Controller Performance Evaluation of Fly-by-Feel (FBF) Technology

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Outline

NARI

- Innovation of Fly-by-Feel sensing/control technology
- Technical approach
- Impact of the innovation

- Phase I results
- Phase II objectives, plans, goals

- Distribution/Dissemination (partners, customers, etc.)

Innovation of FBF

Aeroservoelastic Sensor-based Control

certifiable-by-design with

performance and stability guarantees

Distributed Physics-Based Aerodynamic Sensing

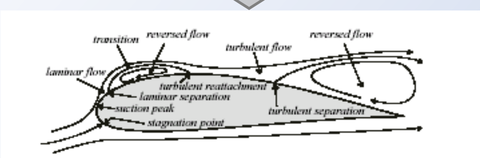
PROBLEM / NEED BEING ADDRESSED

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 Fly-by-Feel (FBF) architecture

Distributed control with alternative sensors

Information-based sensing for efficient mission adaptivity with aerostructural control

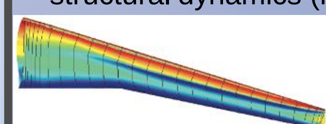
Development of physics-based analytical aerostructural feedback mechanism

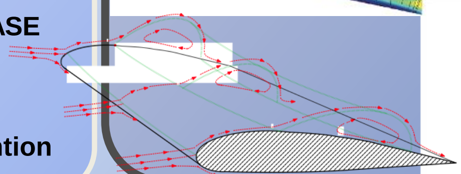
HOW IT WORKS:

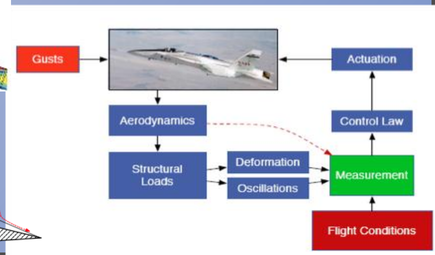
Real-time aerodynamic force measurement improves aerostructural performance and efficiency across all flight regimes (sub/tran/sup/hyper)

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;

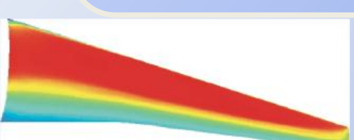
[AvSP] LOC prevention, mitigation, and recovery in hazardous flight conditions

AFRL/LMCO (MUTT), NASA-OCT

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

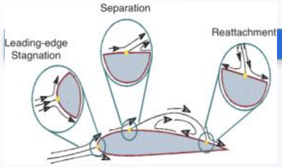
PROGRAM GOALS

- 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

Approach to Enabling Fly-by-Feel Control



PROBLEM / NEED BEING ADDRESSED

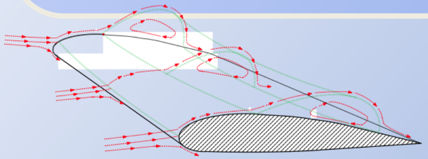
Theoretical/experimental tools to validate stability and performance of robust control with Fly-by-Feel sensing

STATUS QUO

- 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

NEW INSIGHTS

- 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



PROGRAM DESCRIPTION:

Validate robust control laws augmented with aerodynamic observables in aerostructural wind tunnel (WT) / flight test (FT) [currently TRL 2-3]

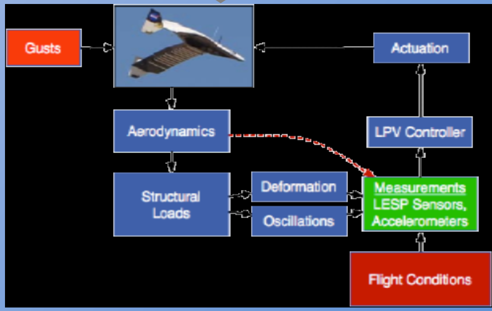
- **Challenges:**
  - Development of analytical codes for nonlinear aerodynamics with compressibility effects
  - Developing aeroservoelastic (ASE) sim with unsteady aerodynamics for developing robust control laws
  - Developing low-power sensor technology robust in operational environments
- **Critical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

QUANTITATIVE IMPACT

- Improved worst-case performance under uncertainty
  - Gust load alleviation
  - Flutter prevention envelope
  - Suppression of limit cycle
- Feedback control performance is limited by time-delay

PROGRAM GOAL



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

Previous Analytical Approaches

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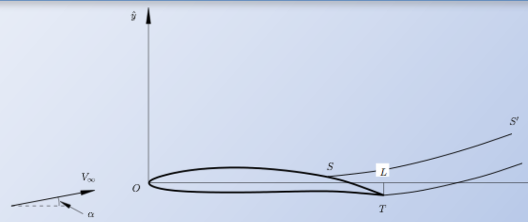
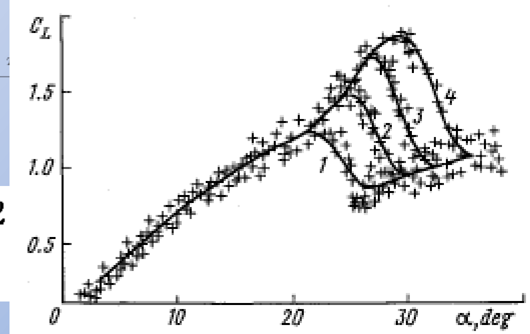
- LE stagnation point (LESP, xl)

  Flow separation point (FSP, xs)
- L.C. Woods: any two of the three (AoA, FSP, LESP) fully determines the system



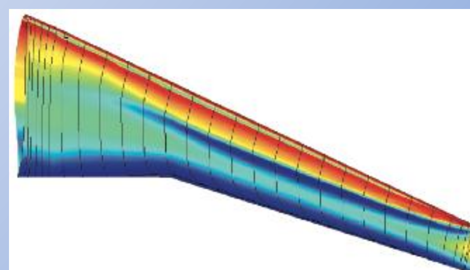
$$C_L(\alpha, x) = \frac{\pi}{2}\sin(\alpha)\left(1+\sqrt{x}\right)^2$$

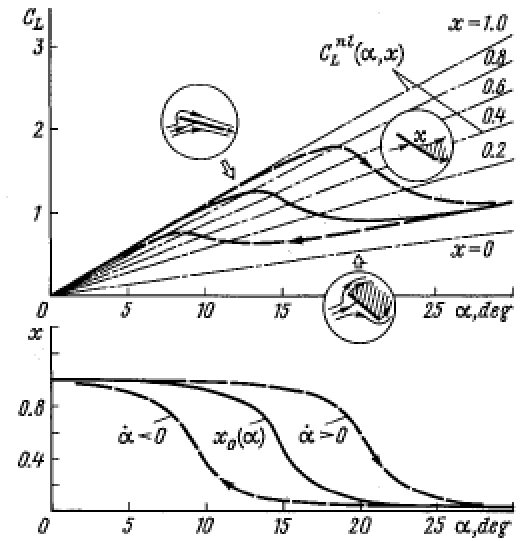


$$\tau_1 \frac{dx}{dt} + x = x_0(\alpha - \tau_2 \dot{\alpha})$$

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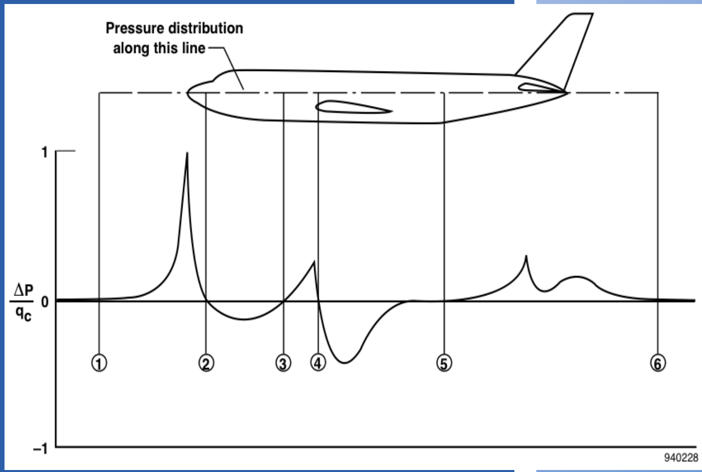
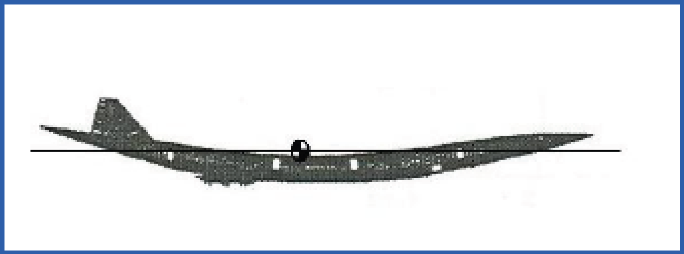
- AFRL/NASA TDT [aeroservoelastic control]
- NASA ATW [flutter]
- Sandia National Lab [smart blade]
- AFRL SARL [flow control]
- AFRL/NASA OSU [transonic shock]
- AFRL/NASA/LM BFF [flutter suppression]
- AFRL X-HALE [aeroservoelastic modeling/ground test/flight test]
- Relevant Past Experiments
    -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





