Some Issues Related to Integrating Active Flow Control with Flight Control

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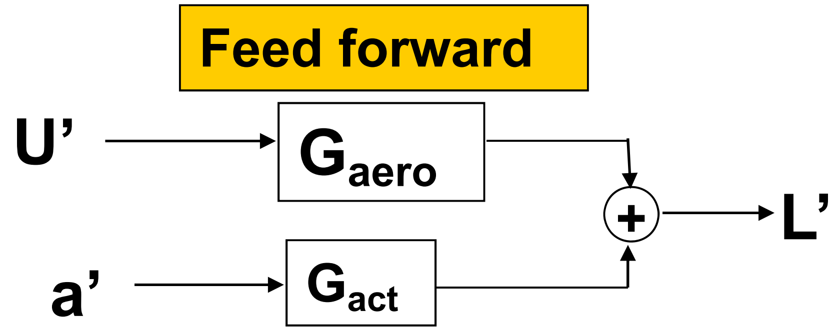
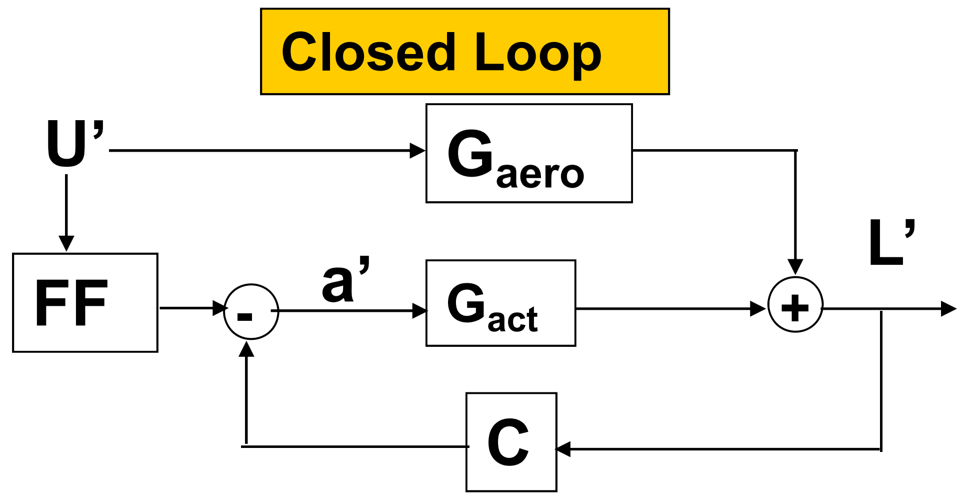
Motivation

- 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?

