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

Project WBS Number: 694478.02.93.02.12.05.24

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Purpose

Fly-by-feel (FBF) is a new paradigm for safely maximizing aircraft stability and performance across a wide range of conditions wherein the aircraft autonomously and intelligently senses the aerodynamic environment and efficiently adapts the aircraft structure and control surfaces to suit the current mission objectives. FBF complements an integrated feedback approach to flight control, structural mode and load attenuation, and flow control. Desired flight performance, gust load alleviation and aerostructural stability in the presence of complex aeroservoelastic (ASE) uncertainties are met by utilizing aerodynamic observables in a robust control law framework.

These observables include leading-edge stagnation point (LESP) and critical flow features (separation, reattachment, reversal, shock, transition) measurable at the surface. In the Phase I effort we began investigating the effectiveness of the FBF approach in suppressing aeroelastic instabilities with a nonlinear ASE wind tunnel test model. Phase II work extended the wind tunnel facility to study the effects of gust loads on the aeroservoelastic wing similar to the X-56A.

Background

The primary objective is to provide a sound technical basis for determining the extent of performance improvement of the FBF approach under operational flight conditions in comparison to conventional flight control. Phase II objectives are to: (1) expand upon determining the relationship between aerodynamic observables and aeroelastic performance, loads/moments, and control surface actuation with a nonlinear unconstrained pitch-and-plunge apparatus (PAPA) for a representative wing with regard to aeroelastic instabilities; (2) validate computational models predicting the aerodynamic coefficients (CL, CM & CD) based on pitch, plunge, and actuator state and aerodynamic observables; (3) determine the accuracy and robustness of system identification techniques in capturing the nonlinear system parameters; and, (4) continue characterizing the performance of conventional and robust control laws using a variety of aerostructural sensors for feedback including aerodynamic observables in unsteady flows.

Approach

Flow bifurcation point sensors are being used as aerodynamic observables to estimate, in real-time without the delay of structural response, aerodynamic coefficients which will be used as direct aerodynamic force feedback for flight control resulting in minimization of aeroelastic uncertainties. Sensors are integrated in a physics-based architecture that improves reliability, control effectiveness and robustness through a spatially distributed network.

Summary of Research

The results can be separated into several parts: (1) design / construction of the pitch / plunge drive system with gust generator, (2) analytical aeroservoelastic (ASE) modeling, and (3) preliminary wind tunnel experimental results.

The experimental setup includes the Nonlinear Aeroelastic Test Apparatus (NATA II) which supports the free wing and the Pitch Plunge Drive System (PPDS) which is mounted upstream of NATA II and supports the gust wing. The various system parameters including inertial, damping and stiffness terms are identified using system identification maneuvers using both PPDS and NATA II.

We developed the apparatus for experiments in Texas A&M University's 3' x 4' low subsonic wind tunnel to investigate aeroelastic response and control of an elastically mounted rigid wing in a gust field generated by a second pitching and plunging wing mounted upstream of the test wing. System identification techniques used in prior experiments on forced oscillations of rigid wing were employed to determine key system parameters. Using analytical methods, the system model was generated and response predicted and compared with experimental values.

Figure 1 shows the design including the upstream gust generator and the free vibration system. The gust generator has capability to pitch and plunge a 'gust' wing spanning the width of the test section (4') and generate gust for the free vibration wing as the moving wing and its wake induces a gust field upstream of the free wing. The free vibration wing has 2 degrees of freedom with capability to allow for non-linear stiffness. The capabilities of the system include direct measurement of position, acceleration, forces and moments. The characterization of gust is be carried out by multi-hole probes and hot wire anemometry. For control, the free wing is fitted with a full span control surface.

The gust generator is a pitch plunge drive system (PPDS) which can oscillate a wing in pitch and plunge motion up to 5Hz in each mode exclusive of each other. The gust generator has the capability of mounting and driving the gust wing from both ends, to avoid excitation of first bending mode. The pitch motion is carried out within the pitch module which houses all the components responsible for pitch motion like servo motor, gearbox, four bar mechanism etc. The two pitch modules are mounted on steel rails through linear bearings. The pitch modules can be locked in places with brakes for pitch only motion. The plunge motion is carried out by a single plunge motor at the bottom of the test section. The drive from the motor located at the bottom of the test section is transferred to a main shaft in the middle of the test section and then transferred to two plunge crank wheel (one on each side) through timing belts and then converted to sliding motion using the plunge connecting rod via a slider crank mechanism.

