Aeroservoelastic Sensor-based Control

(certifiable-by-design with performance and stability guarantees)

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Distributed Physics-Based Aerodynamic Sensing

**PROBLEM / NEED BEING ADDRESSED**

**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
- 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

**Status Quo**

- Lightweight configurations => inherently flexible
- Current limitations:
  - Complex aerostructural control
  - Limited aerostuctural 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

**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

**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

- **LE stagnation point (LESP, \(x_l\))**
  - Flow separation point (FSP, \(x_s\))
- **L.C. Woods:** any two of the three (AoA, FSP, LESP) fully determines the system
  \[
  C_L(\alpha, x) = \frac{\pi}{2} \sin(\alpha) \left(1 + \sqrt{x}\right)^2
  \]
- **Goman & Khrabrov**
  - AoA & FSP \(\Rightarrow\) aero coeffs
  - Unsteady experiments
  - for \(\tau_1, \tau_2\) time constants
  - Based on thin airfoil theory
- **What is AoA in unsteady flows?**
  \[
  x_l = \sqrt{2}x_s^{1/4} \left\{ \alpha_\star - \frac{1}{\pi} \int_{-1}^{x_\star} \frac{G(\zeta')}{\zeta'} d\zeta' \right\}
  \]
FBP: Experiments / Validation

- 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

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
• Low aspect ratio wing stalls ~22 degrees
• LESP location does not decrease until 28 degrees
• Loss in lift obtained from Kutta condition \textit{minus} the actual measured lift
• LESP recession
  – LESP location associated w/ Kutta condition lift \textit{minus} actual LESP
  – \textbf{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-TDT, 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

- 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

Sensor Signal Envelope

-2 -1 0 1 2
LE Sensor [V]

26 26.5 27 27.5 28 28.5
Time [s]

Signal
Envelope

Sensor Magnitude Comparison

LE Sensor [V]
Accelerometer [ft²]

-2 -1 0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6

22 23 24 25 26 27 28
Time [s]

LESP amplitude increases like that of a force measurement
Estimate plunge from co-located fore/aft accels
Work done by fluid on the structure w/Mach

\[ W_L = \int (L - \bar{L}) \dot{h} dt \]
• **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
BFF GLA/Flutter Control Demo: LMCO / AFRL
FBP-LESP Ground and Flight Testing To-Date

- **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: TAMU

- 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: FBP Model for Steady Lift Estimation

Notes - open-loop test in a free PAPA
- CL is 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
- Extension of FBP model to transonic/supersonic flows including effect of shock wave boundary layer interaction
Fly-by-Feel 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

Potential Near-Term Opportunities

- 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

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.
Physics-based sensory perception and reaction
- relevant data-driven autonomy (biomimetic)
- spatio-temporal, multi-scale, viscosity, SBLI
- advanced real-time aerostructural measurement

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

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 (2D/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)

Objectives
- Measure aerodynamic and structural loads with structurally embeddable sensors through the complete fighter flight regime.
- Apply structurally integrated electronics concepts
- Correlate with computational and empirical models for fly-by-feel demonstrations.

Technical challenges
- Transition laboratory sensors to flight environment
- Ingress/Egress of electronics in structure
- Model validation with flight data

Background
- Leverages recent SBIR techs and 853 Stick-to-Stress sim
- Leverages $14M (+$15M labor) NASA upgrade to test bed plus future commitment to this flight research
- Leverages ISHM and contributes to “fly-by-feel” vision
- Testbed capable of sub-, trans-, and super- sonic flight
- LRS, 6th Gen Fighter transition opportunities

Potential Fly-by-Feel Applications
- exploitation of stall to reduce landing distance
- control of unsteady loads for maneuver, LCO, or gust
- active feedback of critical structural load such as wing root bending moment
- diagnostic capability for “high cost events”

Tasks/Schedule

<table>
<thead>
<tr>
<th></th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
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<tbody>
<tr>
<td>“Open loop” load characterization</td>
<td></td>
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<tr>
<td>Develop flight worthy, embeddable electronics</td>
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<tr>
<td>Correlate test data and models</td>
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<tr>
<td>Closed-loop feedback of aero and structural load sensing</td>
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Collaborators

