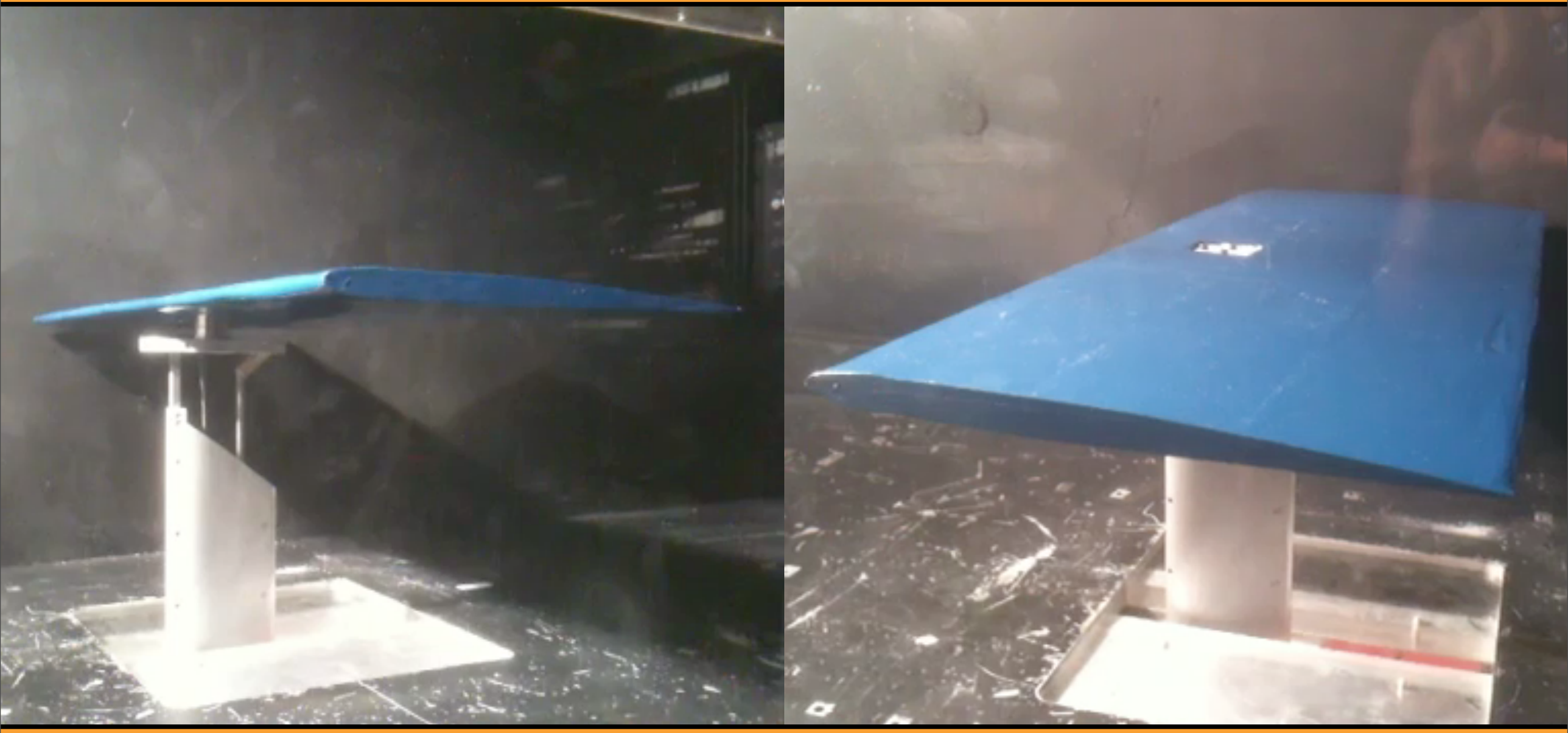
Unsteady Aerodynamic Forces: Experiments, Simulations, and Models



Steve Brunton & Clancy Rowley

FAA/JUP Quarterly Meeting

April 6, 2011

Motivation

Applications of Unsteady Models

- **Conventional UAVs (performance/robustness)**
- **Micro air vehicles (MAVs)**
- **Flow control, flight dynamic control**
- **Autopilots / Flight simulators**
- **Gust disturbance mitigation**

Predator (General Atomics)

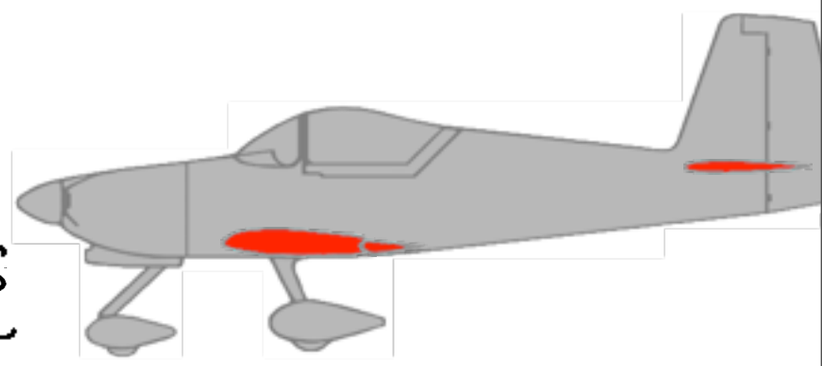
Need for State-Space Models

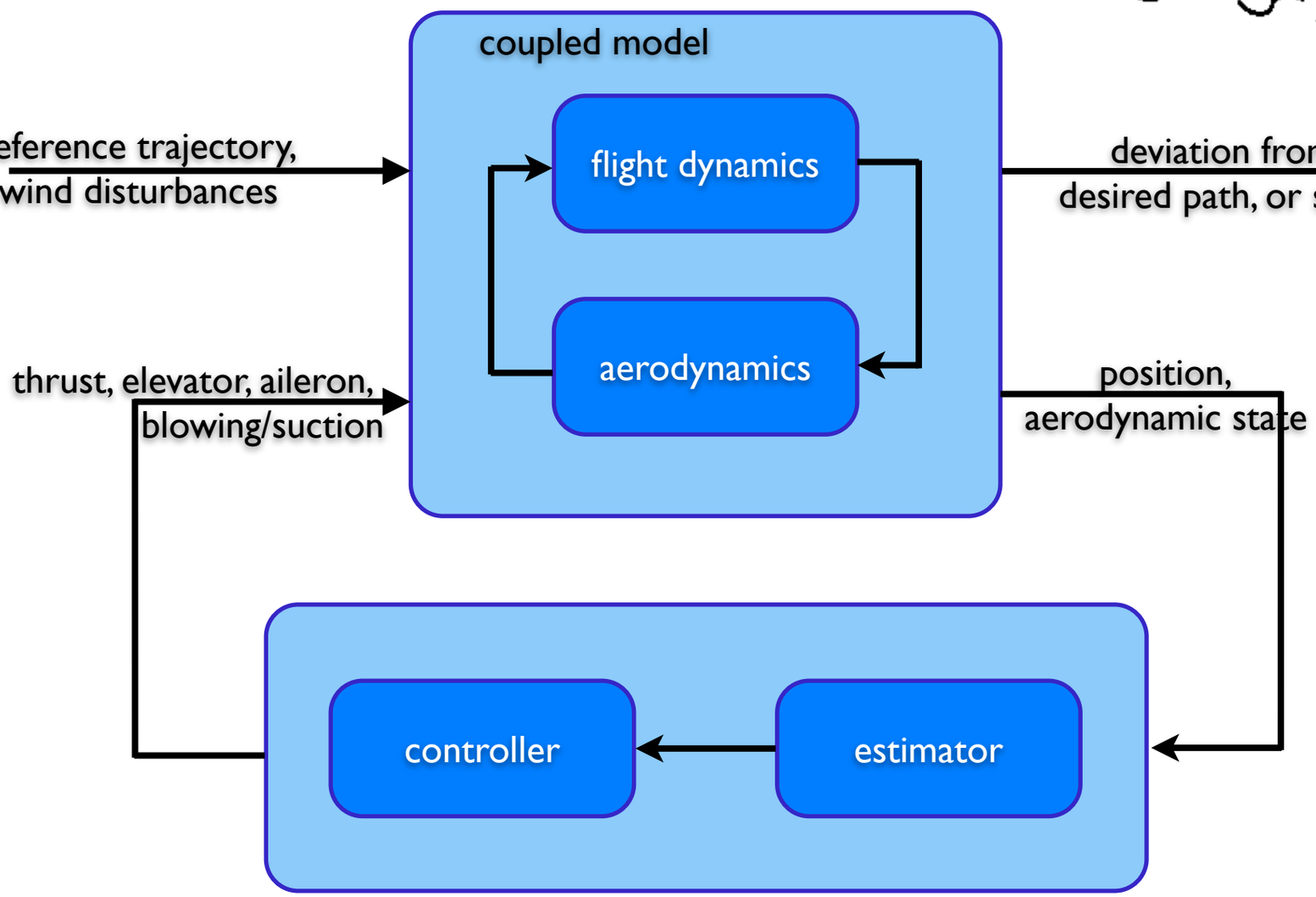
- **Need models suitable for control**
- **Combining with flight models**