As a result of tight mechanical synching, both pitch modules plunge by the same amount at any given instant of time. As the gust wing is pitched and/or plunged, the downwash from the wing and the wake vortices induce a velocity field depending on the time dependent motion of the gust wing. The resulting velocity field serves as gust field for the free wing which forms a part of NATA II. Table 1 provides the motion details of PPDS. The detailed description of PPDS can be found in the references.

Table 1. PPDS motion capabilities and features

Capability/Parameter	Pitch Motion	Plunge Motion	Remarks
Control Type	Closed Loop	Open Loop	Closed loop in progress
Port/ Starboard syncing	Electronic	Mechanical	Plunge mode uses Timing belts
Oscillation Frequency	0 - 5Hz	0 - 5Hz	Adjustable in software
Oscillation Amplitude	2 - 22 deg	0.5 – 3 in	Adjustable in hardware
Frequency Ramp	Yes	Yes	Adjustable in software
Mean Position	0 - 360 deg	±5 in	Adjustable in hardware
Axis	Spanwise, Adjustable	Vertical, Fixed	Pitch axis adjustable in hardware

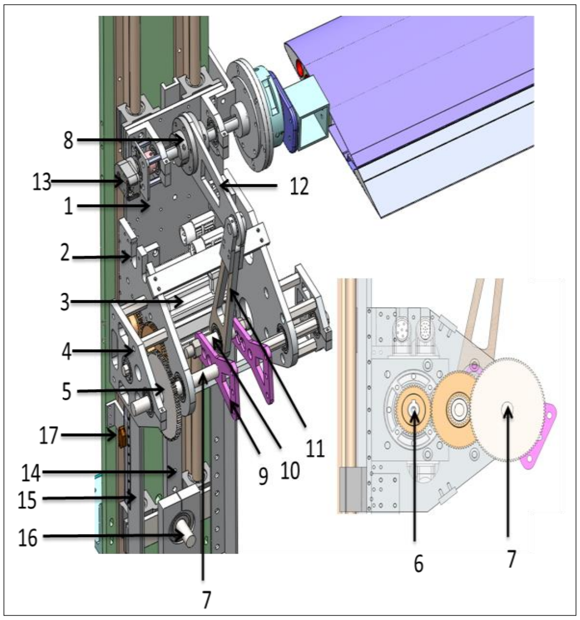

Figure 1. Port side pitch module

1. **Back Plate**
2. **Wall**
3. **Pitch Actuator**
4. **Mini Wall**
5. **Gearbox**
6. **Motor Shaft**
7. **Drive Shaft**
8. **Wing Shaft**
9. **Crank**
10. **Drive Pin**
11. **Connecting Rod**
12. **Wing Bar**
13. **Spine**
14. **Extension Channel**
15. **Plunge Encoder**