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<tr>
<th></th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
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<tr>
<td>AFRL/RB</td>
<td>$2M</td>
<td>$2M</td>
<td>$1M</td>
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<tr>
<td>NASA</td>
<td>$2M</td>
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Real-time Aerodynamic and Structural Sensing for Controlling Aeroelastic Loads (RASSCAL)

Current status of flexible arrays

<table>
<thead>
<tr>
<th>Metric</th>
<th>Target Value</th>
<th>Actual Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Strain range</td>
<td>4000με – 6000με</td>
<td>Discretes linear 7000με; 4x4 arrays shown repeatedly to at least 2000με.</td>
</tr>
<tr>
<td>(2) Operational temperature</td>
<td>-54°C to 190°C (-65°F to 375°F) (Typical fighter class aircraft, top level structural requirements include -54°C to 121°C (-5°F to 250°F) skin temperature)</td>
<td>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.</td>
</tr>
<tr>
<td>(3) Gage factor</td>
<td>Minimum 24</td>
<td>Gage factors range from 20 to 65, significantly dependent on processing.</td>
</tr>
<tr>
<td>(4) Response</td>
<td>Frequency response in millisecond range</td>
<td>Average 0.6ms time constant, -3dB cutoff frequency: 270Hz.</td>
</tr>
<tr>
<td>(5) Gage dimensions</td>
<td>&lt;1 mm in area</td>
<td>Tested discrete sensors with gage area from 0.11mm² to 7.2mm²; sensors in arrays have 0.11mm² area.</td>
</tr>
<tr>
<td>(6) Fatigue life</td>
<td>1 lifetime (i.e., 6000 hours) for fighter aircraft applications‡</td>
<td>Demonstrated functionality exceeding 132,000 tension/compression cycles for discrete sensors. Surpassed 129,000 as in S³TD F-16 case.</td>
</tr>
</tbody>
</table>

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

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, Laser Transfer, etc
  • Sensor and trace consistency
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 enable the aircraft to react swiftly to changes.

While the theoretical benefits of adaptive aircraft have long been known, and dramatic advances in such 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’s lightweight, flexible-structures research program that could build on previous basic research and continue scientists’ “Fly by Feel” testing and development technologies is being launched.

Researchers believe these technologies will not only boost technology readiness levels toward real-world applications of lighter commercial and military aircraft.

As part of the continuing development of lightweight structures, the U.S. Air Force Research Laboratory is looking into the potential for adaptive materials in aircraft. To that end, the “Fly by Feel” program in collaboration with NASA is also exploring advanced materials.

The MIRAC F-16 is equipped with a simulated adaptive controller that compensates for simulated failures in the flight controls. Using MIRAC in a sub-scale aircraft, NASA believes it could take the concept much further.

“This would enable a system on an aircraft that can make the structure and shape that are happening to the aircraft, and use that information to do things that we need to do more of, like the F-16,” explained Peterson. “The key to this is that it can make sense of it and control it in a more efficient way, which could help save weight on load margins. If you can have a lightweight structure that is adaptive, a robot of NASA’s Advanced Safety Program Wet in Safety System office, MIRAC and its local wind tunnel have up until now in the last four years, the follow-on FAI Full-scale Advanced Systems Technology (FAAST) The concept adaptive control system will replace the current gust alleviation algorithm that could be more easily reconfigured for commercial use in the future when new technologies are fully developed and verified,” says Decorsa.

“We are using much more advanced algorithms than the F16. We are not changing what it is doing, if you will,” said Lee, MIRAC project chief engineer. “The goal is to have, in all of the 360 degrees in a circle, a structure that can enable conventional controllers to be used, and that can be allowed to be safe in a commercial application.”

Another project, conducted by Lockheed Martin and Advanced Propulsion Systems, which provides an aerodynamically meshed and controllable vehicle with an adaptive control system that could safely take off. That program, along with a design that allows the algorithm to control a conventional plane, but with the benefits of its adaptive system, is in the final stages. We feel like NASA has the dollars to work on a full-scale vehicle to take this process,” says former LCS chief engineer John Brown.

