evaluation

Assess suitability of Leading Edge Stagnation Point (LESP) and SBLI sensing system for subsonic-to-supersonic aeroelastic modeling and control with external disturbances

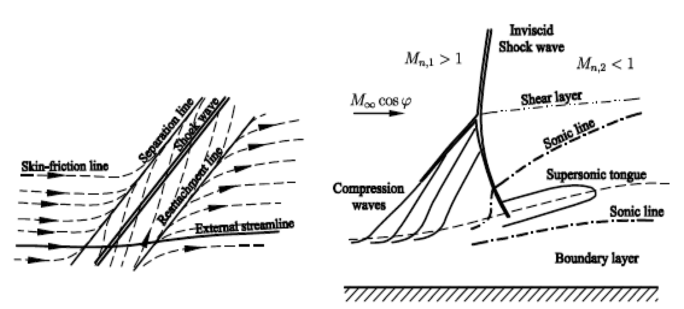
Scope

Sensor characterization of Leading Edge Stagnation Point (LESP) sensor technology with unsteady pressures, shock, and control surfaces

- Help develop ASE and gust load alleviation control laws
- Steady and unsteady FBP and pressure measurements
- Evaluate LESP with shock location and control surfaces
- LESP with SBLI measurements across all flight regimes
- Flight near aero-sensitive regions (high-alpha, stall, STOL)

Unsteady Tran-to-Supersonic Flow over a Transport-Type Swept Wing

NASA Aeronautics Research Institute



RWTH Aachen University - Institute of Aerodynamics

"Weak shock/boundary-layer interaction with incipient separation has minor effects on the wing structure, despite the occurrence of large pressure *fluctuations*, whereas the strong interaction involving shock-induced separation results not only in significantly *weaker fluctuations* in the pressure field, but also in a strong fluid–structure coupling."

Aerodynamic forces increase strongly with speed, elastic/inertia forces unchanged => "transonic dip", then rising flutter stability limit from ***separated flow acting as aero damping***

Lightweight with optimal wing geometries => steady/unsteady aero-wing behavior critical

Periodic shock oscillation due to the ***acoustic feedback loop*** is not induced by the onset of dynamic fluid–structure interaction *but it* ***can excite a structural unsteadiness wrt phase lags***

Shock-induced separation of the turbulent boundary layer occurs without reattachment which indicates the <u>performance boundary</u>

Aero-wing relative phase results in SBLI with unsteady frequencies

Not wing flutter, but a pure response to the distinct oscillation of the flowfield and the shock wave **with Re (scale) dependence**

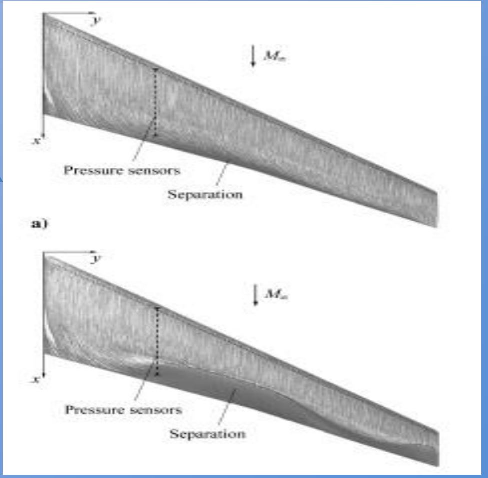


Table 3 Overview of flow test cases for AA-PSP measurements

	Condition 1	Condition 3
Shock/boundary-layer interaction	Weak	Strong
Type of separation	Small trailing-edge separation	Shock-induced separation without reattachment
Unsteadiness	High degree in entire flowfield	Lower, harmonic shock oscillation
Reduced fundamental frequency	$\omega^* = 0.73$	$\omega^* = 0.72$

Partners/Support/Applications

NASA Aeronautics Research Institute

DoD, DARPA (Fly-by-Feel, sensor developments, distributed sensing)

AFRL, Boeing, Northrup-Grumman, Lockheed-Martin, Bell Helicopter, Airbus

ARMD-FAP (X-56A), AvSP, ISRP, *Green Aviation, Wind Energy*

ARMD Seedling Support: AFRL, LMCO, TAMU, UMN (Flow Control), Caltech

Others: IIT, UMN (Aerospace Control), MuSyn, ZONA, AREA-I, UF, STI

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