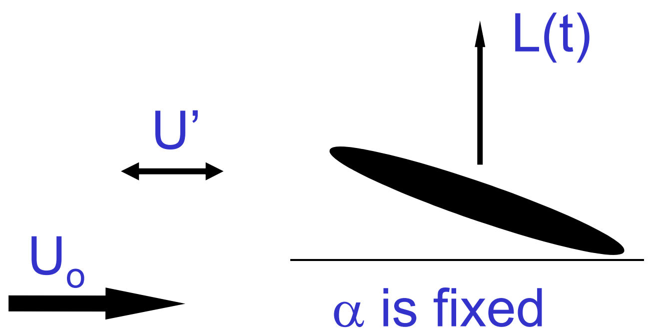


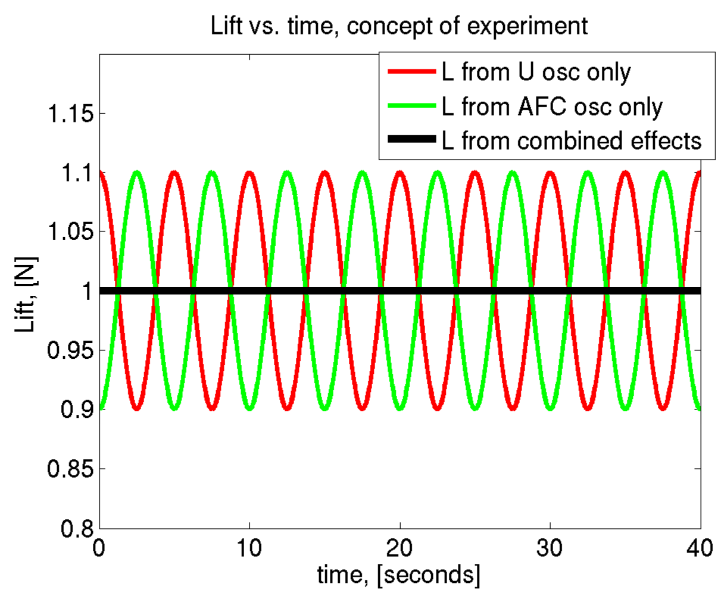
$$a' = -G_{act}^{-1} G_{aero} U'$$



Unsteady flow wind tunnel experiments

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





Semicircular Wing Model

Re_c = 68,000

Pulsed-blowing actuation along leading edge

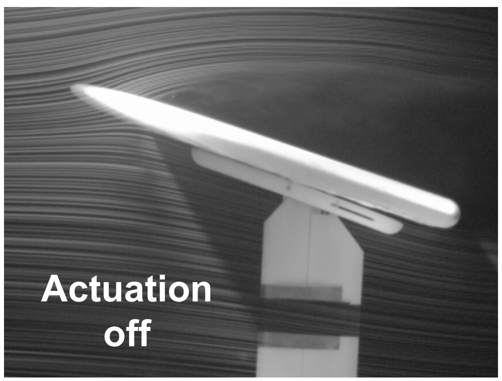
Click to play animation

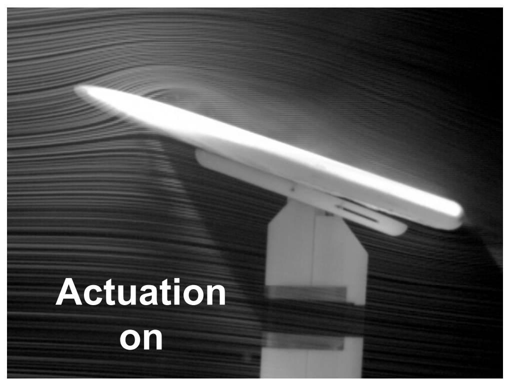
filename: 04fixed_alpha_shutter_view.AVI

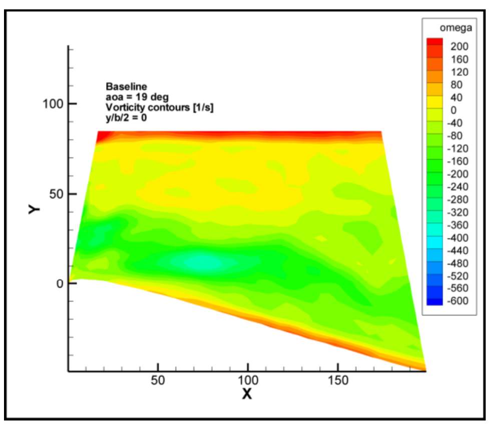
Open-loop LEV control – steady state conditions

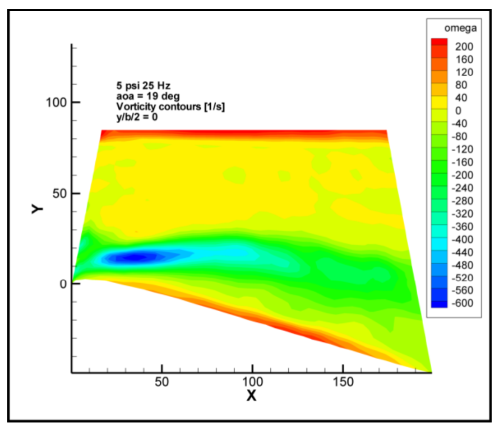
Continuous pulsed-blowing actuation concentrates vorticity at leading edge.

