Physics-Based Stability and Control Derivative Measurement (PSCDM)

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Purpose

New developments in high-aspect ratio wings (structural efficiency) and quiet low-speed performance (aerodynamic efficiency) for next-generation aircraft require a change in measurement/control paradigm to robustly, effectively address the range of maneuver and nominal/off-nominal flight conditions. Conventional approaches using global air data and structural feedback will need to be augmented to improve gust load alleviation and circulation control to autonomously and intelligently sense the aerodynamic environment and efficiently adapt the aircraft structure and control surfaces to suit the current mission objectives. This project we develop a localized system that (1) separates aerodynamic forces and moments into a circulatory and non-circulatory component, and (2) estimates and controls each component independently at each span station.

Effectively, this system re-derives the conventional stability and control (S&C) derivatives, where the circulatory and non-circulatory components are focused on the aerodynamics and structural dynamics, respectively. This approach is enabled by the unique combination of (1) the ability to track in real-time surface flow topology, e.g., leading-edge stagnation point, flow separation, (2) the analytical relationship of the spatiotemporal surface flow topology to circulation, and (3) the ability to measure total inertial response. In Phase I we investigated the effectiveness of the new approach in separating/estimating circulatory and non-circulatory forces for S&C derivatives. Phase II will extend the results to a fixed (PTERA: Prototype – Technology Evaluation Research Aircraft) and flexible-wing (X-56A) vehicle implementing circulation-based robust aeroservoelastic control.

Background

Flow bifurcation point sensors are used to estimate - in real-time without the delay of structural response - circulatory components of aerodynamic forces and moments which could be used as direct aerodynamic force feedback for circulation control, and accelerometers to estimate the delayed total non-circulatory component of aerodynamic forces and moments. Sensors are integrated in a physics-based architecture that improves reliability, control effectiveness and robustness through a spatially distributed network. This research effort provides for the first time an in-flight separation and estimation of circulatory and non-circulatory components of aerodynamic forces and moments enabling fine-scale circulation and aeroservoelastic control.

The National Aeronautics R&D Plan describes concepts that could be separated into two parts: (1) monitoring technology: structurally integrated sensors, distributed sensing systems, physics-based transition prediction, and aircraft-level health-management; and (2) control technology: actively controlled wing structures, novel flow control techniques, and advanced flight controls for aircraft efficiency. The developed system will help satisfy the above needs with a physics-based embedded sensor architecture distributed across the wing span.

Effort provides a foundation for control of subsonic-to-supersonic aircraft, including UAVs and long-endurance platforms, using intelligent sensing with distributed control methodology. Demonstration of a precedent system has shown potential on an AFRL SensorCraft configuration in the NASA Langley Transonic Dynamics Tunnel. This work will provide the basis for transitioning the architecture to platforms such as

X-56A and other potential flight test platforms for circulation control with aeroelastic or novel flush aerodynamic sensing experiments.

Approach

The primary Phase I objective is to provide a technical basis for the PSCDM approach under operational flight conditions. Secondary objectives are to: (1) derive new stability and control derivatives based on the measured surface flow topology, circulatory and non-circulatory components of aerodynamic forces/moments, and control surface actuation for a representative flight vehicle, e.g., PTERA; and (2) validate computational models predicting the circulatory and non-circulatory forces using surface flow topology states. Ultimate ambition is aerostuctrural performance (lift / drag / moment / load) advancement with distributed sensor-based flight control.

To provide a foundation for Phase II we: (1) developed a new aerodynamic model separating circulatory and non-circulatory components, (2) computationally verified the analytical aerodynamic model, and (3) conducted open-loop flight tests in a flight vehicle instrumented with sensors to estimate circulatory and non-circulatory forces to validate the computational results.

Summary of Research

The Phase I effort was composed of two parts: (1) development of a 2D unsteady aerodynamic model using flow bifurcation points for determining circulatory and non-circulatory components of aerodynamic forces for general pitch & plunge maneuvers, and (2) open-loop flight test data collection on a scaled Boeing vehicle, PTERA, with multiple span stations instrumented with flow bifurcation point sensors. Both parts were completed successfully providing a foundation for the Phase II effort.

For a pitch-plunging wing, the following 2D unsteady potential flow model for lift was derived using perturbation theory as a sum of the non-circulatory and circulatory components:

$$L = L_{NC} + L_C = \pi\rho b^2\left(\ddot{h} + U\dot{\alpha} - ba\ddot{\alpha}\right) + 2\pi\rho U^2 b\left(\frac{\dot{\alpha}\, b}{U} - \frac{\delta}{2}\right)$$

where $\dot{\alpha}$ is the pitch rate and δ is the leading edge stagnation point (LESP) location:

$$\delta = \frac{\dot{\alpha} b}{U} - 2\left(\frac{\dot{h}}{U} + \alpha + \frac{\dot{\alpha} b}{U}\left(\frac{1}{2} - a\right)\right)C(k) = \frac{\dot{\alpha} b}{U} - \frac{2L_C}{2\pi b\rho U^2}$$

where L_C is the circulatory component of lift. The pitch /plunge rate terms come from the non-circulatory component of lift, and pitch rate and LESP terms correspond to the circulatory component of lift.