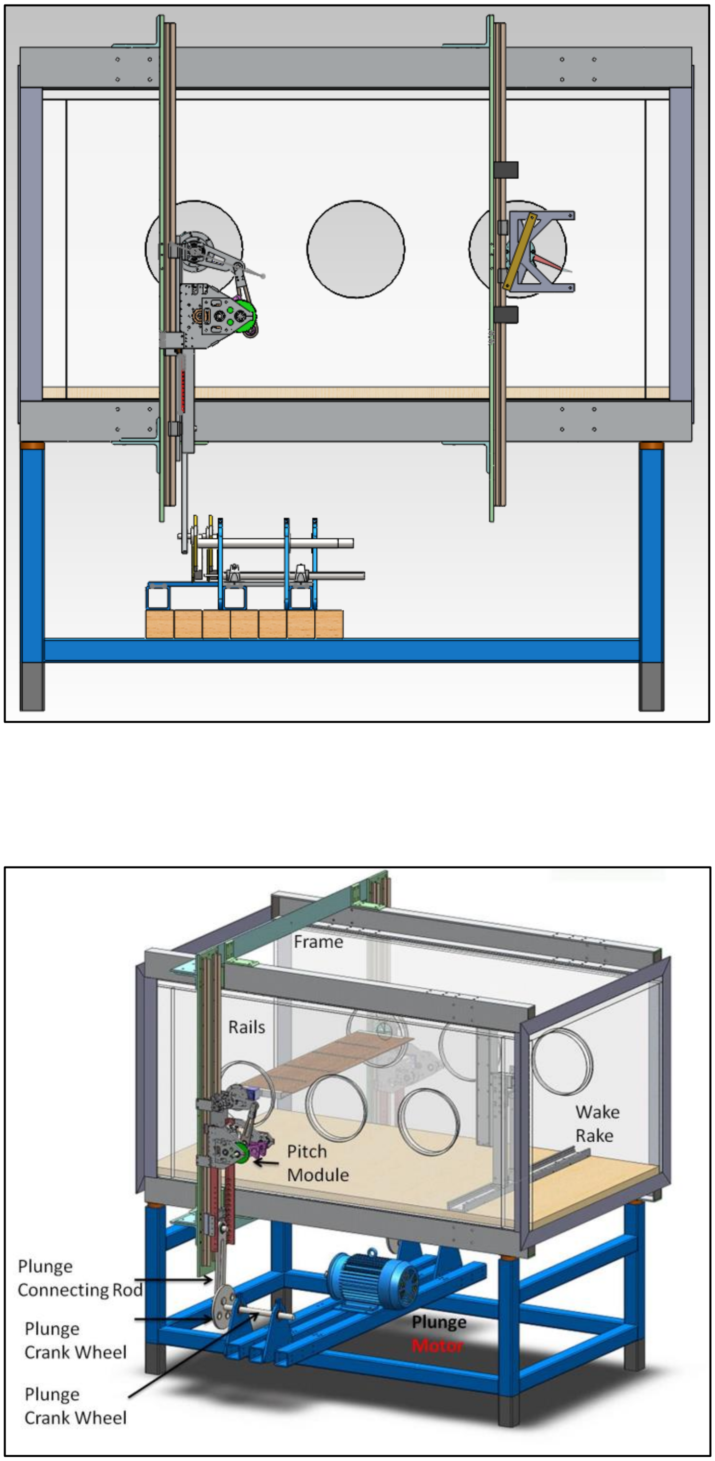

Figure 2: Two views (side and angled) of the free pitch and plunge system and the upstream custom gust generator

NATA II is the successor of NATA which has been the platform for numerous studies on aeroelastic response and control experiments at Texas A&M University in the past. NATA II improves on NATA in the following areas:

1. Lower damping and plunge and pitch bearings
2. Supports a 4 feet wing as compared to 2 feet wing
3. Real time measurement of aerodynamic loads
4. A highly responsive trailing edge flap for control
5. Modular design with adjustable parameters

Figure 3: Views of NATA II and free wing

Figure 4: NATA II and PPDS (gust generator), flow direction from left to right

Figures 1-4 show various views of NATA II and the free wing. Figure 4 shows a view of the test section showing NATA II the PPDS with gust wing. Nonlinearity in pitch stiffness is achieved by a cam and timing belt system. The two ends of the timing belt are connected to two linear extension springs. The following quantities are measured directly:

1. Pitch angle
2. Plunge location
3. Pitch acceleration
4. Lift, Moment and other loads
5. Plunge acceleration
6. Centrifugal acceleration
7. Flap angle
8. Gust wing pitch angle
9. Gust wing Plunge location

The motion limits of NATA II system are:

	Amplitude
Pitch	12 deg (0.2 rad)
Plunge	1.5 inches (0.0381m)
Flap	20 deg (0.35 rad)

Table 2: Motion limits of NATA II

In order to fully characterize the system, the system parameters are identified via controlled maneuvers in wind-off and wind-on conditions. The following quantities were determined from system identification maneuvers using the directly measured quantities:

1. Wing and NATA II inertial parameters
2. Pitch and Plunge Stiffness
3. Pitch and Plunge damping
4. Aerodynamic parameters

Estimates of parameters are tabulated below:

Quantity	**Value**
Wing Mass	2.56 kg
Wing center of gravity location	15% of chord aft of elastic axis (c/4)
Wing Moment of Inertia	0.0178 kgm^2
Pitch Frequency	3.59Hz
Plunge Frequency	3.09Hz
Limit Cycle Frequency	3.385Hz
Pitch Mode damping ratio	0.0276
Plunge Mode damping ratio	0.063
Pitch Stiffness coefficients	577.45, 11.4142,21.27, -0.0690
Plunge Stiffness	3628.1 N/m
Lift Curve Slope	4.1 /rad
CL per unit flap angle	2.04 /rad

Table 3: System parameters determined by system identification maneuvers

The ‘gust’ wing is supported on both sides and is driven by two identical pitch modules. The pitch motion is carried out within the pitch module which houses all the components responsible for pitch motion like servo motor, gearbox, four-bar mechanism etc. The two pitch modules are mounted on steel rails through linear bearings. The pitch modules can be locked in place with brakes for pitch only motion. The plunge motion is carried out by a single plunge motor at the bottom of the test section. The drive from the motor located at the bottom of the test section is transferred to a main shaft in the middle of the test section and then transferred to two plunge crank wheels (one on each side) through timing belts, then converted to sliding motion using the plunge connecting rod via a slider-crank mechanism. As a result of tight mechanical synching, both pitch modules plunge by the same amount at any given instant of time.

As the gust wing is pitched and/or plunged, the downwash from the wing and the wake vortices induce a velocity field depending on the time dependent motion of the gust wing. The resulting velocity field serves as gust field for the free wing which forms a part of NATA II.

Figure 5 shows the complete schematic of the free vibration wing in the wake of the gust generator. The free vibration wing is placed about 3-4ft behind the gust wing.

The wing assembly consists of the wing, a powered flap, two load balances (one on each side) and two struts (one on each side). The assembly passes through two bearings on each side and is free to pitch within the free pitch module. The free pitch modules themselves are mounted on vertical rails and hence providing a free plunge. Figure 6 shows the pitch and plunge springs that provide respective constraints.

This pitch motion is constrained by pitch springs (red) mounted at the end of struts and the free pitch module. As the wing pitches, one spring compresses while other extends. The stiffness and non-linearity of the pitch springs can be controlled by mounting the springs in various ways. The plunge motion is constrained by plunge springs (black). These springs are connected to the free pitch module and between two stops which can be moved up or down as needed. The system can also be made free to plunge if the plunge stops are removed.