$F^{+} = fc/U = 1.1$
$C_{\mu} = .0074$

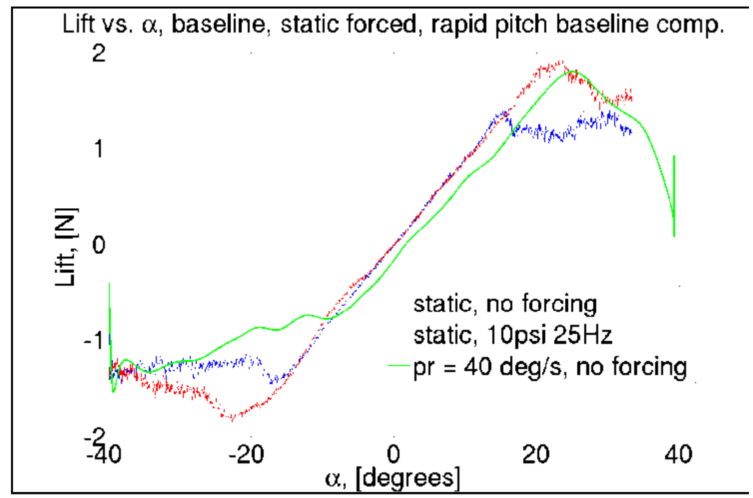








Steady lift enhancement with open-loop control



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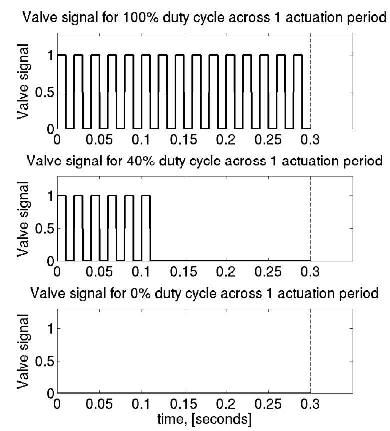
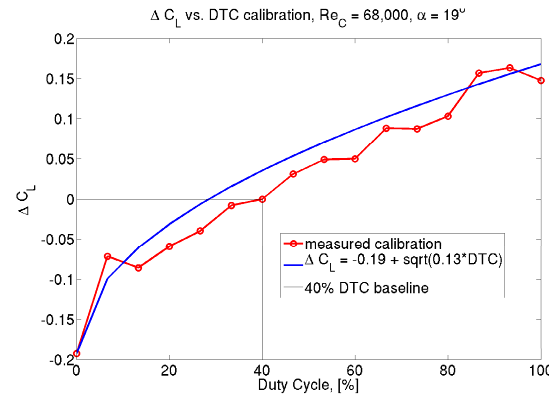
Gust suppression: quasi-static approach

- 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



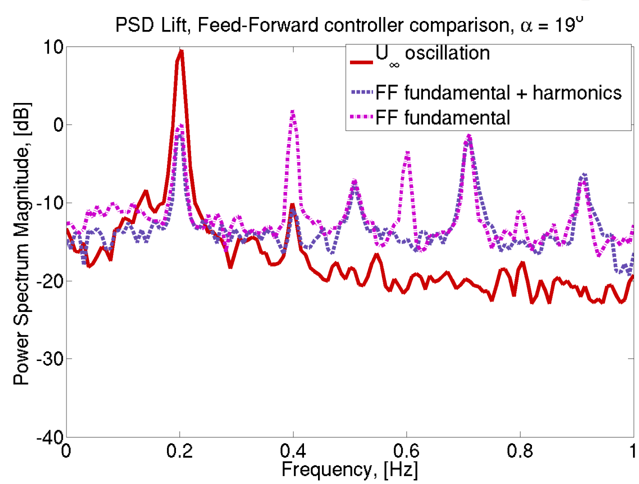


$$U = 5.25 + 0.25\cos(\omega t) \quad \text{m/s}$$

$$L' = \frac{\rho S}{2}\left[C_L'(U_o^2 + 2U_oU' + U'^2) + C_{Lo}(2U_oU' + U'^2)\right]$$