Daedalus Dakota

FLYIT Simulators, Inc.

Flight Dynamic Control





Stall velocity and size

Smaller, lower stall velocity

RQ-1 Predator
(27 m/s stall)

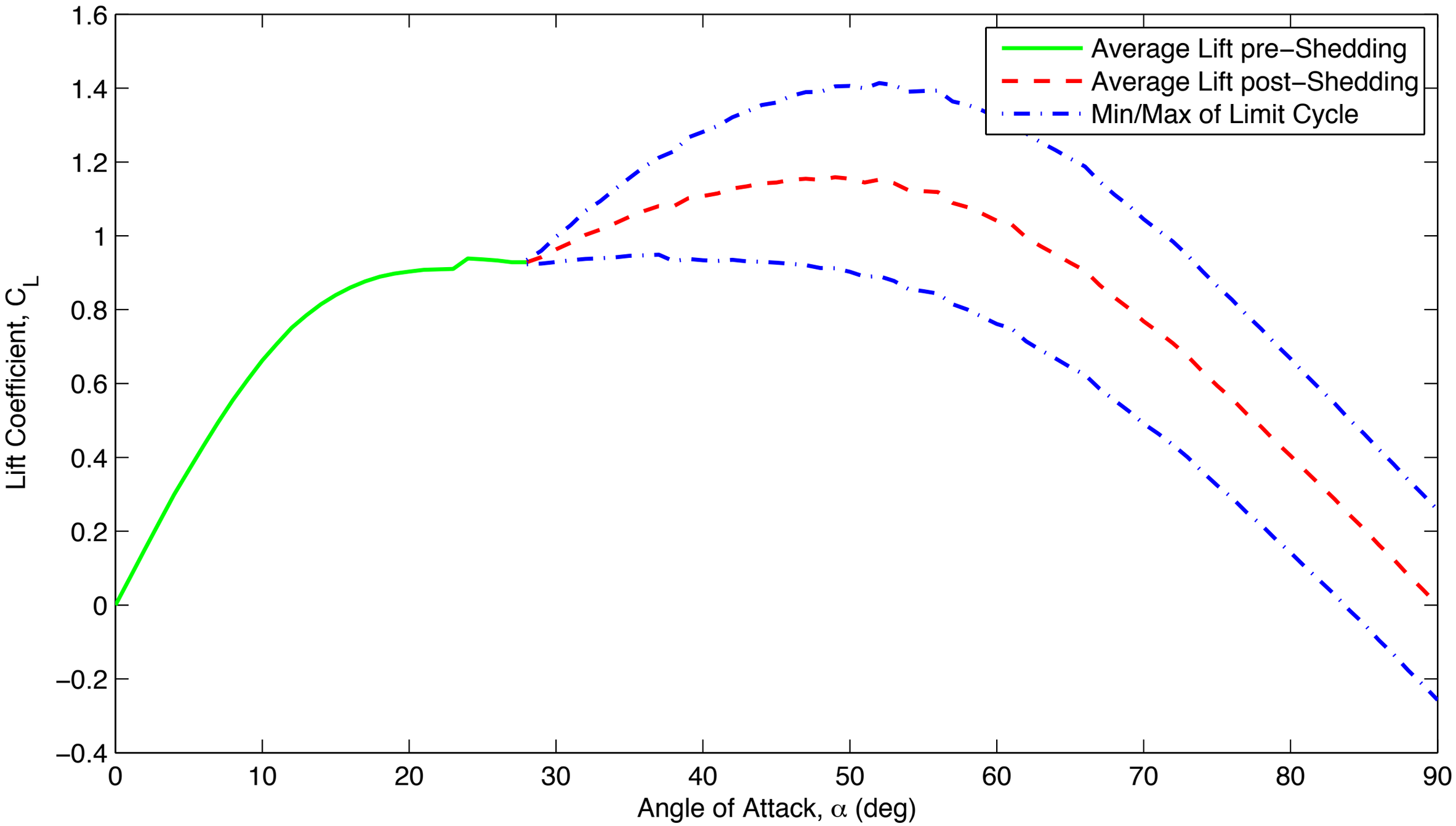
Daedalus Dakota
(18m/s stall)

Puma AE
(10 m/s stall)