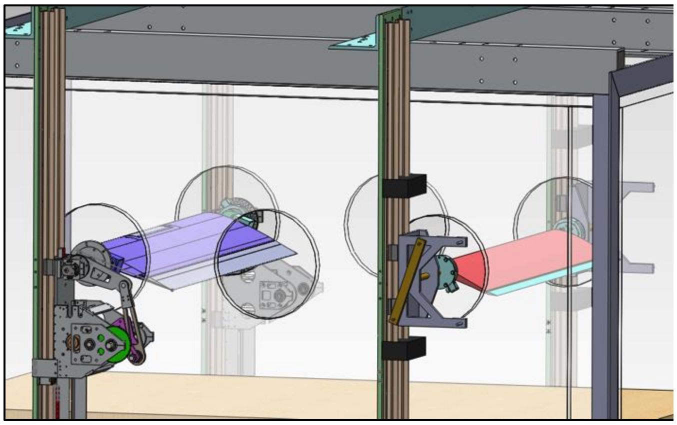

Figure 5: Close up of the two systems

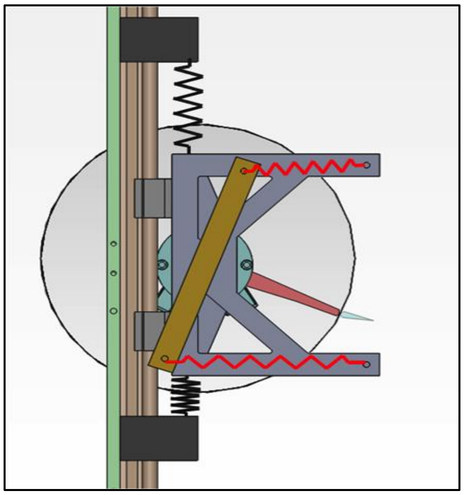

Figure 6: Pitch and Plunge springs

Figure 7 shows measured time response during a limit cycle oscillation without gust at freestream wind speed of 15 m/s. The LCO is initiated with a gentle manual disturbance in pitch. It is observed that the pitch response damps quickly but then gradually builds up along with plunge response and attains its maximum amplitude in about 6 seconds. Thereafter, the responses remain at constant amplitude. The observed LCO frequency is observed to be 3.385Hz as demonstrated in the Figure 8 frequency response. As expected, the frequency of pitch and plunge mode are exactly the same.

Figure 9 shows the system response as it is excited by a ramped sinusoidal oscillation of the gust wing. The maximum frequency of the gust wing was chosen to be 3.3Hz close to measured LCO frequency of 3.385Hz. As can be seen, the gust energizes the system but as soon as the gust dies away, the response quickly returns to LCO values. After about 7 seconds, the ramping sinusoidal gust hits the wing again. The system response reduces at first but as gust frequency is in vicinity of LCO frequency, the system response is elevated. After the gust dies away, the system returns to LCO values.

This interaction of gust with a wing in LCO is under further exploration. Control strategies are also being developed with the wing out of LCO and reduced gust response.