Zero lift fluct. →

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



Limit: 0.2 Hz (not fast enough)

Re=68,000

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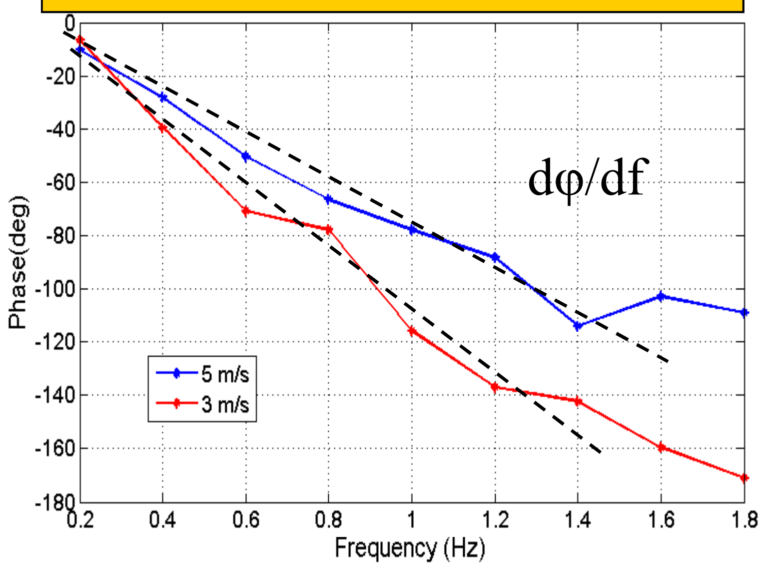
Use ‘dynamic models’ to obtain faster response

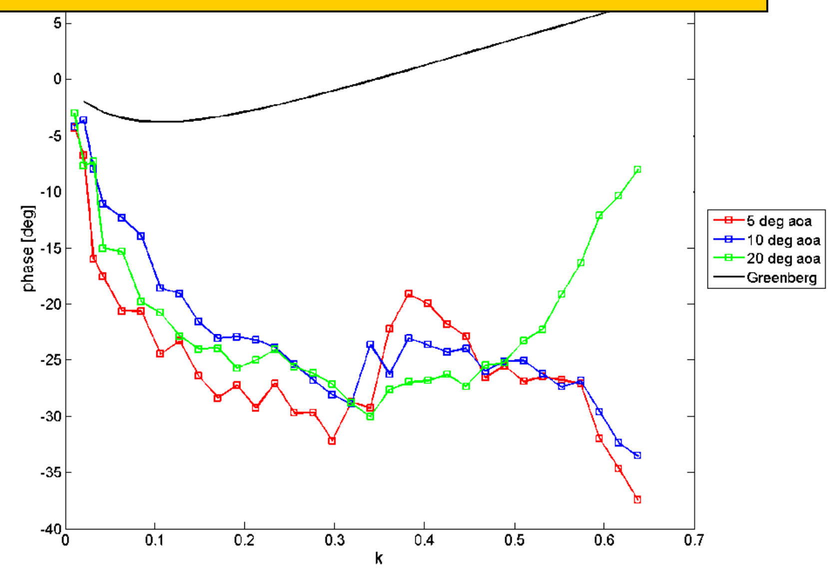
- Principal limitation is the phase lag (time delay) associated with change of lift force relative to
  - Actuator input
  - Unsteady freestream
- Amplitude/phase empirically determined from measured lift response as a function of freestream/actuation modulation frequencies