Following the end of MIRAC, and a new name change, the F-16 will be fitted with fiber optic wing flaps. As can be seen in real airplanes, the F-16 will be fitted with wing flaps that will work in tandem with the flight control system to improve stability and performance.
ASE Sensor Applications: X-56A

- Flutter suppression reduces SensorCraft costs
- MAD Research Vehicle

185 ft

28 ft
Fiber Optic Strain Sensing (FOSS) Technology Development: Advantages over Conventional Sensors

- Unrivaled density of sensors for spatially distributed measurements
- Measurements immune to EMI, RFI and radiation
- Lightweight, Small fiber diameter
- Can determine out-of-plane displacement and load at points along the fiber
- Single calibration value for an entire lot of fiber
- Wide temperature range (cryogenic – 550F)

- Develop small, lightweight multipurpose system
  - Support small UAVs platforms
  - Support more aggressive manned vehicles like NASA’s 853 (F-18)
  - Support launch vehicles and space applications
  - Robust thermal management
FOSS Technology Development: Multi-Utility Technology Testbed (MUTT = X-56A)

Goal: robust data, model-independent AE control applications

- Control of flexible structures is critical (SFW, SUP, 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
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)
• “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

<table>
<thead>
<tr>
<th>Shock/boundary-layer interaction</th>
<th>Condition 1</th>
<th>Condition 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of separation</td>
<td>Weak</td>
<td>Strong</td>
</tr>
<tr>
<td>Unsteadiness</td>
<td>Small</td>
<td>Shock-induced separation without reattachment</td>
</tr>
<tr>
<td>Reduced fundamental frequency</td>
<td>$\omega^* = 0.73$</td>
<td>Lower, harmonic shock oscillation $\omega^* = 0.72$</td>
</tr>
</tbody>
</table>
Object-Oriented MDAO tool Development

**Problem**
- Reduce the structural weight further down than current technology can take care of, we need to develop a new innovative structural design concept
- Global optimizer, Genetic Algorithm (GA), in the current MDAO tool requires too much iteration to have a reasonable solution
  - A global optimizer is needed for topology optimization with curvilinear sparibs and sizing optimization with discrete design variables (DDV)

**Proposed solution**
- Use *aeroelastic tailoring* based on composite material as well as *curvilinear sparibs concept* together with an *active flexible motion control* technique
- Use *Big Bang-Big Crunch (BBBC) algorithm* as a global optimizer

**Approach**
- Develop multilayer, multifidelity, & multidisciplinary design, analysis, & optimization tool using O³ tool
  - Inner-layer: mainly for structure and control design
  - Outer-layer: mainly for aerodynamic design

- Incorporate the following analysis modules
  - weight, stress/strain, buckling, open & closed-loop flutter, gain/phase margin, maneuver load alleviation, & automatic mesh generation for curvilinear sparibs
  - lift/drag, gust, & sonic-boom
  - internal noise & etc
Application (X-56A)

- Finite Element Model Tuning of X-56A Aircraft using Parallelized Big Bang Big Crunch Algorithm
  - The primary objective of this study is to reduce uncertainties in the structural dynamic finite element model of an aircraft to increase the safety of flight.
  - This model tuning technique is applied to improve the flutter prediction of the X-56A aircraft.
  - This work is supported by ARMD SFW and SUP projects under FA program.
  - Deliverables: finite element model for MSC/NASTRAN simulation

- Unsteady aerodynamic model tuning of X-56A Aircraft based on indirect method
  - An automatic aerodynamic mesh generation code is under development.
  - Deliverables: unsteady aerodynamic model for ZAERO simulation and paper/report

- Create Reduced Order X-56A Aircraft Structural Dynamic Model
  - Use Equivalent Beam Model
  - Create target frequencies and mode shapes using full-3D FE model
  - Use Structural dynamic model tuning code
  - Deliverables: finite element model for MSC/NASTRAN simulation
Aeroservoelastically Tailored Wings and Aircraft

**Design Approaches**
- Simultaneously update structural as well as control design variables during early design phase
  - Perform topology optimization with curvilinear sparibs
  - Use aeroelastic tailoring up to Vd line
  - Use aeroservoelastic tailoring between Vd and 1.15 Vd

**Future Applications**
- N+3 Concept Aircrafts for Fixed Wing and High Speed Aircrafts; ERA

**Deliverables**
- Finite element structural models for preliminary and detailed design, papers, & reports

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**Aeroelastic stability envelope**

- Equivalent Speed
- Flutter Boundary
- Use Aeroelastic Tailoring
- Use Aeroservoelastic Tailoring

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**Curvilinear sparibs**

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Flexible Motion Controls with ASE System Uncertainties

**Problem**
- The increased flexibility, due to weight reduction, creates an aircraft that is more susceptible to aeroelastic phenomena such as flutter, divergence, buzz, buffet, and gust response.
  - Uncertainties are exist in aeroservoelastic system even with the test validated aeroservoelastic model due to
    - time-varying uncertain flight conditions,
    - transient and nonlinear unsteady aerodynamics and aeroelastic dynamic environments.