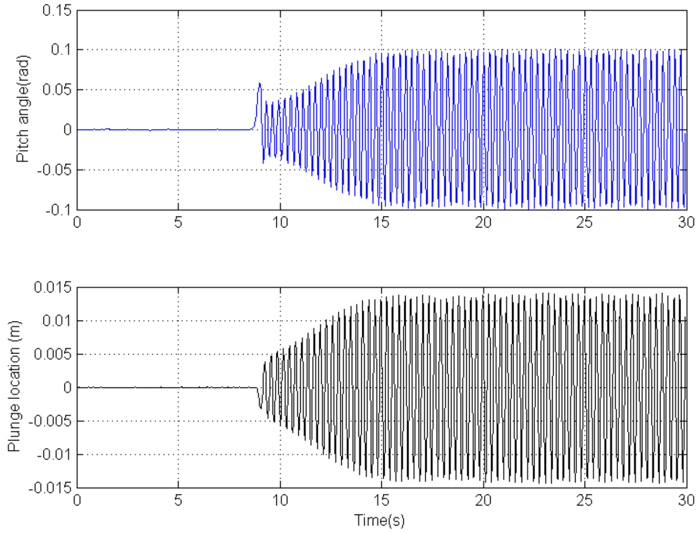

Figure 7: LCO as initiated by a manual trigger

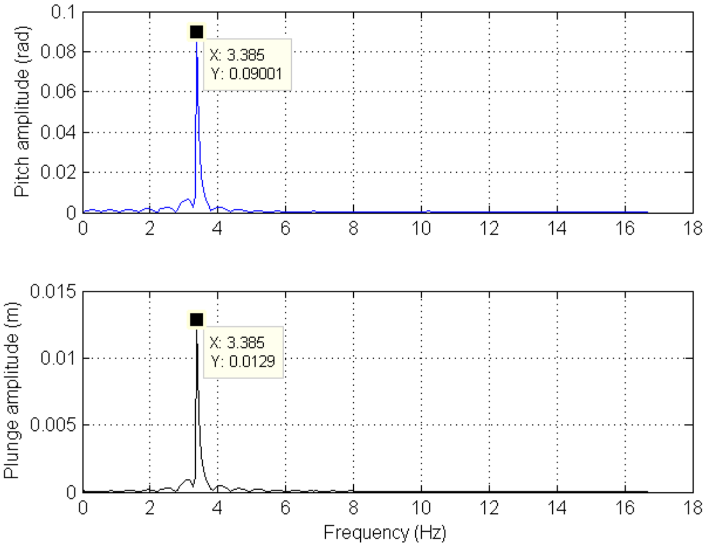

Figure 8: LCO response in pitch and plunge

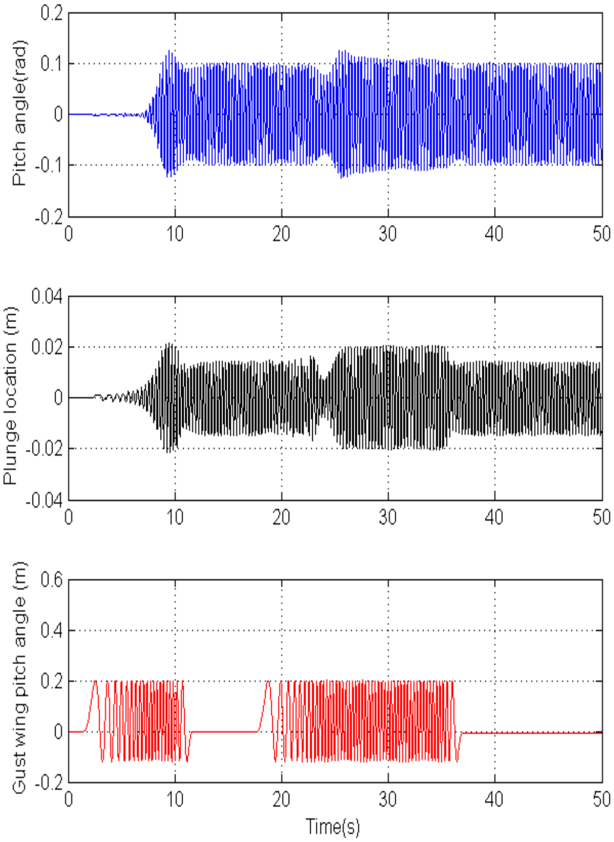

Figure 9: Interaction of free wing at LCO speeds and sinusoidal gusts

The increasing interest in the development of high-performance flight vehicles featuring flexible wings and associated rigid-body dynamic interactions, has been a primary motivation for research in aeroservoelastic (ASE) stability and control. The difficulty in the design and control synthesis process, lies in the complicated interactions between the structural dynamics and aerodynamics.

Several phenomena result from these interactions: Limit Cycle Oscillations (LCOs), Body Freedom Flutter(BFF), Buffet, Gust response, etc. The approximation of these complex, and often nonlinear, systems has spurred recent interest in the development of reduced-order models, in an effort to make the problem practically tractable. However, the validity of linear reduced-order models is questionable outside the operating space from which they were derived.

From the control systems perspective, the principal source of the difficulty lies in the limited availability of sensors. Typically, the aerodynamics is derived from sensors measuring the structural response. With the exception of very low reduced frequencies, the aerodynamic model will need to include certain internal flow states to account for the wing motion history. The model quickly becomes more complex once higher reduced frequencies, large angles of attack and finite-span induction effects are considered. Coupled with a non-linear structural model for the wing, control synthesis using conventional techniques becomes a formidable task. In addition, delays incur as a result of estimating aerodynamic states from the structural response, further deteriorating flutter suppression performance.

However, with the availability of new sensing technologies capable of measuring the leading-edge stagnation point (LESP), possibilities exist to measure unsteady aerodynamic loads in real-time. For steady-flows, it is well-known that the angle-of-attack, and hence lift and moment, are highly-correlated with the LESP. Herein, using two-dimensional potential flow unsteady aerodynamics, we show a relationship that exists between lift and the LESP displacement for unsteady flows. Several simplifying, possibly restrictive assumptions are enforced, particularly small disturbances/airfoil displacements. However, the model provides several new insights, in particular, confirming intuition that the LESP does contain the history of motion. The model also provides a structure for experimental identification. Enforcing first-order approximations, a simple linear state-less model is obtained.

A necessary requirement for ASE controllers is the active suppression of LCO/Flutter, apart from other objectives such as Gust Load Alleviation (GLA). We explore a new approach towards control synthesis for LCO suppression and GLA utilizing the energy perspective that greatly simplifies the analysis. A proof-of-concept LCO suppression while attenuating gusts for a two dimensional wing section is experimentally demonstrated. A proposed approach to extend the concept to a finite-span wing as a distributed sensing and control problem is briefly described. The distributed energy-based control using LESP and rate sensors can be shown to be more efficient and robust than conventional large-order state-space techniques.