FBP Model Validation: SARL

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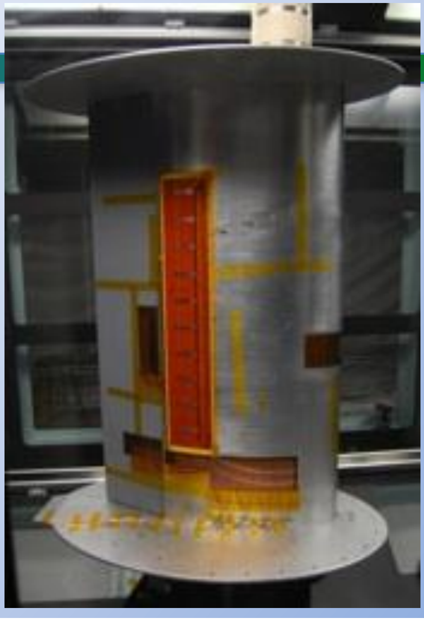
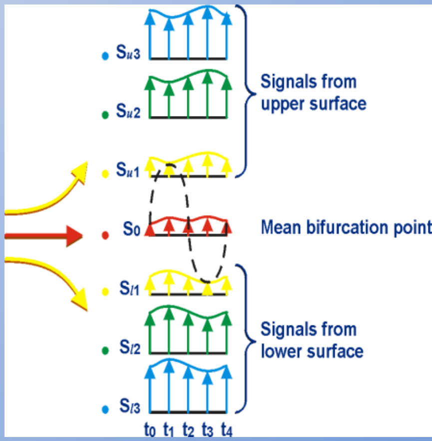
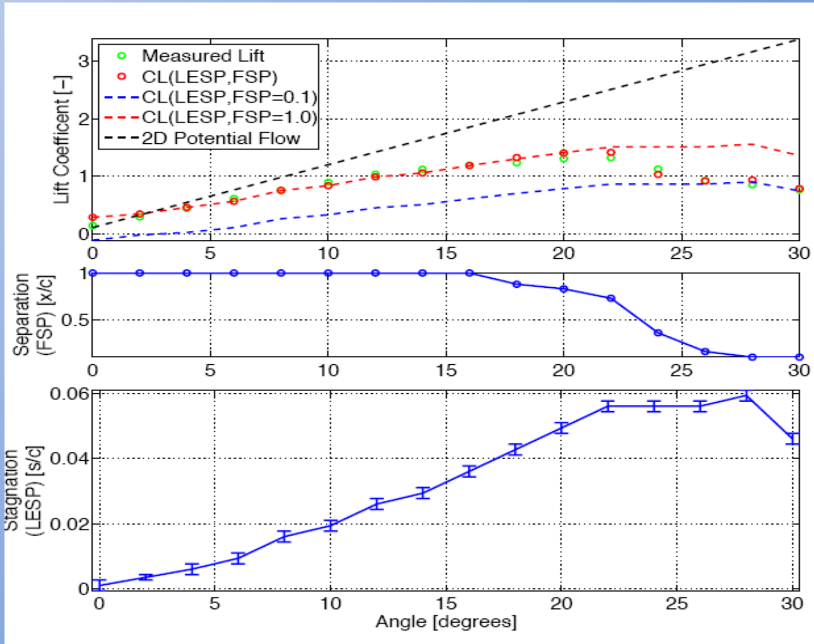
Subsonic Aeronautics Research Laboratory (SARL) @ Wright-Pat AFB

- Cambered airfoil w/ Flexsys conformal flap
- Low aspect ratio => significant 3D flow
- Pressure taps to obtain pressure distribution & lift / moments





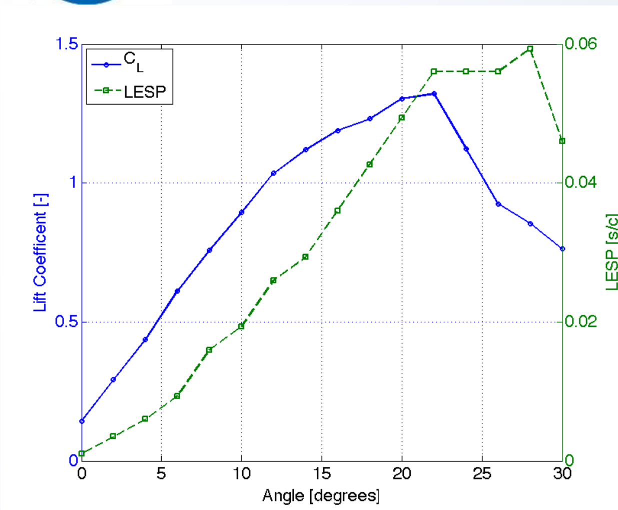
- Hot-film sensors
  - Leading-edge => stagnation point
  - Upper surface => flow separation
  - Phase reversal signature

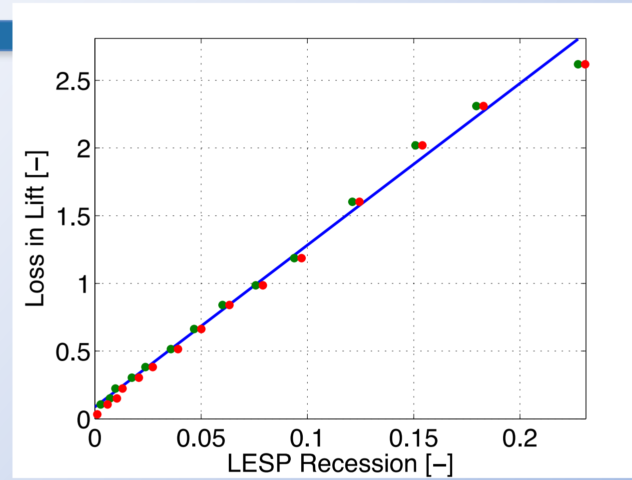


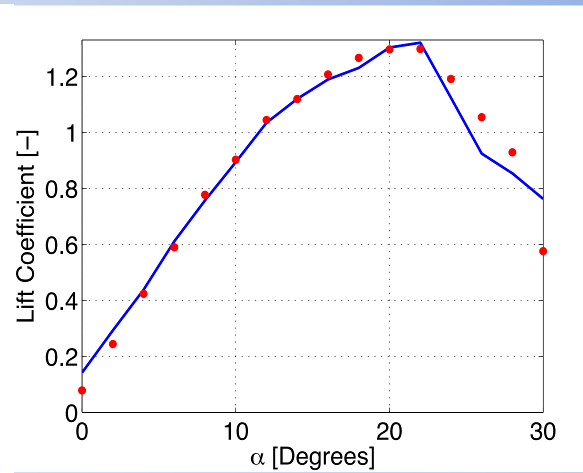
Effect of plasma on circulation/flow separation

- Trigger control on FBP characteristics

FBP Model Validation: SARL



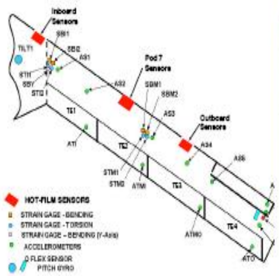


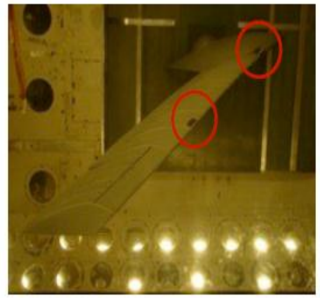


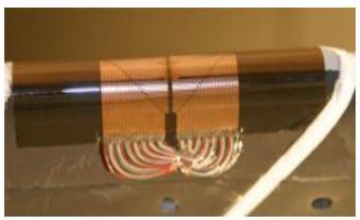
- Low aspect ratio wing stalls ~22 degrees
- LESP location does not decrease until 28 degrees
- Loss in lift obtained from Kutta condition minus the actual measured lift
- LESP recession
  - LESP location associated w/ Kutta condition lift minus actual LESP
  - Monotonic (one-to-one mapping) & mostly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