$$V_{\text{stall}} = \sqrt{\frac{2}{\rho}\left(C_{L_{\max}} S\right)^{-1} W}$$

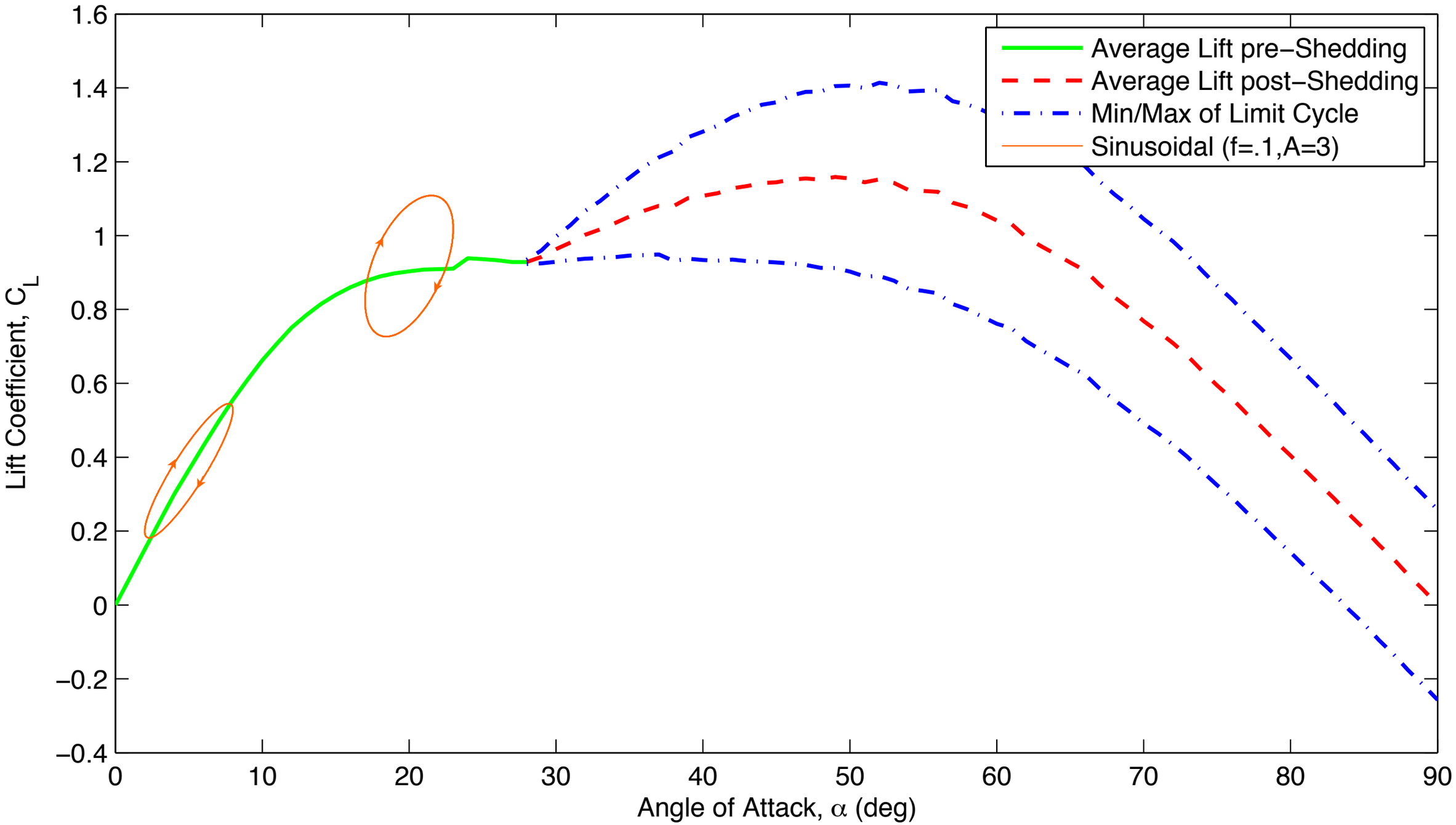
S	Wing surface area
W	Aircraft weight
L	Lift force
C_L	Lift coefficient
V	Velocity of aircraft

Lift vs. Angle of Attack



Need model that captures lift due to moving airfoil!

Lift vs. Angle of Attack



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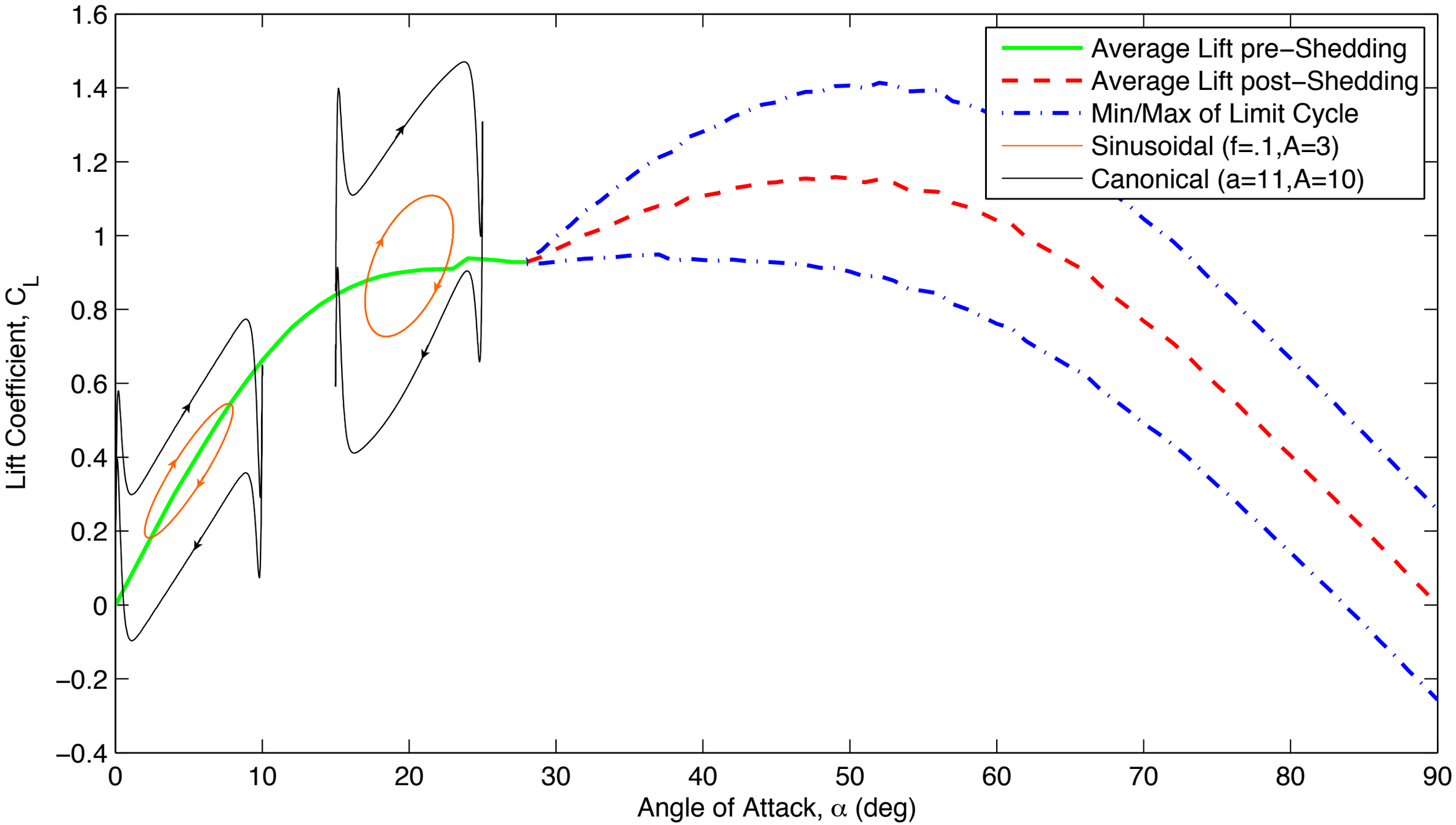
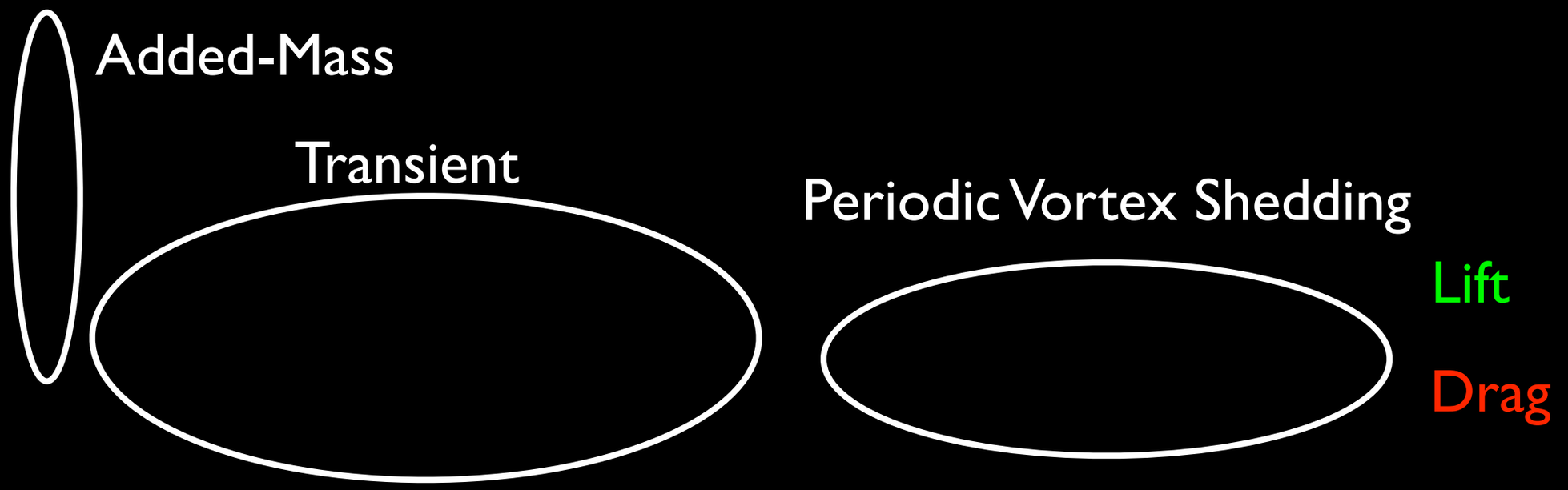
Lift vs. Angle of Attack



