Some Issues Related to Integrating Active Flow Control with Flight Control

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Motivation

- Time varying control of $C_L$ is necessary for integrating AFC and Flight Control
  - Gust load alleviation
  - Energy extraction maneuvers
- Lift response to actuation is usually only in the positive direction, so how can $C_L$ be decreased?
- Quasi-steady models of aerodynamic & actuator response quickly become inaccurate ($k>0.1$) in unsteady flow.
- Lift response to actuation has significant time delays that must be accounted for in the controller. How does this affect controller bandwidth?
Unsteady flow wind tunnel experiments

• Unsteady wind tunnel used to obtain
  – Models of lift and actuator dynamics
  – Demonstrate gust suppression experiment

Semicircular Wing Model
Reₖ = 68,000
Pulsed-blowing actuation along leading edge

L(t)

U'

U₀

α is fixed

Lift vs. time, concept of experiment

Click to play animation

filename: 04fixed_alpha_shutter_view.AVI
Open-loop LEV control – steady state conditions

Continuous pulsed-blowing actuation concentrates vorticity at leading edge.

\[ F^+ = \frac{f_c}{U} = 1.1 \]

\[ C_\mu = .0074 \]

Steady lift enhancement with open-loop control
Gust suppression: quasi-static approach

- Internal micro valves have no proportional control (on/off)
- Need to vary lift (+ other forces/moments) via actuation
- Duty-cycle approach
  - Pulsation frequency: 50 Hz (0.02 s)
  - Actuation period: 0.3 seconds was chosen
- Feed forward compensator
  $$U = 5.25 + 0.25 \cos(\omega t) \text{ m/s}$$
  $$L' = \frac{\rho S}{2} \left[ C_L' (U_o^2 + 2U_o U' + U'^2) + C_{L0}(2U_o U' + U'^2) \right]$$

$$C_L' = \frac{-2C_{L0}U'}{U_o + 2U'}$$

Zero lift fluct.

Re=68,000

Limit: 0.2 Hz (not fast enough)
Use ‘dynamic models’ to obtain faster response

- Principal limitation is the phase lag (time delay) associated with change of lift force relative to
  - Actuator input
  - Unsteady freestream
- Amplitude/phase empirically determined from measured lift response as a function of freestream/actuation modulation frequencies

\[ \tau^+ = \frac{t_d}{t_{conv}} = 5.8 \pm 0.5 \]

\[ k = \pi \frac{f_c}{U} \]
Feed forward control increases time response 5X

Suppressing & enhancing 1.0 Hz oscillation

\[ a' = -G_{act}^{-1}G_{aero} \cdot U' \]
Further increase in bandwidth by considering actuator transient- pushing for 5 Hz

Lift response to single pulse

\[ w(k) = C \sum_{j} K(j)u(k - j) \]

- \( u = \) input signal
- \( K = \) kernel (single-pulse response)
- \( C = \) calibration
- \( w = \) output signal

Note: wiggles are sting vibrations

Lift response curves similar to results of Woo, et al. (2008) for 2D airfoil with pulse-combustion actuators
Lift response to 3, 5, & 10 pulses

- Actuator input at fixed pressure
- Pulse duration .017s on/0.017s off
- Convective time $c/U = 0.04s$

3-pulse input to actuator

Graph showing the lift response with different pulse inputs and convective time.
Quasi-linear behavior of lift response to actuation

**INPUT** = sequence of 0.017s pulses, 50% dtc used to create square wave pattern as input signal

**OUTPUT** = convolution between kernel and input

0.4 Hz

No forcing $C_L$

1.4 Hz

Shift in mean $C_L$

5 Hz
Black-box model agrees with pulse-response

- System Identification of a ‘black-box’ model (6\textsuperscript{th} order state space) of the separated flow
  - Impulse response of black-box model matches single pulse response in experiment
  - Phase variation with frequency matches experimental measurements
Summary

• Time varying control of $C_L$ is necessary for integrating AFC and Flight Control
  - Biasing allows for +/- changes in lift

• Time delays associated with actuation are long ($\sim 5.8 \text{ c/U}$) and must be included in controllers

• Convolution of input signal with single pulse kernel gives reasonable prediction of lift response