**Proposed solution**
- Use Active/Adaptive Flexible Motion Control
- An adaptive “delta control” methodology is proposed.
  - On-line parameter estimation will be applied to the prediction error, uncertainties in the validated aeroservoelastic model.

**Approach**
- The online update for the delta control gain is determined on the basis of a test-validated aircraft model whose predicted output response is compared with the actual aircraft measurements.
- The delta control scheme will act in addition to a nominal control law developed solely from the test-validated model so has to help offset some of the model’s inaccuracies and uncertainties.

**Assumptions & Limitations**
- Dynamically linear assumption will be used for the prediction error model.
- On-board computer should be powerful enough to perform on-line estimation and control law updates.
ASE Maneuvering Simulation Development

PROBLEM / NEED BEING ADDRESSED
Maneuvering simulation of general aircraft aeroservoelastic dynamics with reduced-order state-consistent models

PROGRAM DESCRIPTION:
Development of aeroservoelastic maneuvering simulation facility with efficient and direct implementation of multi-fidelity models for general active/adaptive and distributed sensing control architectures

• Challenges
  – Appropriate state-space representations of flight dynamics with aeroelastic interactions and general multi-disciplinary components
  – Multi-rate synchronization of various disciplines into multidisciplinary environment for maneuvering flight
  – Real-time accuracy with sufficient fidelity

• ARMD Program Goals
  – FAP: Improved Comp/Exp Tools & Methods, System Integration, MDAO Simulations
  – AvSP: Aircraft Loss of Control Prevention, Mitigation, and Recovery (LOC) Analysis

QUANTITATIVE IMPACT
• Verification of implementation
• Additional flight data over the flight envelope will ensure more accurate ASE characterizations
• Analysis of novel distributed sensing and control schemes

NEW INSIGHTS
• Integration of aeroelastic with flight dynamics requires multirate integration with proper rigid-elastic-controls coupling and aeroelastic model interpolation schemes
• Aeroelastic effects becoming more essential for accurate flight dynamics modeling

STATUS QUO
• Integration of ASE dynamics of the F18-853 aircraft into the NASA Dryden simulation
• AAW models and flight data used for full-envelope flight dynamics simulation

PROGRAM GOAL
• ASE integration framework with the NASA Dryden F/A-18 simulator is established
• Proven process should simplify integration in support of the development of ASE models for other flight test programs
• Provides a basis for future flight research endeavors in distributed sensing and controls
Modular Architecture for Distributed Autonomous Aerospace Systems
Modular Architecture for Distributed Autonomous Aerospace Systems (Summary Slide)

Persistent, atmospheric aerial coverage for planetary exploration
- detailed science data gathering, e.g., planetary surface, atmospheric
- terrestrial/aerial/satellite network to support human habitation or entry/descent/landing of other vehicles, auto rendezvous/docking

Modular architecture for distributed, autonomous aerospace systems
- enables separate but dynamically integrated sub-systems, where faults are distributed and dynamically re-allocable, increases mission duration

  Applies to aeronautics (lightweight, disturbances, aerostructural) and space

Evolving systems as applied to self-assembling systems, robotic maneuvering
- designing control systems with strict passivity/dissipativity
- ensure reliability, coordination and mission adaptivity
- adaptive communication and control network topology

Multi-objective, multi-level control and estimation architectures
- decentralization with information-based sensing for comm&control
- consensus-coordination using multi-agent systems (behavioral)

Phase 1: Identify modular UAV design, control architecture, metrics evaluation

OCT Roadmap&Priorities:

Provides capabilities that would enable new projects/missions that are not currently feasible during the next 10-20 years

Impacts multiple missions in NASA space operations and science, earth science, and aeronautics

Influential across aerospace and non-aerospace communities

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