Lift-phase response to actuator



$\tau^+ = t_d/t_{conv} = 5.8 \pm 0.5$

Lift-phase lag due to aerodynamics



$k = \pi fc/U$

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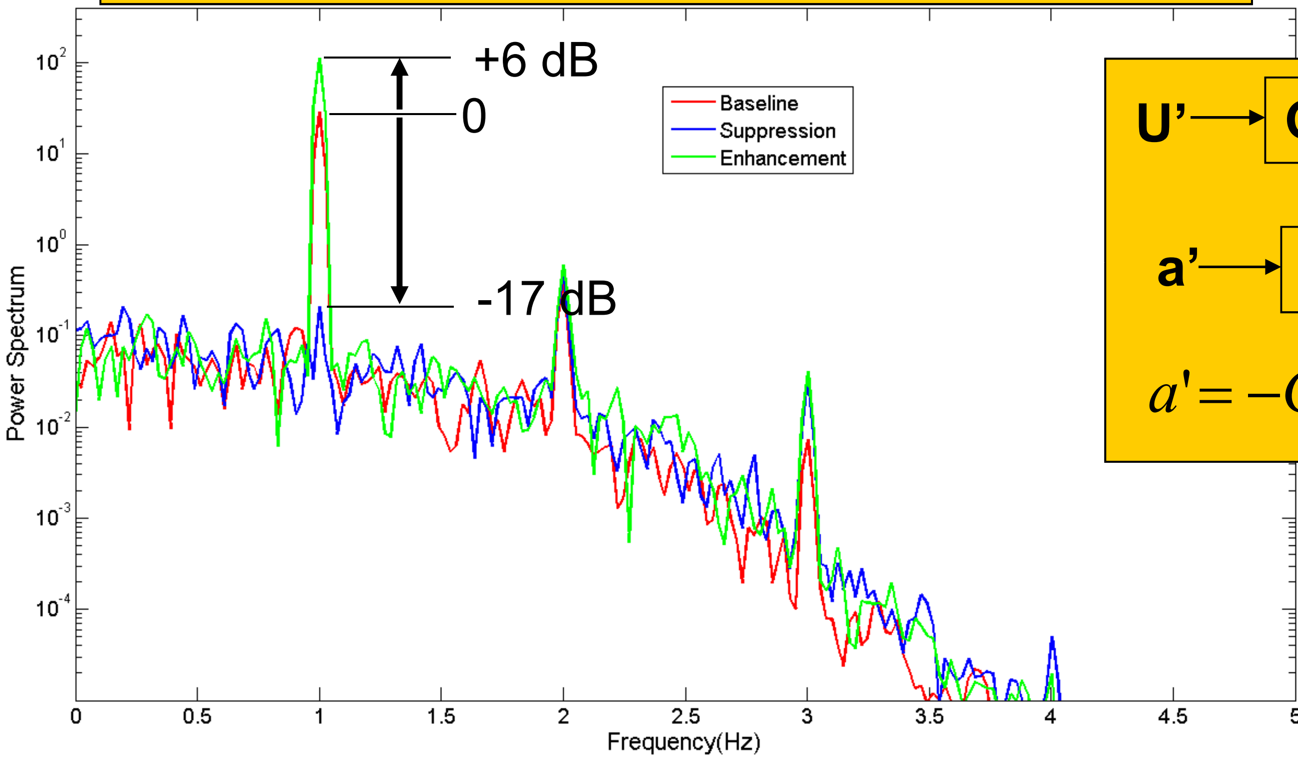
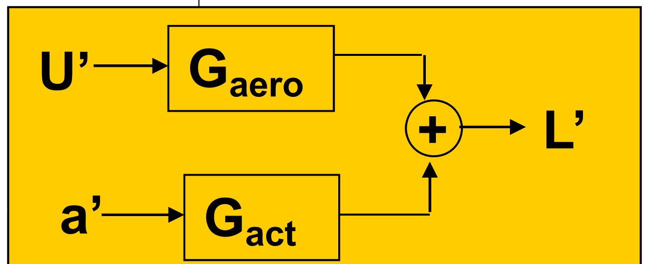
Feed forward control increases time response 5X