Here we outline the major steps to derive a relation between the LESP displacement and unsteady aerodynamic loads. For a pitching/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.

We immediately observe for pure plunge motions the aerodynamic loads track the LESP signals with negligible phase. For pure pitch motions, however, some phase-offset may be expected. Pitch rate can be directly measured from an accelerometer measuring the centrifugal component or, equivalently, a gyroscope.

Previous approaches to the problem of LCO/flutter LCO suppression have primarily involved model based controllers such as LQR, adaptive feedback linearization, LPV control, etc. Some success has been achieved with these approaches. However, even for simple configurations such as the nonlinear pitch and plunge apparatus, the analysis required is quite involved. In addition, not all systems are feedback linearizable. The extension of such approaches to more complicated higher dimensional structures such as flexible wings and/or to nonlinearities which are not easily handled analytically is likely to be difficult.

We propose an alternative framework to synthesize controllers using work-energy principles rather than conventional state-space techniques. Viewed from this perspective, the control design problem significantly simplifies. Only the aerodynamics is of interest in this case. Except for the purpose of predicting the LCO frequency, the structural dynamics and associated nonlinearities are not necessary for the analysis. Stability is guaranteed in this case, if the work done by the aerodynamic forces is dissipative. From this definition, we recognize flutter as that condition where the positive work done by the aerodynamic loads is exactly dissipated by the structural damping forces for every cycle of oscillation.

By feeding back the LESP signal, a suitable compensator can be designed for optimum tracking performance. We note that, as a consequence of feedback, the controller also possesses natural disturbance rejection properties. In addition, disturbances are also rejected, since negative work is done while the LESP tracks the reference signal. Thus, the controller, in addition to LCO suppression also serves to alleviate gust induced loads.

The controller based on the LESP output was demonstrated experimentally. The controller is implemented on the recently constructed Nonlinear Aeroelastic Test Apparatus (NATA II).

The NATA II is also equipped with an upstream gust generator. The gust generator is essentially a pitch and plunge drive system. A unique feature of this setup is the availability of load sensors (ATI Delta 6DOF), that are capable of measuring unsteady aerodynamic loads. The load sensors measure both aerodynamic and structural forces. The unsteady aerodynamic load data can be used for studies concerning the LESP's relation to loads and other relevant signals.

To use the control law, we require plunge rate. This is estimated from the plunge accelerometer, using a point-by-point trapezoidal integration scheme. A low-pass windowed mean filter is used to estimate the drift in the integrated signal, which is subsequently subtracted at each time-step. MATLAB was used for data-acquisition and control using a software-timed loop structure.