Need model that captures lift due to moving airfoil!

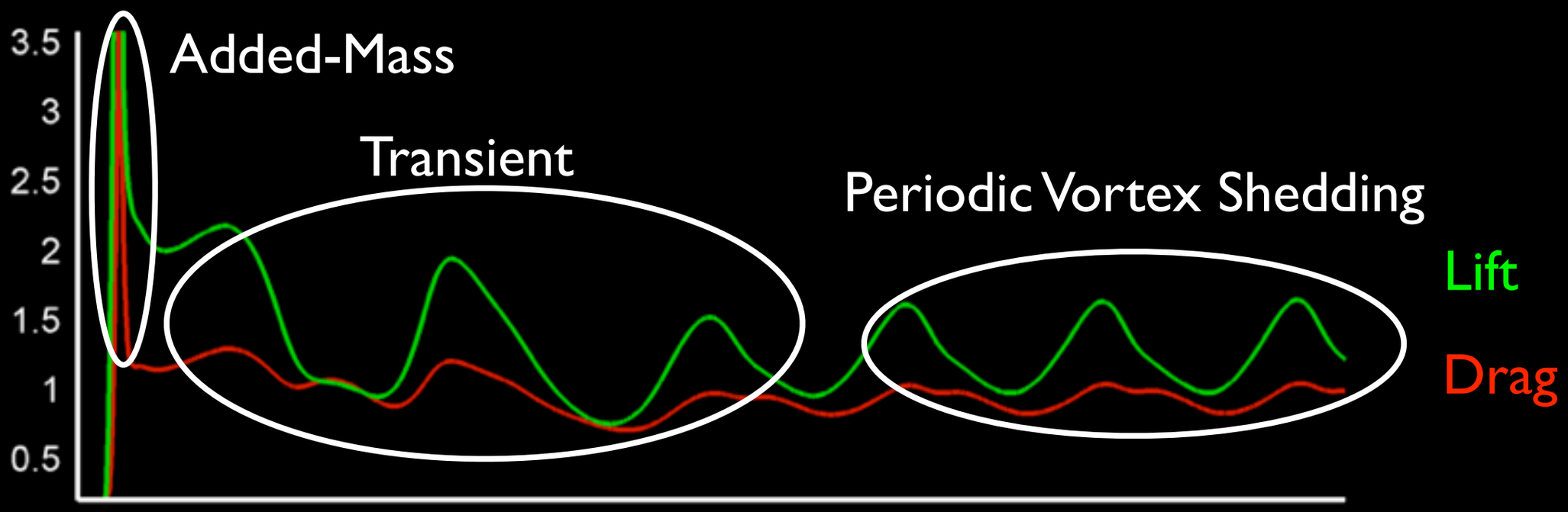
2D Model Problem



$\mathrm{Re} = 300$

$\alpha = 32^\circ$

2D Model Problem



$\mathrm{Re} = 300$

$\alpha = 32^\circ$

Reduced Order Indicial Response

$$C_L(t) = C_L^S(t)\alpha(0) + \int_0^t C_L^S(t-\tau)\dot{\alpha}(\tau)d\tau$$

fast dynamics

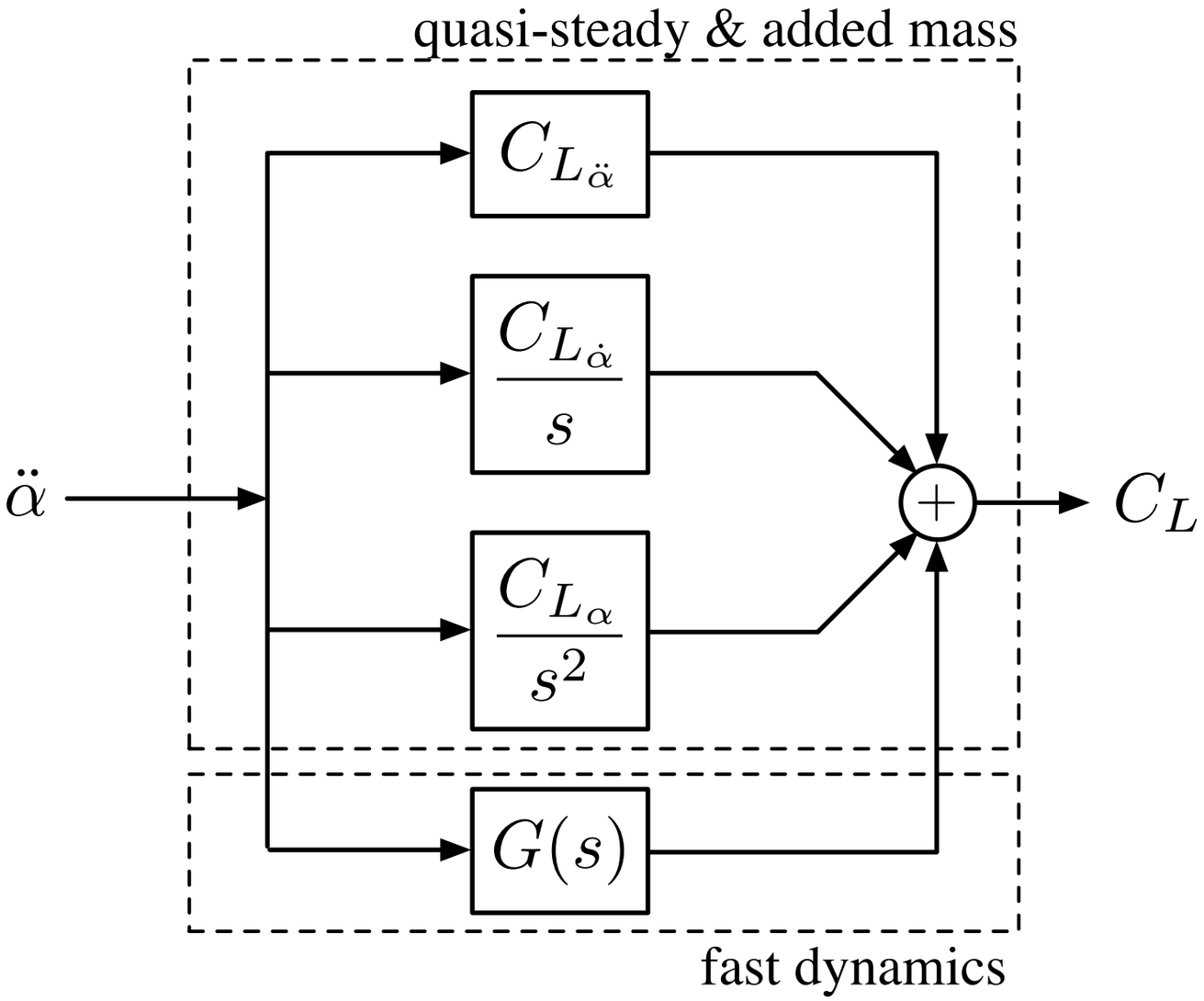
Reduced-order model

$$\frac{d}{dt}\begin{bmatrix}\mathbf{x}\\ \alpha\\ \dot{\alpha}\end{bmatrix} = \begin{bmatrix}A_r & 0 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\mathbf{x}\\ \alpha\\ \dot{\alpha}\end{bmatrix} + \begin{bmatrix}B_r\\ 0\\ 1\end{bmatrix}\ddot{\alpha}$$