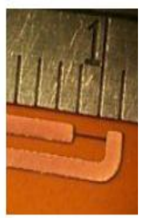
FBP Low-speed ASE Control

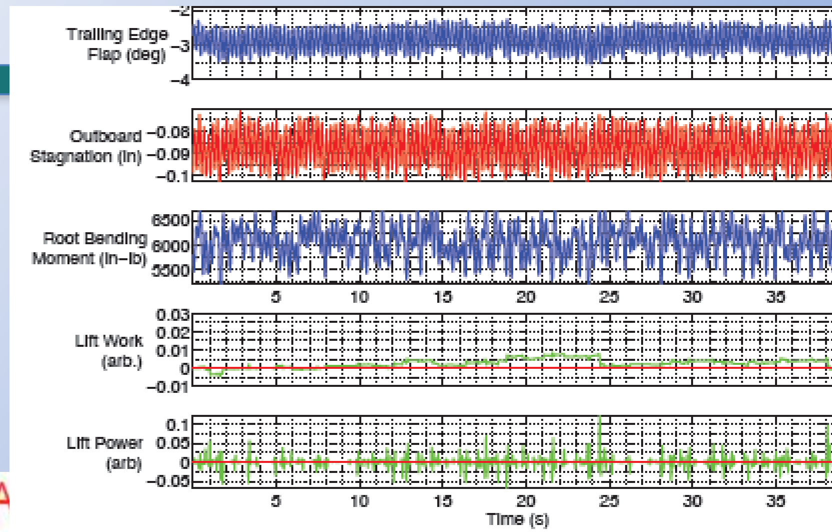
NASA LaRC TDT Test : NGC / LMCO

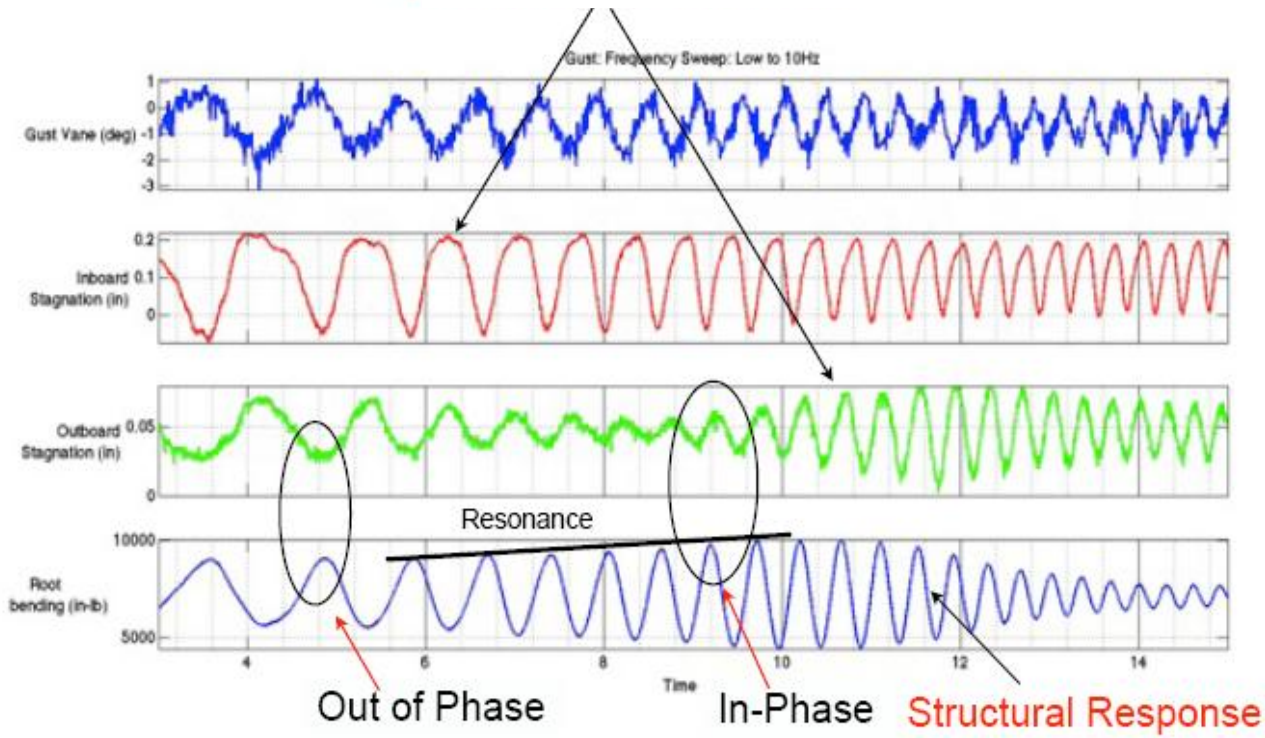








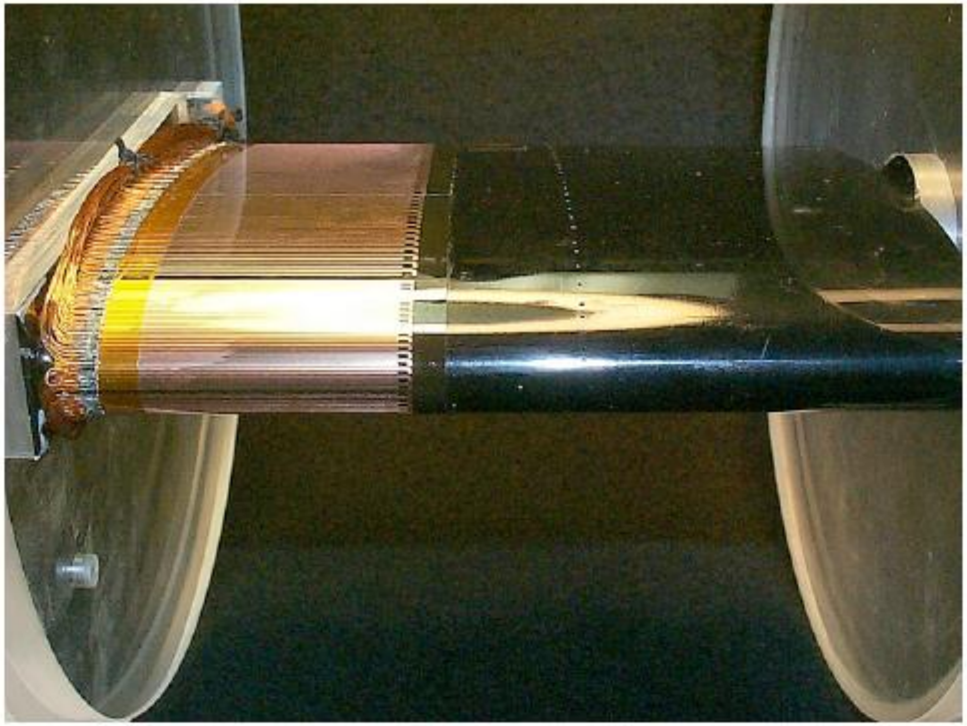




ASE control techniques
- Effect of delay in ASE control
- Adaptive control: requires bounded uncertainty in physics
-Bounds particularly important for aeroelastic applications (3D)

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

FBP: High-speed OSU Transonic Wind Tunnel



- OSU Tunnel
  - 6” x 22” blow down facility
  - Mach: 0.2 – 0.77
  - Re: 5 – 25 M
- Airfoils
  - NACA 0021
  - NACA 4415
- Instrumentation
  - Hot-film sensors
  - Pressure sensors

NASA ATW Flight Test

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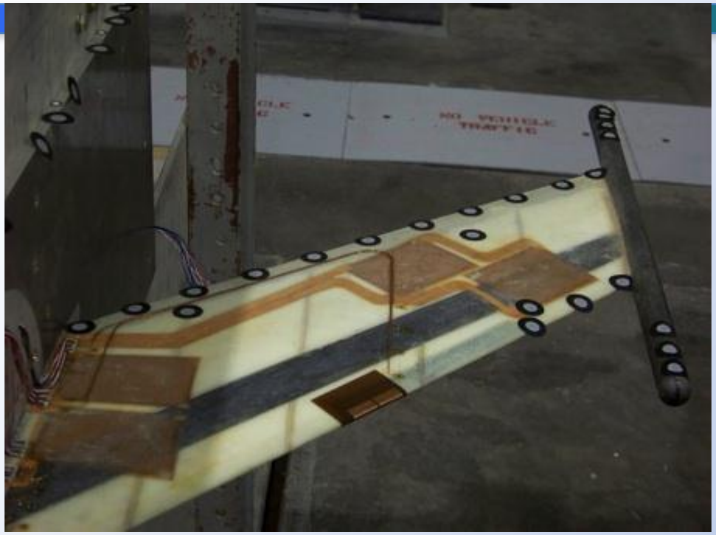

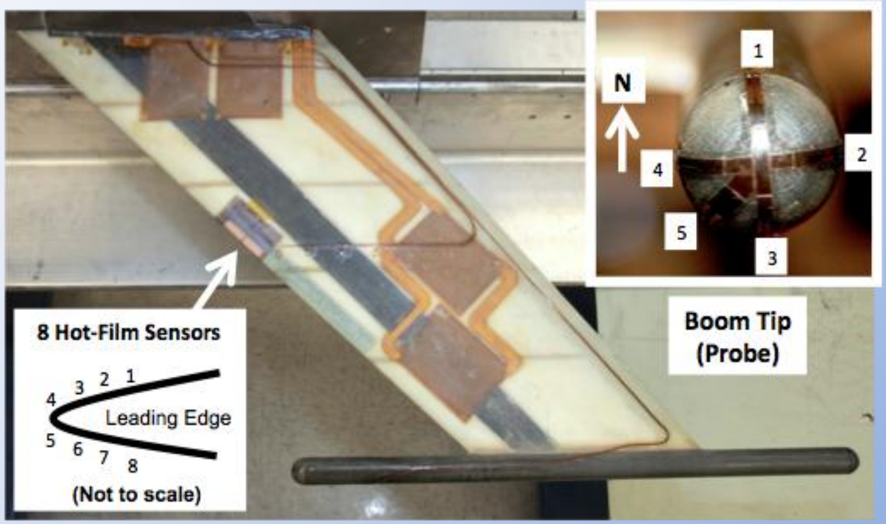

- Aerostructures Test Wing
- On F-15 test fixture
- Onset of flutter
- Instrumentation
- Hot-film sensors
  - Leading-edge
  - Angularity probe
- Accelerometers
- Strain gages
- Air data

ATW Test Data

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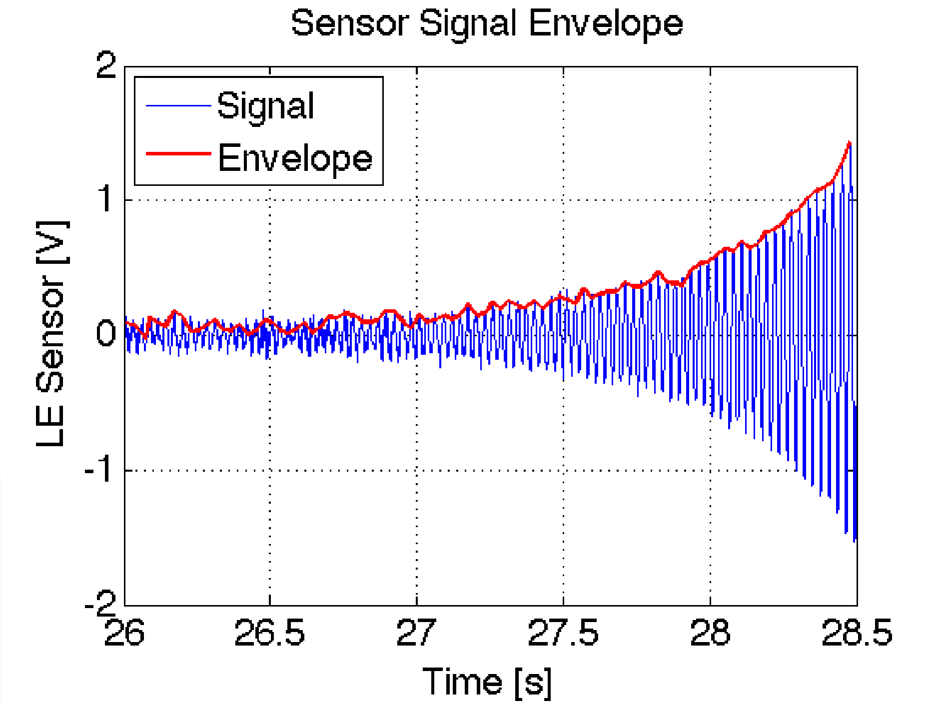