Suppressing & enhancing 1.0 Hz oscillation

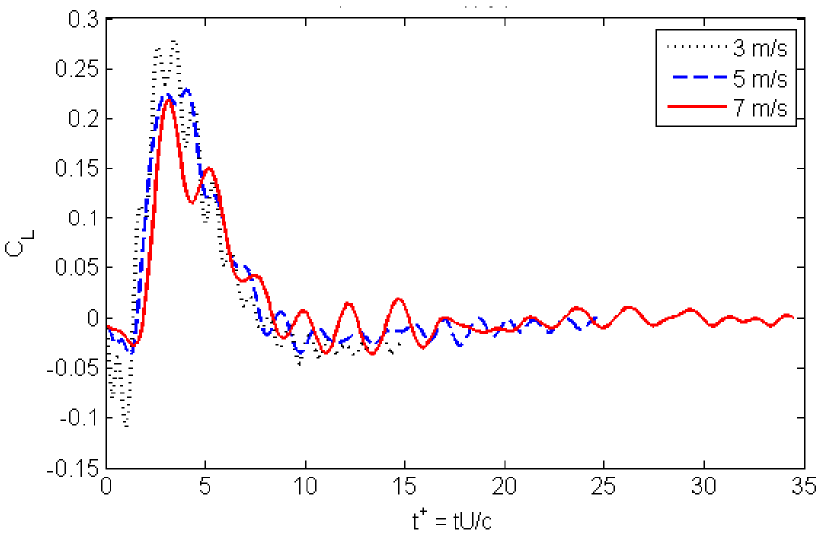




$$a' = -G_{act}^{-1} G_{aero} \cdot U'$$

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

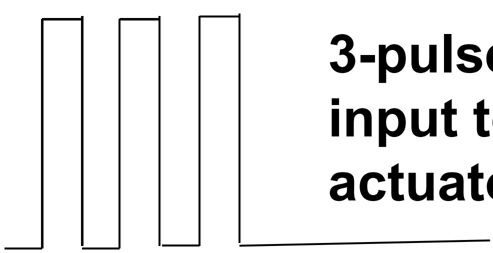
w = output signal

Note: wiggles are sting vibrations

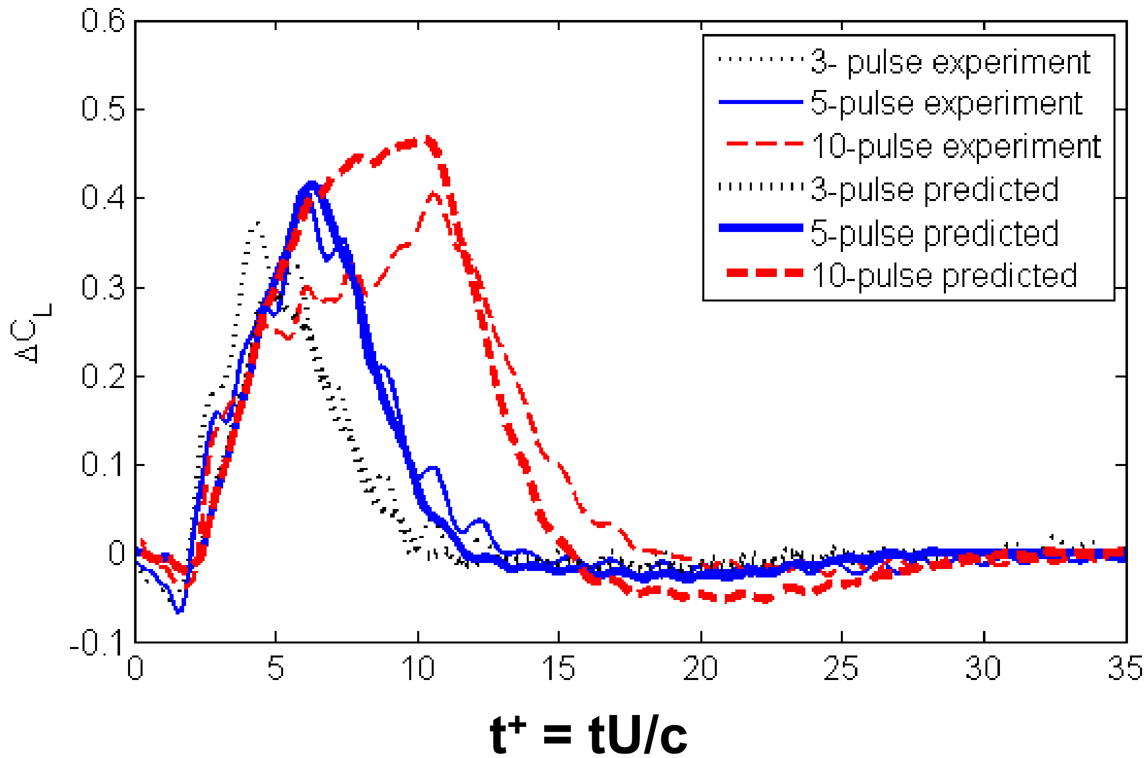
Lift response curves similar to results of Woo, et al. (2008) for 2D airfoil with pulse-combustion actuators