input

$$C_L = \begin{bmatrix}C_r & C_{L_\alpha} & C_{L_{\dot{\alpha}}}\end{bmatrix}\begin{bmatrix}\mathbf{x}\\ \alpha\\ \dot{\alpha}\end{bmatrix} + C_{L_{\ddot{\alpha}}}\ddot{\alpha}$$

quasi-steady and added-mass



Model Summary

Linearized about $\alpha = 0$

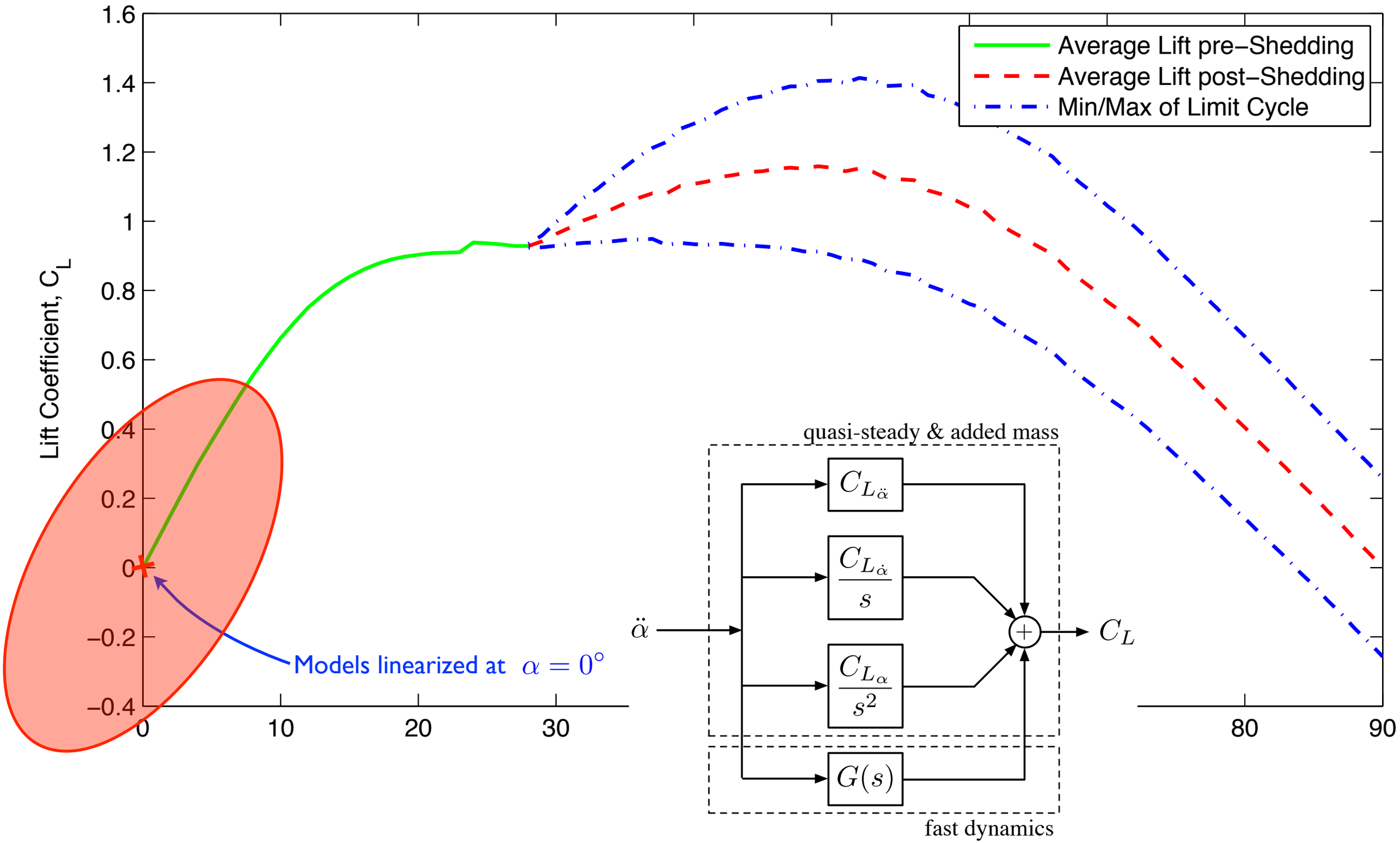
Based on experiment, simulation or theory

Recovers stability derivatives $C_{L_\alpha}, C_{L_{\dot{\alpha}}}, C_{L_{\ddot{\alpha}}}$ associated with quasi-steady and added-mass

ODE model ideal for control design

Brunton and Rowley, *in preparation*.

Lift vs. Angle of Attack



Bode Plot - Pitch (QC)

Frequency response

input is $\ddot{\alpha}$ (α is angle of attack)