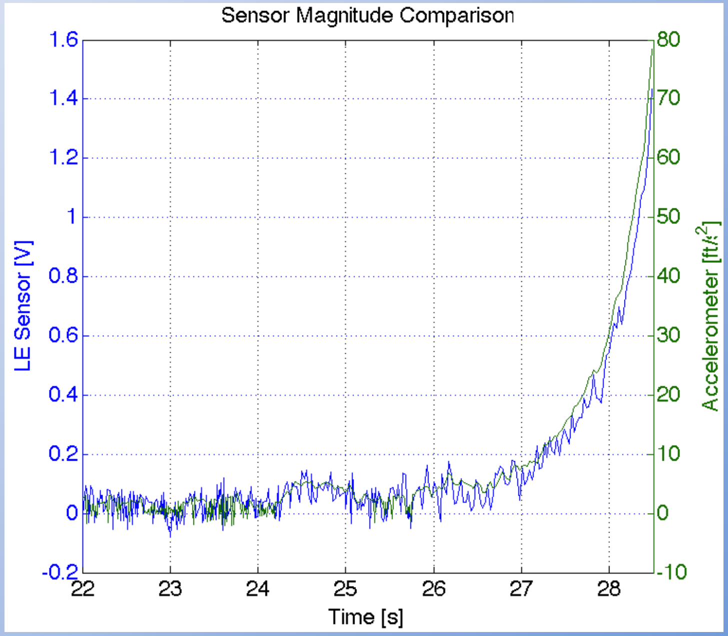

LESP amplitude increases like that of a force measurement

ATW Test Data

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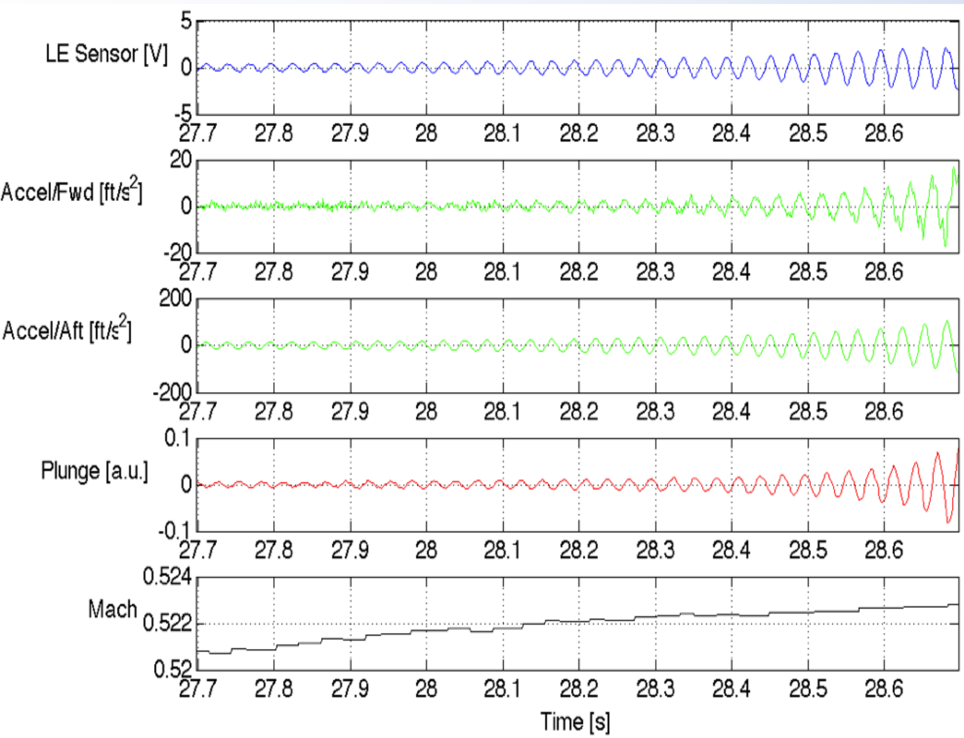

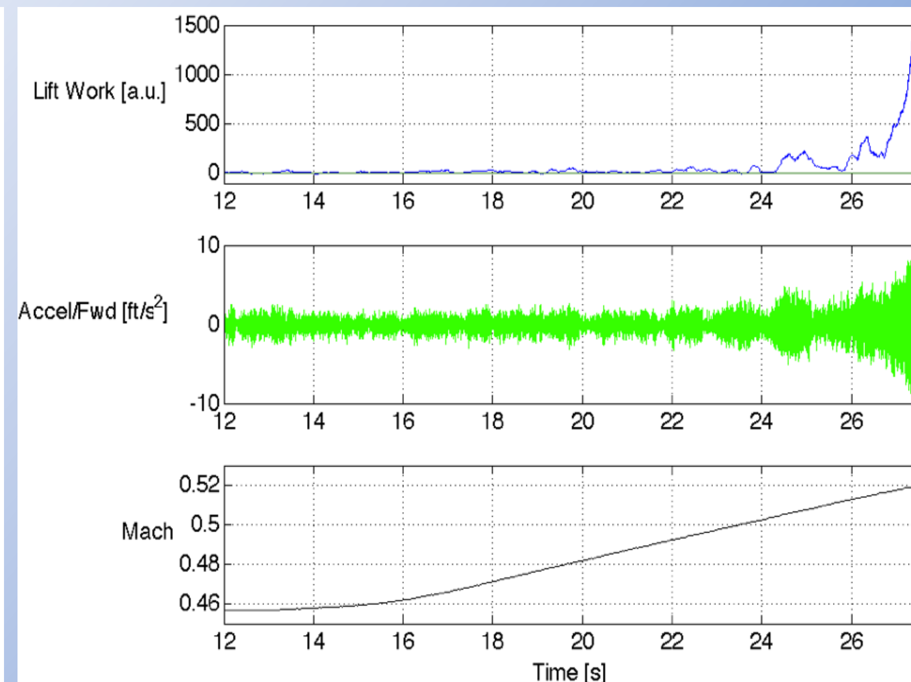

Estimate plunge from co-located fore/aft accels

Work done by fluid on the structure w/Mach

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

FBP/ATW Summary

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- 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

Past FBP-LESP Ground and Flight Testing

NARI

- 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 aero. coeffs.
- Optimized sensor & instrumentation for FBP detection
  - Sub-millisecond response
  - Minimal sensor calibration (automated)
  - Identification of LESP with minimal # of sensors
  - Instrumentation: practical immunity to EMI/RFI
  - Flight-hardened multi-channel system
- Demonstrated gust load alleviation (GLA) using FBP feedback
  - Improved GLA w/ less control effort than structural feedback alone
- Test Applications
  - Low-speed (SARL) [flow control] and high-speed (OSU) [transonic]
  - Flight tests: ATW2 (DFRC) [flutter] and BFF (LMCO) [flutter]
  - Other: Sandia [wind energy]

FBP Model Validation – Phase I

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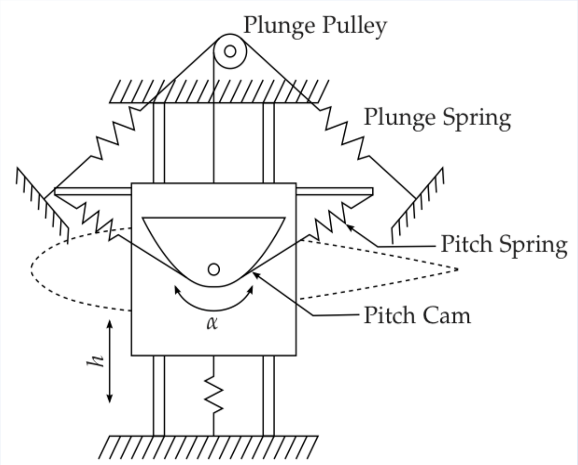
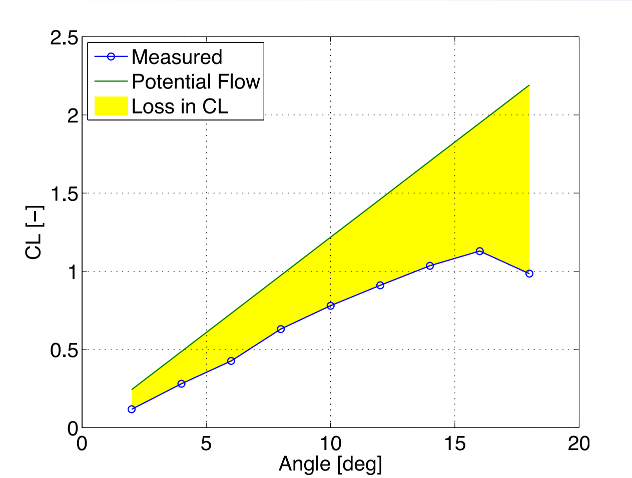