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

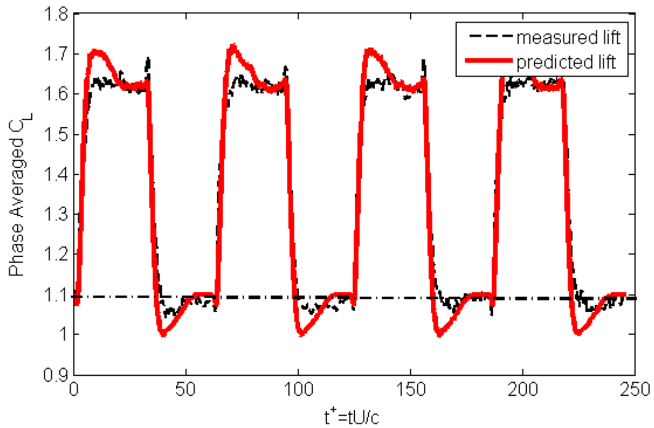


3-pulse input to actuator



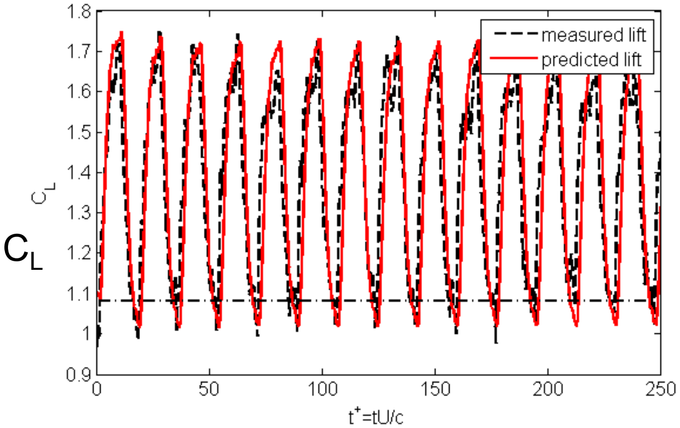
Quasi-linear behavior of lift response to actuation