output is lift coefficient C_L

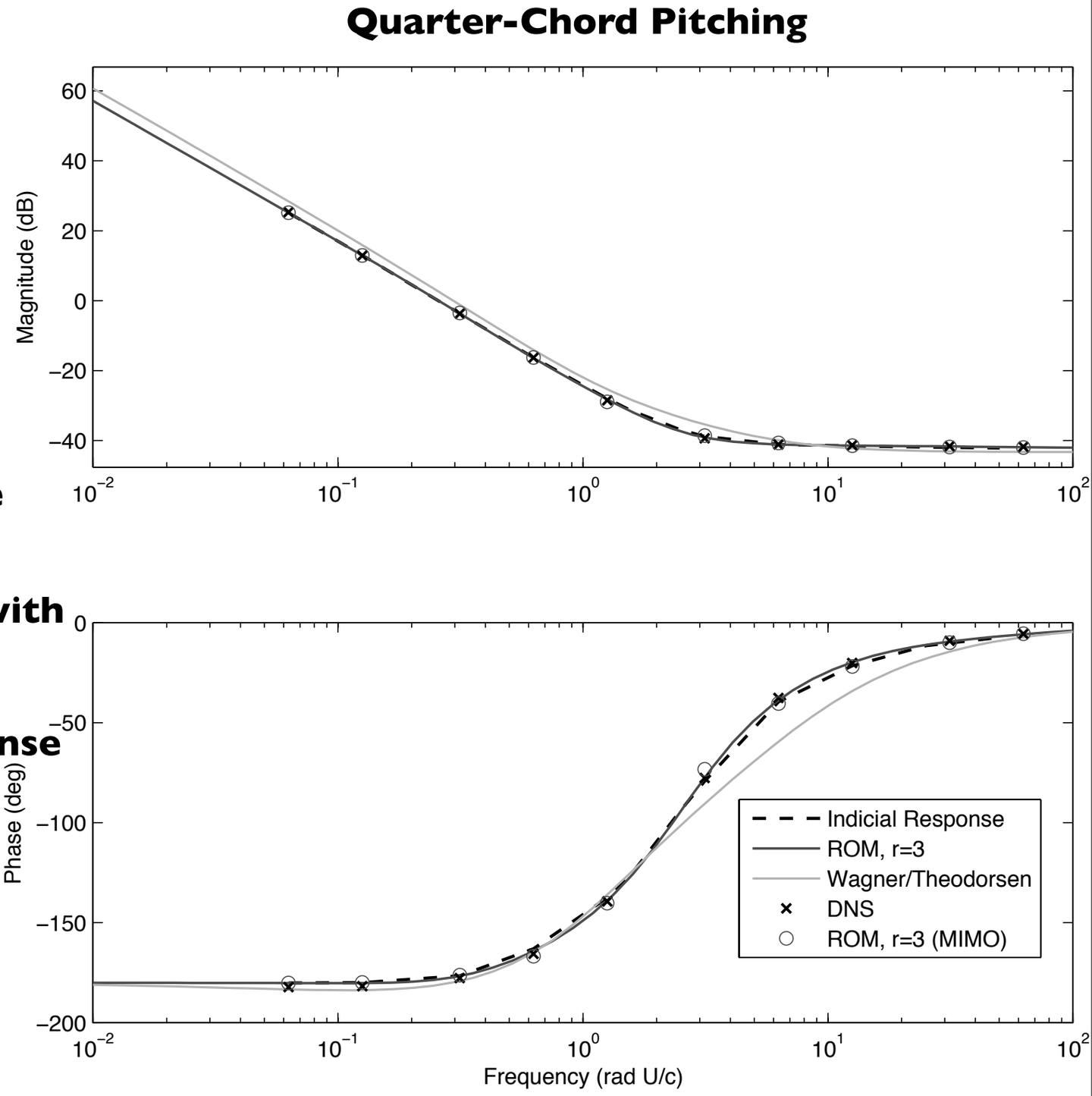
Pitching at quarter chord

Reduced order model with ERA r=3 accurately reproduces Indicial Response

Indicial Response and ROM agree better with DNS than Theodorsen's model.

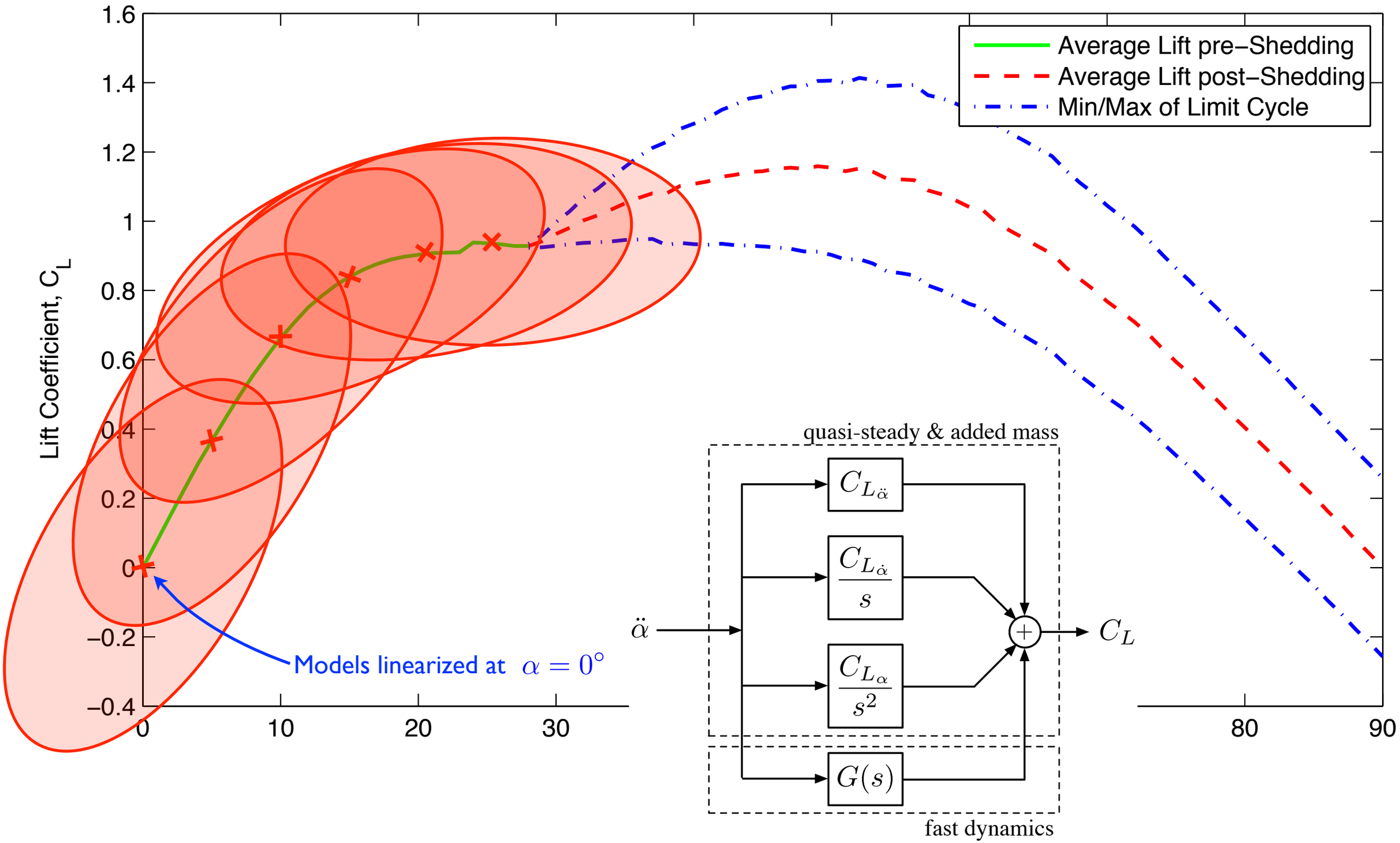
Asymptotes are correct for Indicial Response because it is based on experiment

Model for pitch/plunge dynamics [ERA, r=3 (MIMO)] works as well, for the same order model