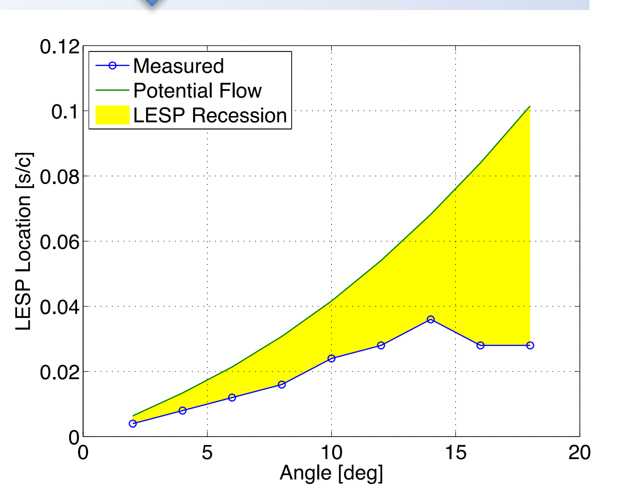
- Does the FBP relationship with aero coeffs hold for unsteady cases?
- Texas A&M Pitch-and-Plunge Apparatus (PAPA)
  - Free PAPA: LCOs / flutter and robust control law development
  - Forced PAPA: pitch/plunge dwell/sweep with pitch/plunge dwell
  - Wings with control surfaces and instrumented w/ load balance, accels, optical encoders, etc. for developing relationship between FBPs, pitch/plunge rates, control surface deflection and aero coeffs

Fly-by-Feel Testing – Phase I:

FBP Model for Steady Lift Estimation



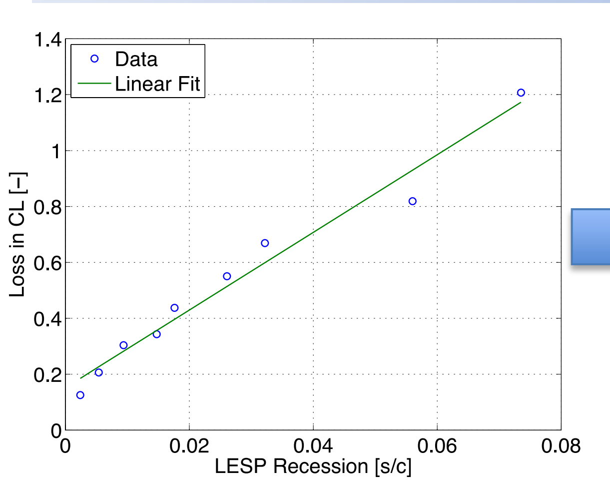
(CL,AoA) &
(LESP,AoA)



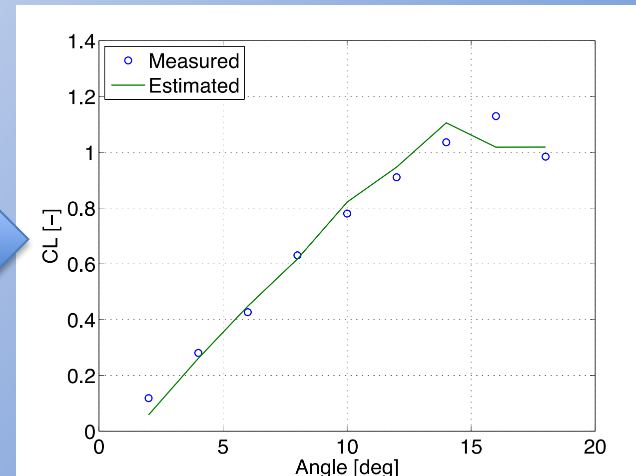
Notes - open-loop test in a free PAPA

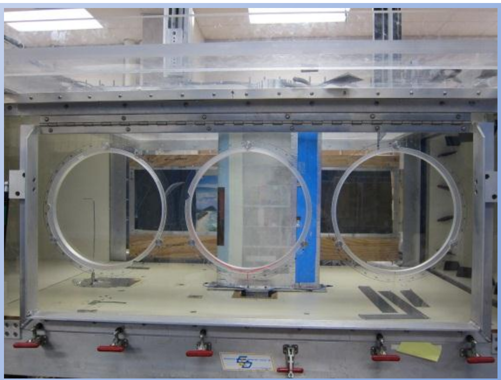
- CL is non-monotonic, non-unique function of AoA through stall
- Loss in CL is monotonic function of LESP recession through stall (new)

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
- Extension of FBP model to transonic/supersonic flows including effect of shock wave boundary layer interaction

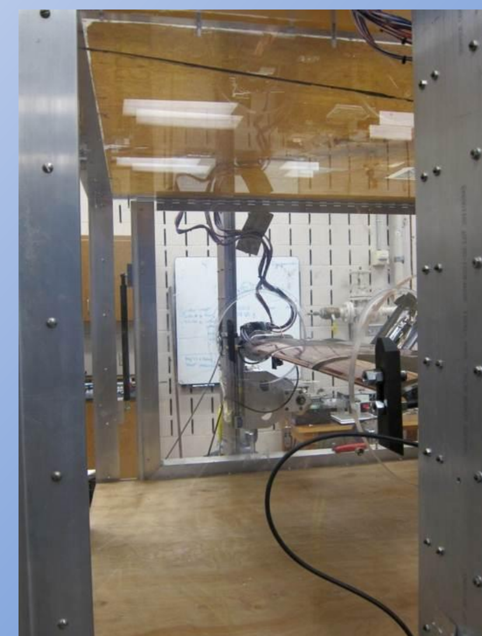
Fly-by-Feel Phase I-II Testing:

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

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

MUTT-like wing instrumented at three span stations



Follow-on Work
Develop open-loop / closed-loop test procedures for upcoming tests on the F-18 with AFRL under the RASSCAL program,

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

Fly-by-Feel Aerodynamic Sensing for Control

Potential Near-Term Opportunities

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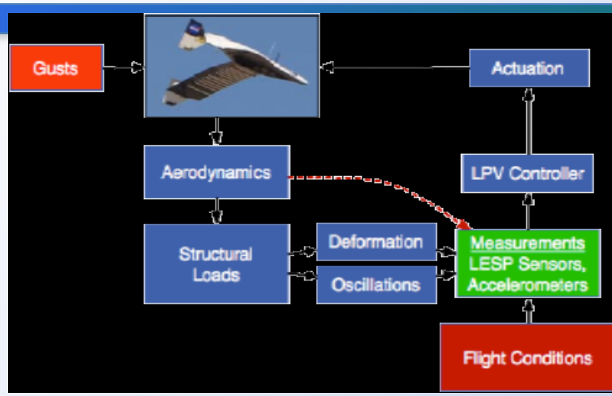

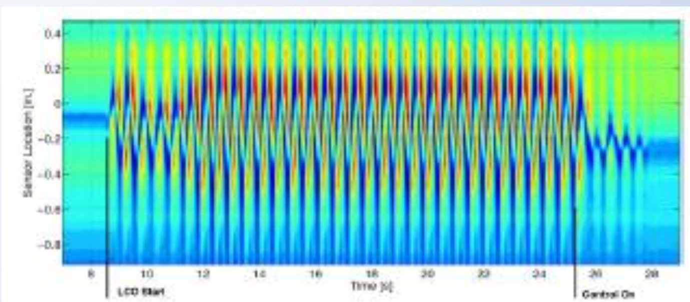

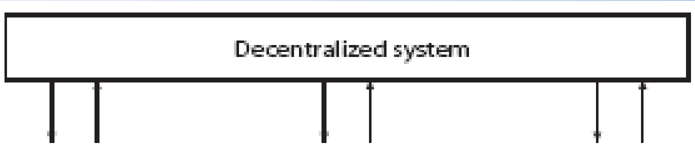

Fig. 1. Diagram of a decentralized system.

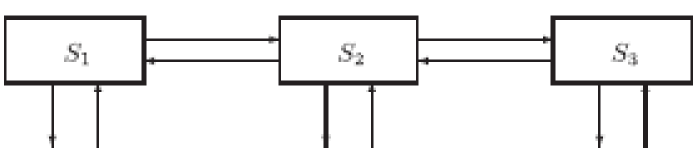

Fig. 2. Diagram of a distributed system.

- **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 enabled 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, CalTech, SBCs, LMCO, AFRL, etc.**

Robust-Network Sensor-based Distributed Control

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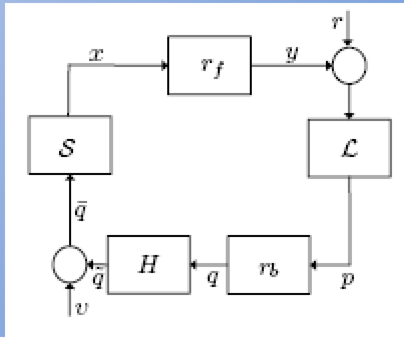
Spatially distributed physical components with sensors/actuators/processors interconnected in arbitrary ways: **problem-dependent traffic interaction**

Processing units interconnected by dynamic communication networks requiring closed-loop ID with distributed estimation/optimization/control



Multi-scale-level information sharing with layering architecture

Model structure exploited for optimal performance design

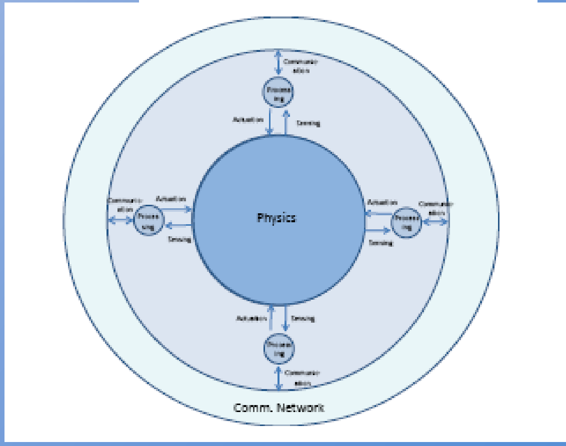
"Layering as Optimization Decomposition"

Optimal solution in modularized and distributed manner

Top-down design layered stacks -> conceptual simplicity

Functionality allocation motivated by "architecture first"

Enables scalable and evolvable network designs



Decompositions have different characteristics in efficiency, robustness, asymmetry of information and control, and tradeoff between computation and communication.