0.4 Hz



No forcing C_L

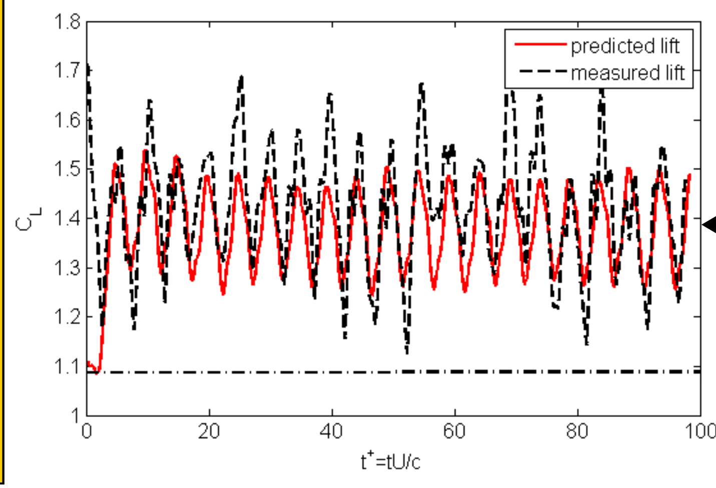
1.4 Hz



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

OUTPUT = convolution between kernel and input

5 Hz



Shift in mean C_L

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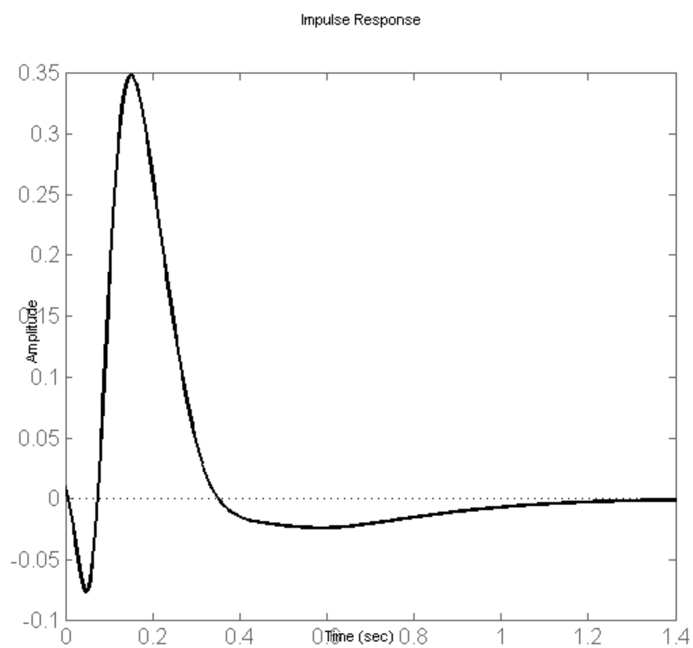
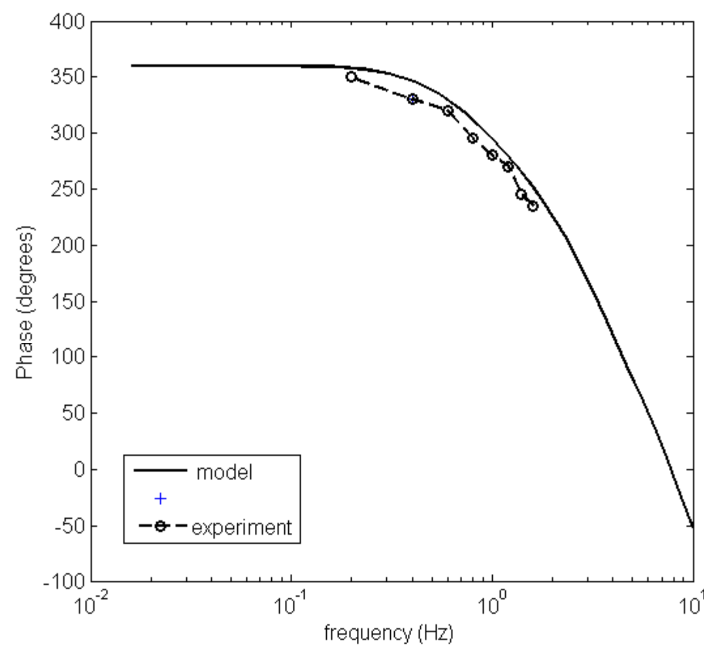
Black-box model agrees with pulse-response

- System Identification of a ‘black-box’ model (6th 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





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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 (~5.8 c/U) and must be included in controllers
- Convolution of input signal with single pulse kernel gives reasonable prediction of lift response