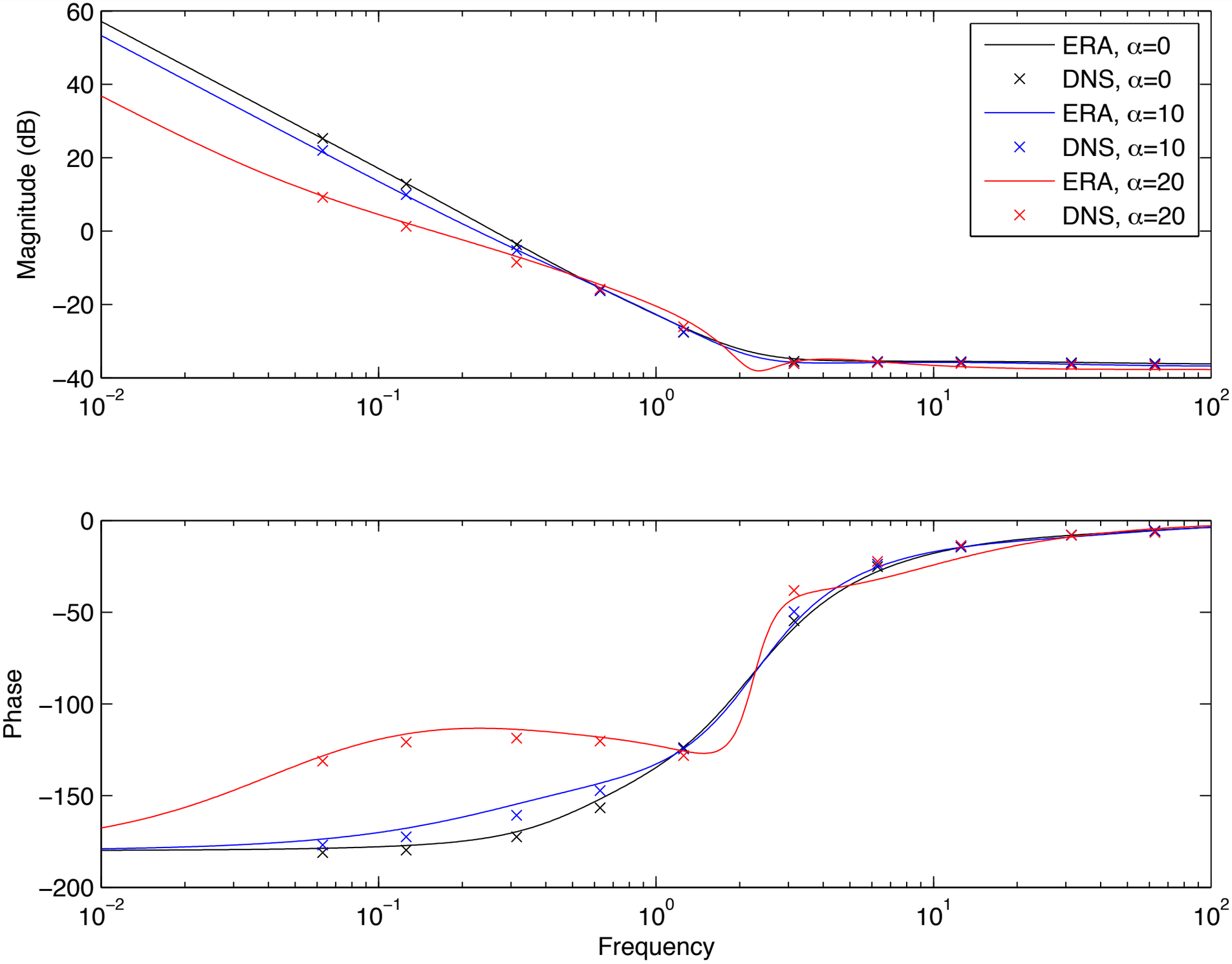


Brunton and Rowley, *in preparation*.

Lift vs. Angle of Attack



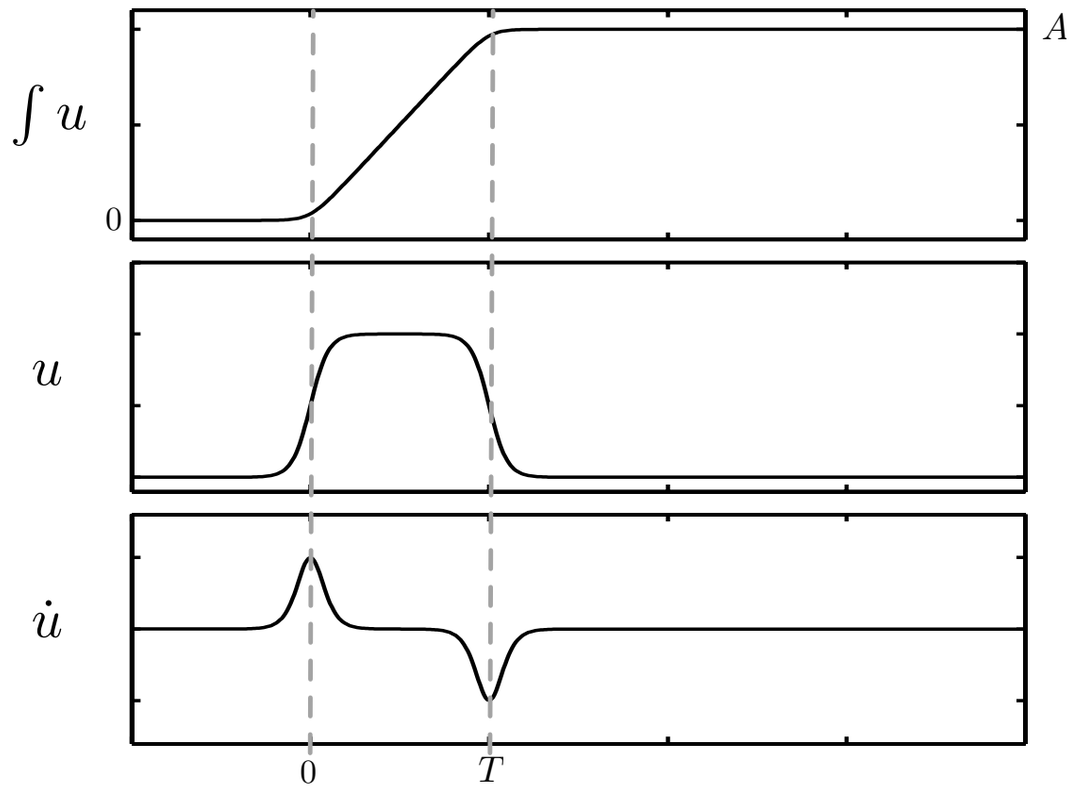
Bode Plot of Model (-) vs Data (x)

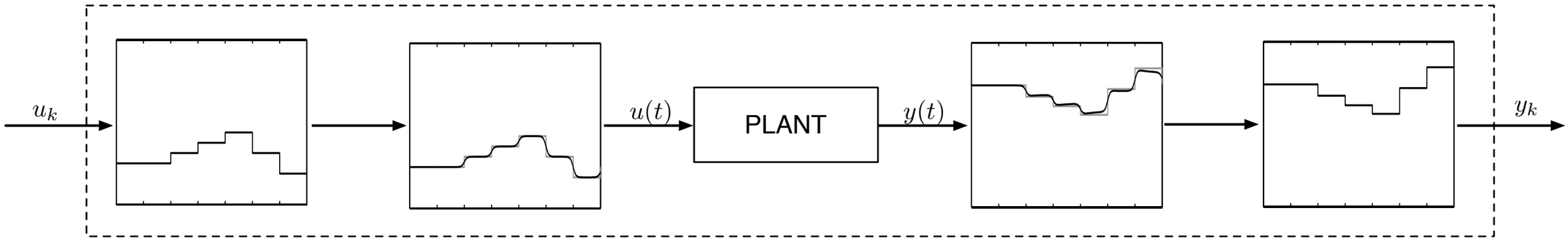


Direct numerical simulation confirms that local linearized models are accurate for small amplitude sinusoidal maneuvers