Essentials of Sensor-based Distributed Control

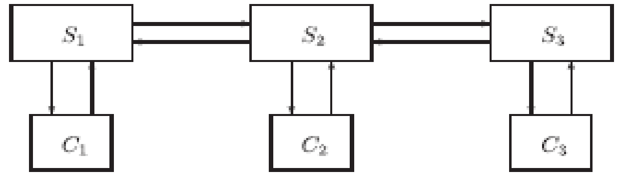
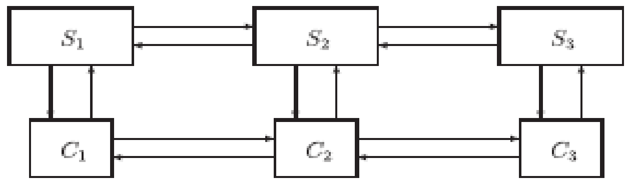


Fig. 3. Diagram of the control architecture of distributed control.



Physics-based sensory perception and reaction

- relevant data-driven autonomy (biomimetic)
- spatio-temporal, multi-scale, viscosity, SBLI
- advanced real-time aerostructural measurements

Distributed multi-objective energy-based control

- efficient mission adaptivity with reliability and safety
- inherent passivity/dissipativity with optimal energy-force distribution
- **spatial uncertainty minimization** with local control and robust global feasibility
  centralized (fusion-centric) vs decentralized / **coordinated degree of hierarchy**
- coordinated subsystem-independent control (min state variance and input)

Network sensor/comm modeling (adaptive layered topology, who-what-when?)

– Sensornets: complex interactions <–> protocol layering = optimal decomposition

– Multi-level network control/estimation and **information architectures**

Decentralization with compressive information-based sensing/identification

Consensus-coordinated network control with coupling/compatibility constraints

Multi-MIMO stability / robustness analysis in sensing/communication/control

Robust Networks for Sensor-based Distributed Control

NARI

Advanced technology's near-biological complexity

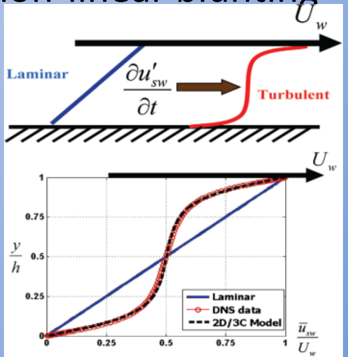
- level of organization, architecture, and the role of layering, protocols, and feedback control in structuring complex multi-scale modularity
- protocol layers hide complexity of layer below and provide service to layers above
- follows necessarily from their universal system requirements to be fast, efficient, adaptive, evolvable, and robust to perturbations in their environment and component parts
- local algorithms attempt to achieve a global objective (consensus-based)
- make transparent the interactions among different components and their global behavior

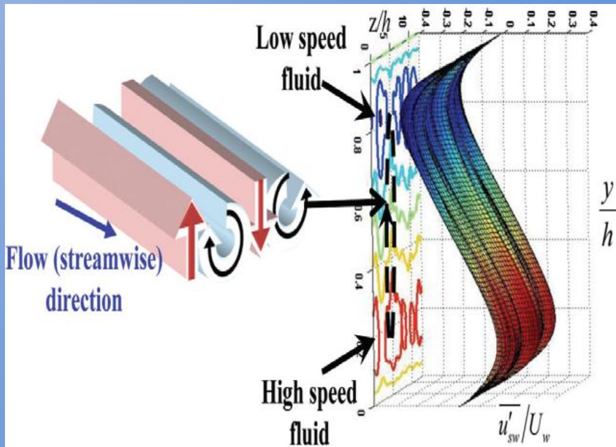
Lack of stability robustness plays fundamental role in wall turbulence (Caltech, etc)

- 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



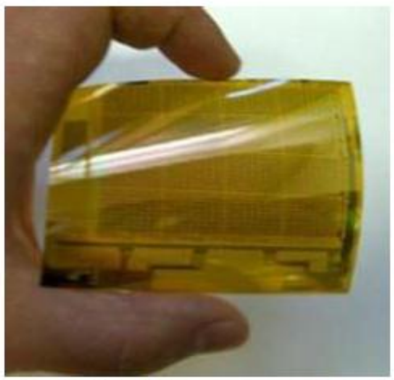


Real-time Aerodynamic and Structural Sensing for Controlling Aeroelastic Loads (RASSCAL)

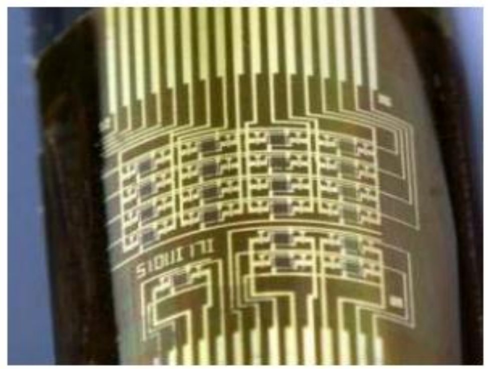
NARI

Current status of flexible arrays

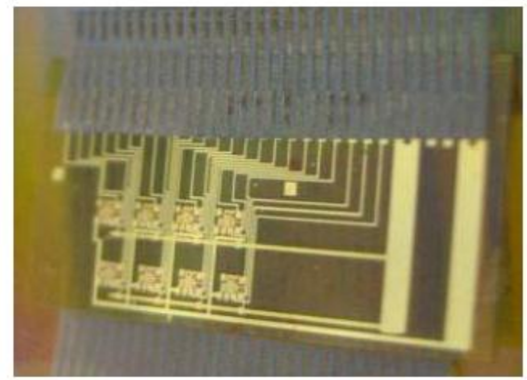
NextGen Aeronautics



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 0.11mm² to 7.2mm²; sensors in arrays have 0.11mm² 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 S³TD F-18 case.

RASSCAL <–> Fly-by-Feel

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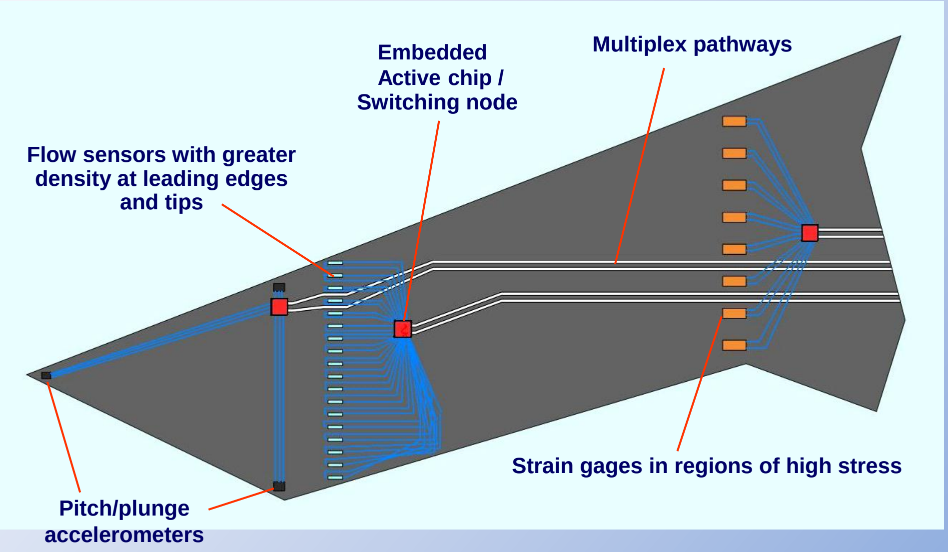
"Fly-by-Feel" is an expansion of ISHM through active sensing of the flight environment.