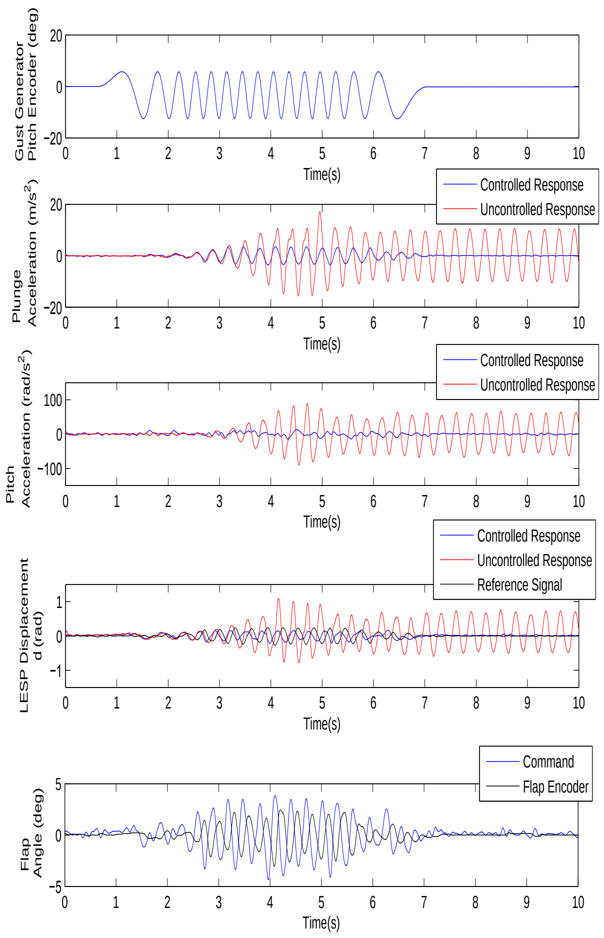

Figure 10: Interaction of free wing at LCO speeds and sinusoidal gusts

Communication with the servo was established using the SSC-32 servo controller via a serial port. The LESP displacement was estimated using the unsteady aerodynamic model. Pitch rate was measured directly from an accelerometer measuring the centrifugal component. Of particular significance, in using LESP feedback, the two-mode pitch-plunge system is effectively reduced to a single-input single-output system for which familiar control synthesis techniques for the compensator can be readily applied.

Figure 10 shows the controller performing the dual role of suppressing LCOs and alleviating gust induced responses. The gust generator is first started, inducing loads and responses in the free structure (NATA II) downstream. After about 5 seconds, the gust generator is turned off, leaving NATA II in a state of LCO. This experiment is then repeated with the controller activated. The significant reduction in gust responses using the controller is clearly visible.

Better performance can be expected for optimal compensator designs with a suitable trade-off between tracking and disturbance rejection. We note, that the LESP (or loads) responds ahead of the acceleration signals. This result is of significance for active flutter suppression performance, i.e., LESP based feedback can be more effective in suppressing flutter than structural response based feedback.

An important advantage of the passivity-based control approach, due to its model-free approach, is in its application towards distributed control. If the wing were to be discretized into sections, with each section embedded with sensors (LESP, rate sensors, accelerometers, etc) and actuators, control laws can be developed using the passivity argument irrespective of the nonlinearities/complicated modes the wing structure might possess.

Accomplishments

The following were accomplished in the Phase II effort:

- Design / construction of the pitch / plunge drive system with gust generator
- Analytical unsteady aeroservoelastic modeling for LCO suppression and gust load alleviation
- Preliminary wind tunnel experimental results for suppressing LCOs and gust load alleviation using an ASE wing

Next Steps

Control of extremely lightweight, long endurance aircraft poses a challenging aeroservoelastic (ASE) problem due to significantly increased flexibility, and aerodynamic, structural, and actuator nonlinearities.

To obtain the benefits of increased aerostructural efficiency, the controller needs to trim at a specified optimal shape while minimizing structural fatigue from gust disturbances. Next steps are to therefore develop a distributed, passivity-based, ASE controller using sectional aerodynamic and structural output-only feedback. This scalable, decentralized approach has the potential to minimize the impact of aerodynamic and structural uncertainties, and control surface free-play and saturation, while guaranteeing global asymptotic stability.

Current TRL: 4

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 F-18 FAST aircraft to investigate subsonic-to-supersonic shock formation and shock-boundary layer interaction besides LESP for subsonic distributed sensing for distributed control.

[ASP] Loss-of-control prevention / mitigation / recovery in hazardous flight conditions.

[NASA OCT-CIF] NASAs Office of Chief Technologist Center Innovation Fund has also expressed interest in this research as an ARMD-external partner and contributed substantially to the effort with supplemental funding.

[External] LMCO for flight test applications and follow on R&D for X-56A; AFRL procurement funding for R&D under the RASSCAL program; Texas A&M, Caltech, and University of Minnesota for testing support, distributed controls and aerostructures modeling research for controls.

ARMD Advanced Air Vehicles Program (X-56A, F18-FAST), Integrated Aviation Systems Program (GIII-ACTE), and Transformative Aeronautics Concepts Program all have current or proposed infusion applications of this technology.

Publications and Patent Applications

AIAA Atmospheric Flight Mechanics Conference, Aug13-16 2012, Invited Oral Presentation: "Development and Performance of Fly-by-Feel (FBF) Control".

Invited Presentation: 8 Feb. 2013: Invited Dept Seminar meetings and presentation at AME Dept, U of Minnesota, discussing “Fly-by-Feel (FBF) Aeroservoelastic Sensor-based Control, X-56A, and ARMD-FW”.

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

“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.

Awards & Honors: Seedling Research

N/A