The LESP location incorporates the effective angle of attack from pitch and plunge, as the LESP location is itself a function of pitch angle and rate, plunge rate and circulation, so it could be used as a high observability internal parameter in a reduced order model (ROM). The above function, while valid for 2D unsteady inviscid flows, has the potential to work even in unsteady viscous flows, since the circulatory effects due to separated flows are implicit in the movement of LESP location (as described by L.C. Woods in *The Theory of Subsonic Plane Flows*).

The above unsteady aerodynamic model has been preliminarily verified using a 2D Euler computational simulation (see Figure 1). The LESP location was extracted from the meshed surface of the airfoil, which is challenging due to the minute changes in LESP location (less than 0.004/chord movement per degree pitch) near the leading edge with high radius of curvature. While there is a slight difference between the resulting estimated LESP-based and Euler-CFD-based lift due to the mesh resolution, the response is time-accurate and the accuracy will improve as we improve the leading-edge mesh resolution and extraction algorithm.

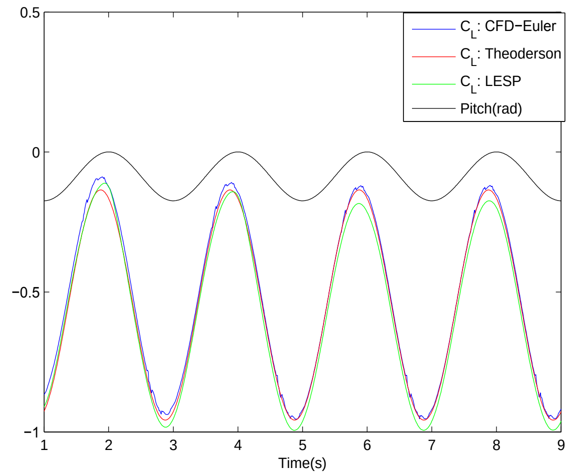

Figure 1: Verification of unsteady aerodynamic model with pitch oscillation

The highest risk element of this research effort was conducting the flight test. Four sensors were designed, fabricated and installed on four span stations on the Area-I (http://areai.aero/) PTERA-BL (baseline) vehicle (see Figures 2 and 3). Figure 3 depicts two sensors installed at the wing leading edge at two span stations. Tao Systems' Lead-edge Stagnation Point System (LSPS) was installed in the PTERA-BL fuselage and interfaced with the PTERA flight data system to record real-time data from sensors at the four span stations.

Figure 2. Area-I PTERA-BL on tarmac

Figure 3. Close-up of the sensors at two span stations on the right wing

Figure 4. Area-I PTERA during flight test

Figure 5. Area-I PTERA during flight test

Area-I (http://areai.aero/) carried out a series of system identification test flights on the PTERA-BL platform (see Figures 4-5). Area-I flew the PTERA baseline configuration six times: first two flights for system checkout, and the remaining four flights for aerodynamic parameter identification. The following are some of the relevant flight maneuvers that were completed:

- Full throttle pass
- Full flaps pass
- Longitudinal-Input Command: Pitch Up, Neutral (2x), Up-Down (2x), Neutral
- Longitudinal-Input Command: Pitch Down, Up, (6x)
- Lateral-Input Command: Yaw Left, Neutral, Right, Neutral (2x), Yaw Left, Right, Left, Neutral then Aileron Roll Right, Left, Right, Neutral
- Lateral-Input Command: Yaw Right, Neutral, Left, Neutral (3x) then, Left, Right (3x) then Aileron Roll Left, Right (3x)
- Stall with control surface noise leading up to Stall; Input Commands on rudder, ailerons, and elevator
- Post Stall, Pre Half-flap
- Half-flap Stall
- Landing

The maximum ground speed for the flight tests was 144knots, and maximum altitude was 1350ft. Tests included 0–2knot gust conditions. Some maneuvers were repeated in conditions of 10+knot gusts.

Stall maneuvers are the most interesting aspect of these tests since the surface flow topology is the most nonlinear with the onset of flow separation and consequent loss in lift. The aircraft was successfully stalled three times: (2) traditional, power-off stall, (2) with control surface noise, and (3) with half-flaps. The stall speed without control surface noise is about 45knots.