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 means of processing sensor data**
  - **Identification of "critical points" for characterization of aerodynamics and airframe response**
  - **Switching and multiplexing algorithms**
  - **Understanding how to use new sensors and parameters in controllers**
- **Efficient means of manufacturing multifunctional structure**
  - **Direct Write (Mescoscribe), Laser Transfer, etc**
  - **Sensor and trace consistency**

ASE Sensor Applications: X-56A

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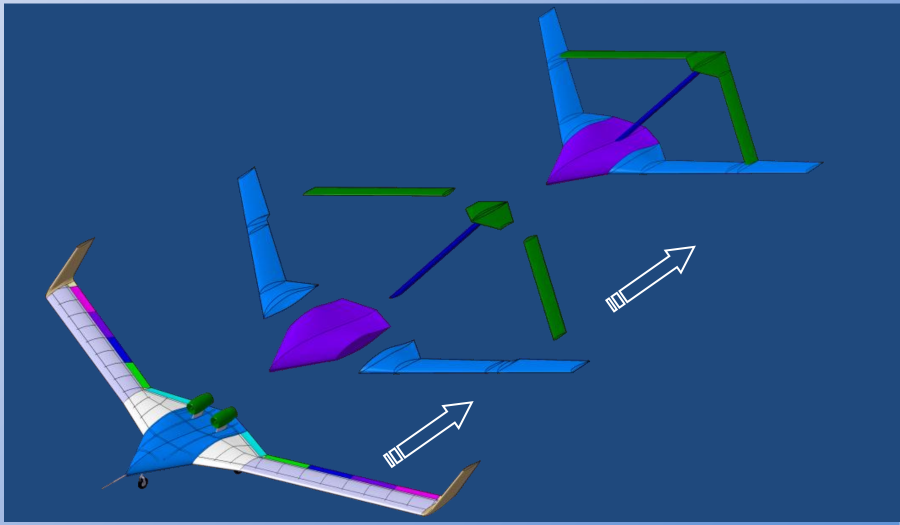
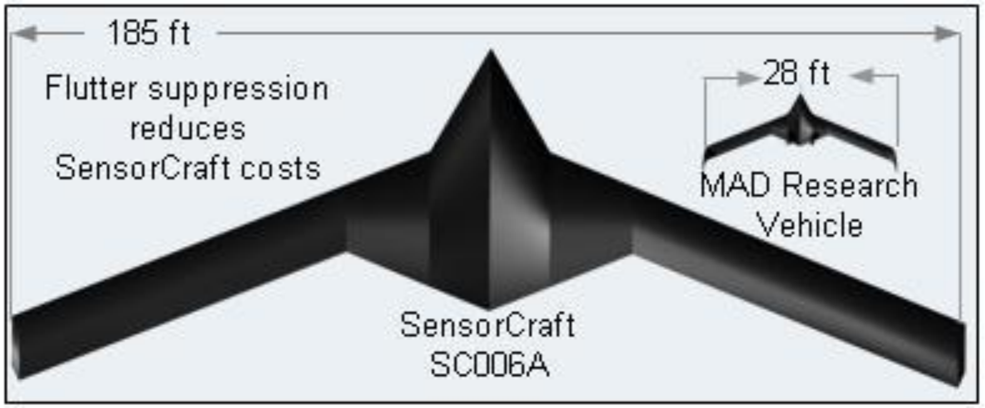




Full-Scale Advanced System Testbed (FAST) F18 Flight Research

LESP and SBLI Aero Sensing

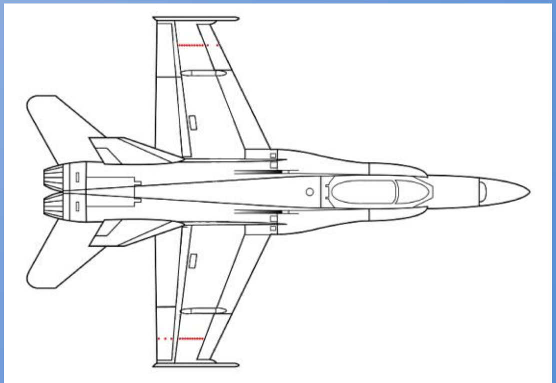
Aero Sensing LESP / SBLI Flight Evaluation

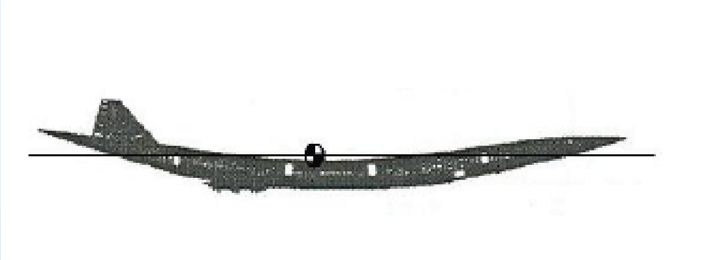
- Assess suitability of Leading Edge Stagnation Point (LESP) and SBLI sensing system for subsonic-to-supersonic aeroelastic modeling and control with external disturbances

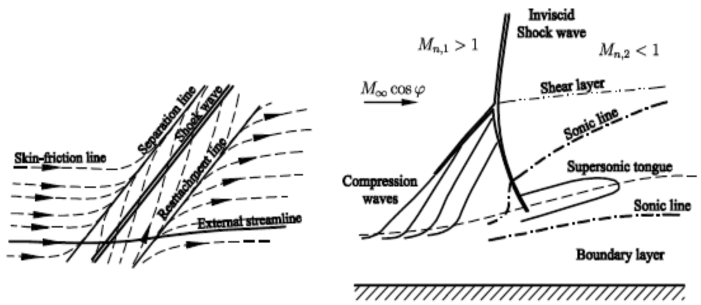
Scope

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 surface position/rate
- LESP with SBLI measurements across all flight regimes
- Flight near aero-sensitive regions (high-alpha, stall, STOL)







FAST-F18 ASE Flight Research

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

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 performance boundary

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

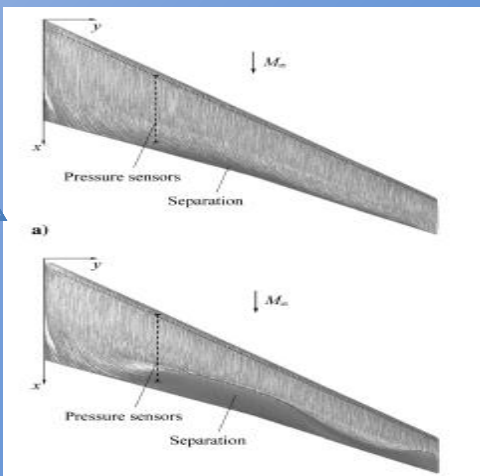


Table 3 Overview of flow test cases for AA-PSP measurements

	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	$\omega^* = 0.73$	$\omega^* = 0.72$

Elements/Objectives/Approach: Phase I-II

NARI

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 *able to be* ***certifiable-by-design***

Objectives/Approach: Phase I

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Phase I Technical Objectives/Approach

– developed a representative 2D wing with control surfaces instrumented with flow sensors, accelerometers and load cell

– modeled dynamic interactions and uncertainties in aerodynamics, structures, sensing and actuation

– initial development of system identification techniques to capture the nonlinear parameters of the system

– designed and simulated control laws augmented with the aerodynamic observables

– conducting open-loop/closed-loop wind tunnel tests in an unconstrained PAPA to validate computational results

– will be conducting a post-test analysis of the initial FBF system identification with control performance to launch into Phase II

Objectives/Approach: Phase II

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Phase II 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 a representative wing with regard to aeroelastic instabilities

– validate computational models predicting the aerodynamic coefficients (CL, CM & CD) based on pitch/plunge/actuator state and aerodynamic observables

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

– continue characterizing the performance of conventional and robust control laws using a variety of aerostructural sensors for feedback including aerodynamic observables in unsteady flows

Progress Report: Phase I

NARI

Tunnel data from Texas A&M was analyzed to determine the extent of LESP correlation with airfoil lift and flow conditions

Scope of work was to understand the dynamics of LESP movement and the measured aerodynamic coefficients as related through circulation for various pitch/plunge rates.

(1) developed a wind tunnel LESP test and data correlation plan,

(2) acquired the dynamics of LESP movement along with loads/moments, wing displacement, acceleration and control surface deflection, e.g., pitch/plunge dwells and pitch/plunge frequency sweeps,

(3) validated analytical relationship between LESP and aero coefficients for unsteady cases, and

(4) demonstrated physics-based closed-loop control of aeroelastic instabilities, like limit cycle oscillations (LCOs)

Progress Report: Phase I

NARI

Accomplishments

A wing with active control surfaces was calibrated with the free-movement unconstrained PAPA at the Texas A&M University (TAMU) 2x3-ft subsonic tunnel

Procedure was developed to test the wing at increasing airspeed to determine the limit cycle oscillation (LCO) margin

Same airfoil section as the LM MAD/MUTT vehicle has been instrumented and installed in the TAMU 3-ft x 4-ft subsonic tunnel. The wing has been installed in a forced PAPA for pitch/plunge experiments and was used for calibrating sensors for upcoming ASE flight tests

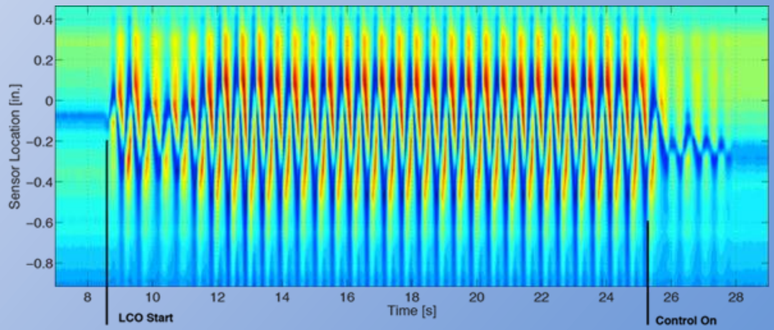
Controller was developed and simulated for demonstrating FBF-based sensing and control of aeroelasticity

Progress Report: Phase I

NARI

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 an unsteady test of a 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 and the aerodynamic forces.



LESP visible as the oscillating minimum shear stress (blue)

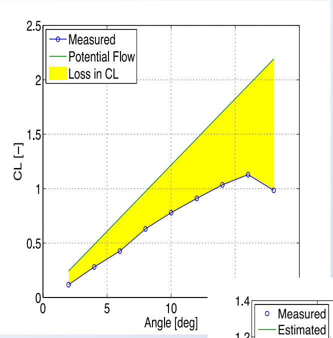
Progress Report: Phase I

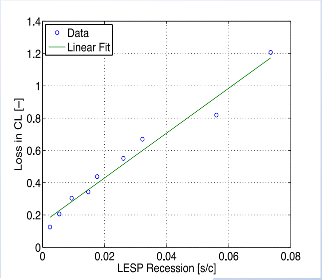
NARI

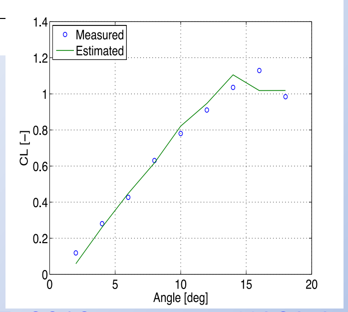
Statically calibrated the LESP sensors with aerodynamic lift and use the constituent aeroelastic equations to develop an ASE controller to suppress the LCOs

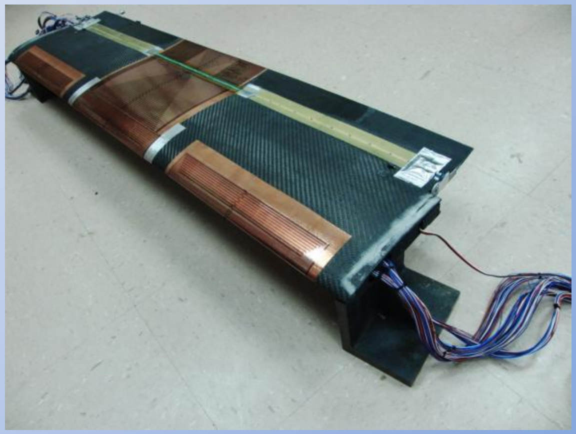
Second test relates the movement of flow bifurcation points, e.g. LESP, and flow separation point to the aerodynamic forces under increasing pitch rates.

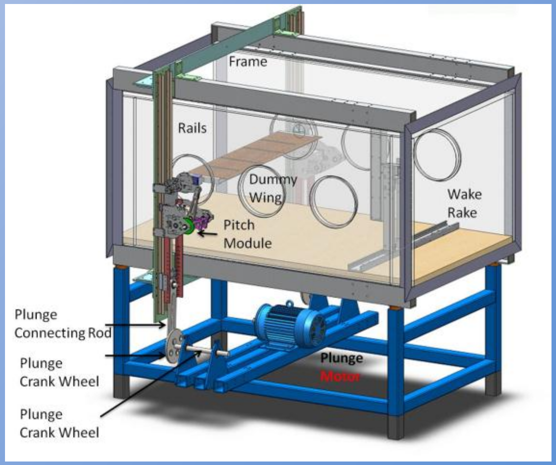
Enables calibration of the wing for unsteady response, thereby providing a basis for flight testing the actual MAD/MUTT wing with a model for the sensor dynamics.











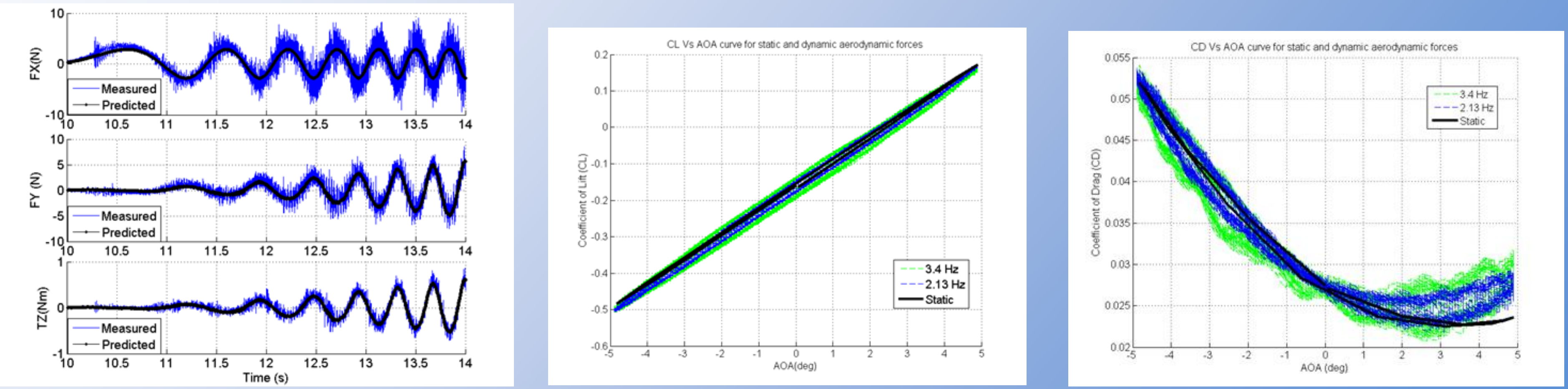
MUTT section and Pitch-Plunge-Flap Drive System (PPFDS)

Progress Report: Phase I

NARI

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

PPFDS was significantly modified to correct mechanical design issues for accurate aero forces wrt inertial pitch/plunge loads, and also to enable a 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

Progress Report: Phase I

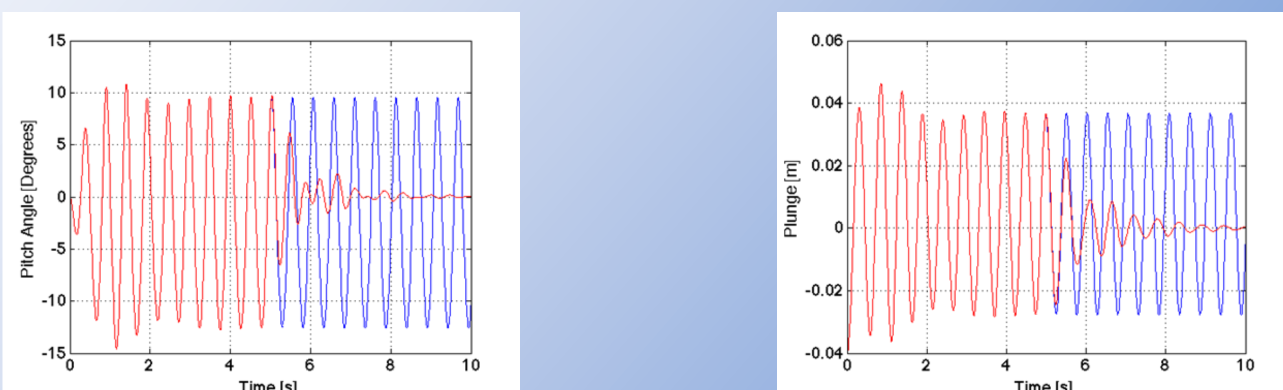
NARI

Develop controller that ensures that the time derivative of the total energy is strictly decreasing, i.e., $\frac{dE}{dt} < 0$:

$$M(q,\dot{q})\ddot{q} + C(q,\dot{q})\dot{q} + \frac{\partial U(q)}{\partial q} = T$$

Energy-based approach does not require or assume full knowledge of the underlying structural or aerodynamic model - uses only the outputs and related calibration

LESP sensing provides the output to calculate the aerodynamic forces and moments, and accelerometers provide output for pitch and plunge rates. This approach is especially useful in highly flexible vehicles with *distributed control capability*.



Pitch and Plunge in Open/Closed-Loop in the PPFDS

Progress Report: Phase I

NARI

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

Developing aerodynamic model that better 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 an absolute sense

Developing robust controllers that incorporate these bounds to address a wide range of flow conditions where, for example, flow separation plays a more dominant role like near stall at maximum lift coefficient

Objectives/Plans/Goals: Phase II

NARI

Phase II will extend the work to transition the technology to research aircraft

Requires addressing delays and nonlinearities such as actuator free-play in uncertainty

Propose aeroelastic simulations and predictions of free-play instabilities with validation by representative experiments of control system/actuator free-play in the WT

Purpose of these simulations and experiments is to provide a foundation for a systematic approach to fully understand the mechanism underlying free-play response and stability using novel sensing and control

Objectives/Plans/Goals: Phase II

NARI

Specific Phase II objectives are:

Verify the predictive capability of the analysis using legacy experimental data from WADC testing in the 1950s and use the method to predict changes in flutter behavior as free-play increases over the operational life of an aircraft

Document findings that could be used to establish new guidelines on control surface free-play limits, thereby supplementing or replacing the limits set forth in regulations such as Military Specification MIL-A-8870

Develop an accurate framework for new actuation mechanism and wrap-around controller design based on analytical methods. In particular, the development of methods based on the analysis of nonlinear dynamical responses under loads for prediction of LCO formation and response in flight structures with free-play.

Extend energy-based controller to the X-56A moving from free PAPA to a flying-wing configuration with wing sections structurally and aerodynamically cross-coupled

NARI

Objectives/Plans/Goals: Phase II

Phase II Tasks/Milestones

Task1. Development and validation of predictive free-play model.

Task2. Development and evaluation of new actuation surface feedback controller design based on analytical methods. Control mechanism will be implemented, tested and compared with existing models.

Task3. Simulation of robust energy-based controller for implementation on X-56A. Evaluation of simulation will be based on comparison with existing controllers given the same uncertainties.

Task4. Implementation and evaluation of energy-based controller on actual aircraft.

Task5. Post-test analysis, reporting, etc.

Distribution/Dissemination

NARI

AFRL, DoD, DARPA

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

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

Phase II Proposal Letters-of-Support: AFRL, LMCO, TAMU, UMN (Flow Control), Tao

Other partners: Caltech, IIT, Georgia Tech, UMN (Aerospace Control), MUSYN