Figure 6 depicts the AoA and the shear stress for a pressure side shear stress sensor as a function of time for a stall maneuver. When the LESP approaches a shear stress sensor, the shear stress generally reduces, and since this particular sensor is farthest from the leading edge, it will continue to reduce as the LESP approaches with increasing AoA. As the AoA increases from 5 to around 23 degrees, we expect (1) the flow separation point (or line) to move towards the leading-edge of the wing, and, simultaneously, (2) the LESP to move downstream as circulation (or lift) is increasing.

We observe that as the AoA approaches 23 degrees, the shear stress drops consistently, and then precipitously as the AoA reaches near maximum. Just after stall, with the sudden drop in lift, the LESP and flow separation should move back towards the leading-edge. The comprehensive analysis of the flight tests, especially the stall behavior of the aircraft in terms of surface flow phenomena, will be completed in the Phase II effort.

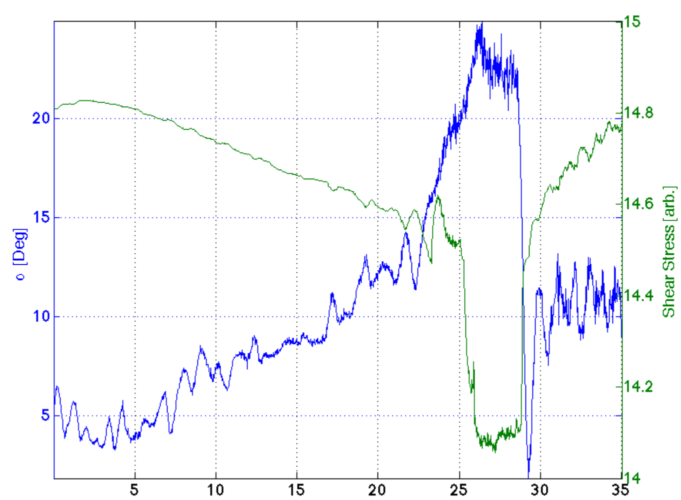

Figure 6. Area-I PTERA during stall maneuver

Accomplishments

The following were accomplished in the Phase I effort:

- Developed a physics-based, analytical unsteady aerodynamic model separating circulatory and non-circulatory components of lift using surface flow and inertial measurements;
- Computationally verified the analytical unsteady aerodynamic model for inviscid flows; and
- Conducted open-loop flight tests in a flight vehicle instrumented with surface flow sensors to estimate circulatory and non-circulatory forces to validate the computational results.
    - Tao Systems LSPS system (originally designed for and compatible with X-56A) and surface flow sensors integrated into PTERA aircraft fitting into the low volume and weight constraints
    - LSPS data interface compatible with both X-56A and PTERA
    - LSPS system ready to be used in a real-time control law

Next Steps

The next steps are to: (1) extend the unsteady aerodynamic model separating circulatory and non-circulatory components from two-dimensional (2D) to three-dimensional (3D) flows, (2) develop reduced-order computational models of the dynamic interactions and uncertainties in aerodynamics, structures, sensing and actuation, (3) validate the ROM in a set of comprehensive wind tunnel tests for a wing with structural, aerodynamic, and control surface nonlinearities undergoing pitch / plunge in the presence of gusts in predicting / suppressing limit cycle oscillations (LCOs), (4) validate the ROM with the Phase I open-loop flight tests of PTERA instrumented with spanwise flow sensors to estimate circulatory and non-circulatory forces / moments, and (5) develop an observer / controller for an available flight vehicle (X-56A, PTERA) for flight test demonstration of the technology.

Current TRL: 3

Applicable NASA Programs/Projects

[ARMD] Instrumentation and measurement technology test technique for aeronautics in all flight regimes; Distributed and autonomous concept for aviation and extra-terrestrial vehicles; Technology enabling new flight applications with aeroelastic sensor networks; Game-changing flight vehicle concept for performance enhancement.

[FAP] Reduce drag & weight; Increase performance & energy efficiency; Improve computational / experimental tools & processes with reduced uncertainty; Develop, test, and analyze advanced multidisciplinary concepts and technologies.

[FW, HS, AS] Expressed interest and support for this research in FY12-16 for SE; Supporting flight test on the X-56A and PTERA aircraft to investigate LSPS for subsonic distributed sensing towards distributed and circulation control.

[External] Texas A&M, Caltech, and University of Minnesota for testing support, distributed controls and aerostructures modeling research for controls. AFRL for HS applications (F18-FAST).

ARMD Advanced Air Vehicles Program (X-56A, X-54), Integrated Aviation Systems Program (GIII-ACTE), and Transformative Aeronautics Concepts Program (PTERA) all have current or proposed infusion applications of this technology.

Publications and Patent Applications

"Fly-by-Feel Sensing and Control: Aeroservoelasticity", Arun Mangalam and Marty Brenner, AIAA Atmospheric Flight Mechanics Conference, Jun16-20, 2014, in Atlanta, GA, and near future NASA TM and AIAA Journal papers.