Brunton and Rowley, AIAA ASM 2011

(Indicial) Step Response

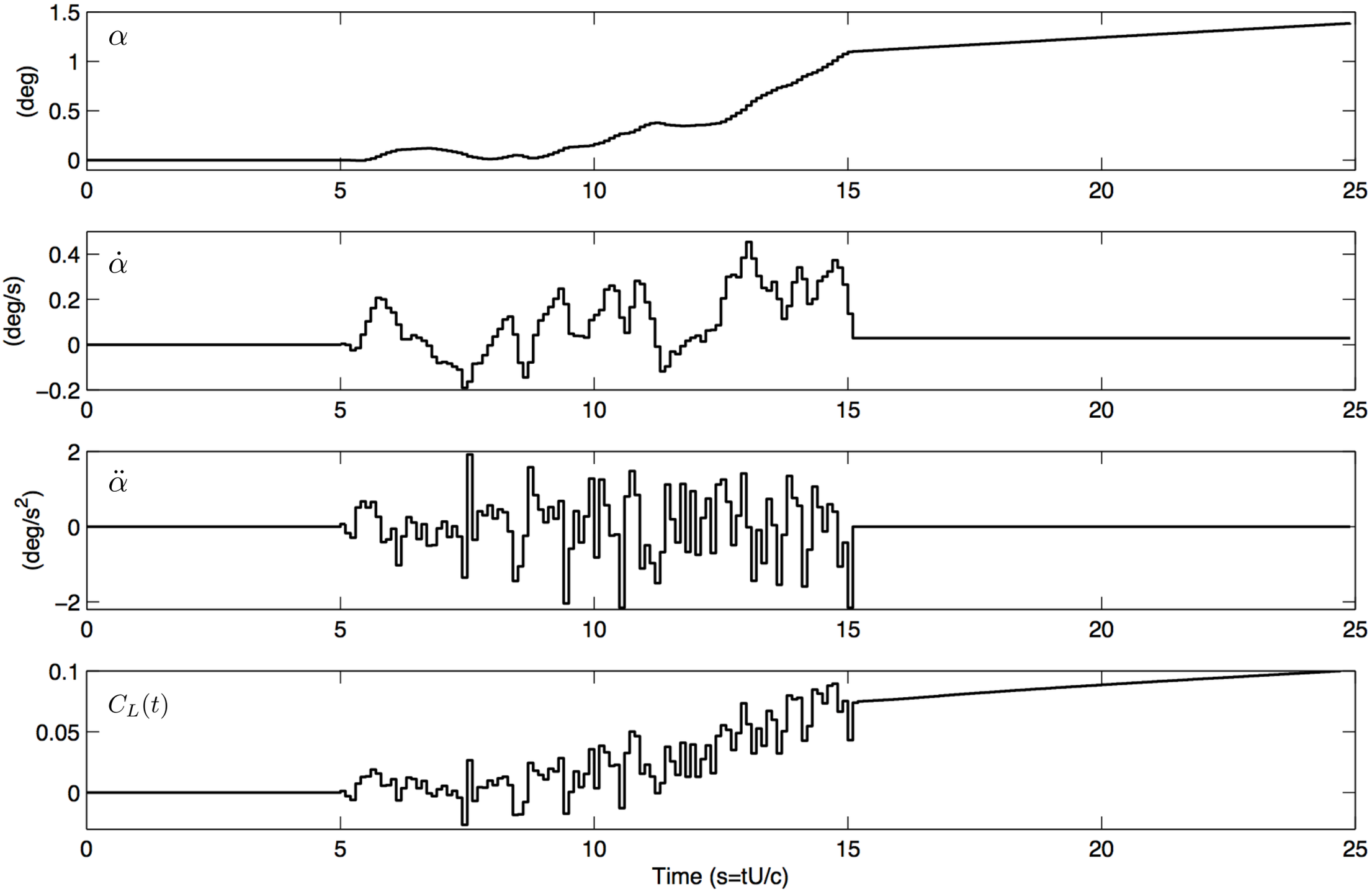




Previously, models are based on aerodynamic step response

Idea: Have pilot fly aircraft around for 5-10 minutes, back out the Markov parameters, and construct ERA model.

Random Input Maneuver



Idea: Have pilot fly aircraft around for 5-10 minutes, back out the Markov parameters, and construct ERA model.

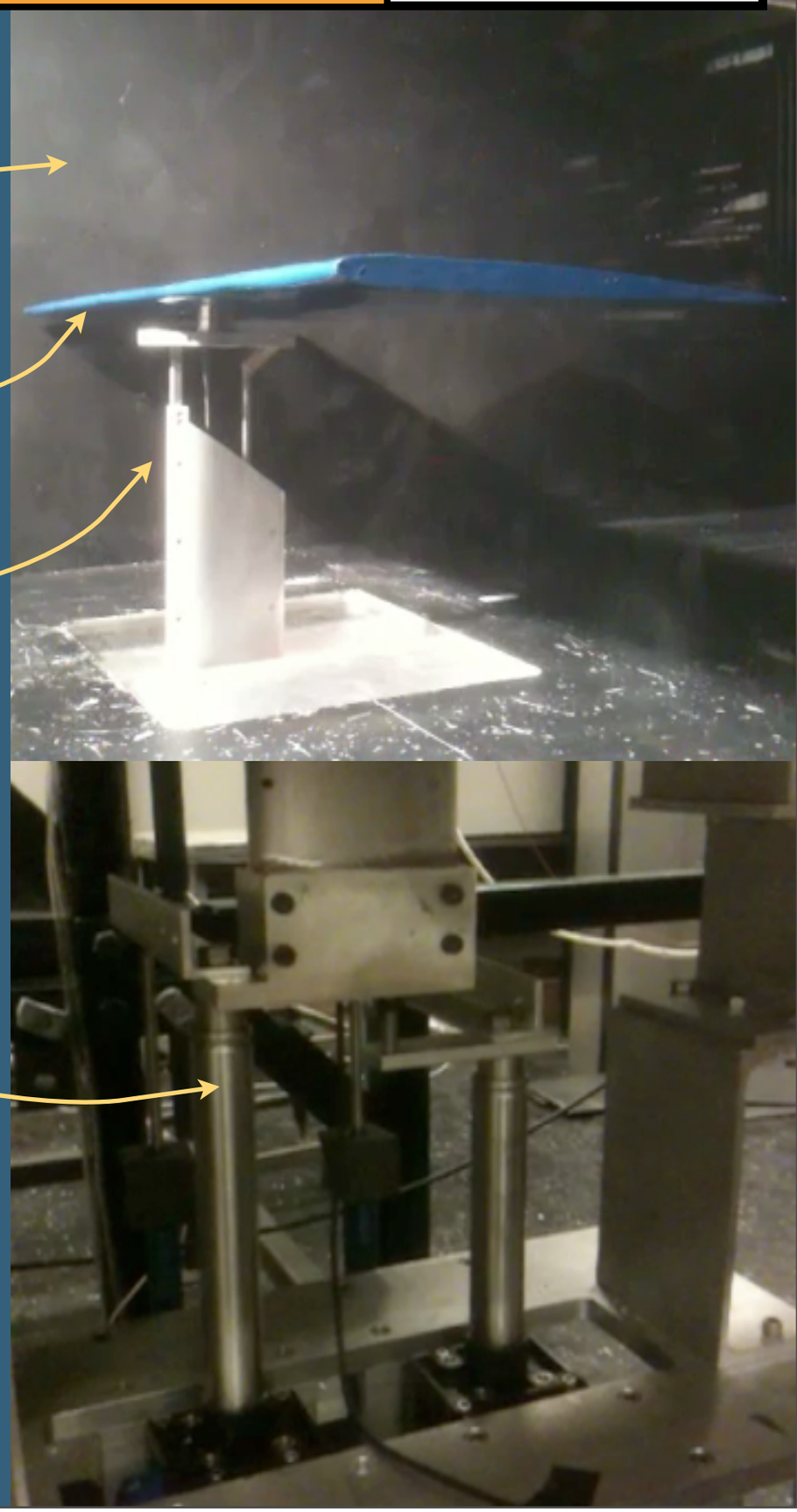
Wind Tunnel Setup

Test section

NACA 0006 Airfoil
(24.6 cm chord)

Push rods and sting

Servo tubes



Experimental Information

Andrew Fejer Unsteady Flow Wind Tunnel

(.6m x .6m x 3.5m test section)

NACA 0006 Airfoil

Chord Length: 0.246 m

Free Stream Velocity: 4.00 m/s

1.0 Convection time = .06 seconds

Reynolds Number: 65,000

Pitch point x/c = .11 (11% chord)

Velocity measurement: Pitot tube,
Validyne DP-103 pressure transducer

Force measurement: ATI Nano25 force transducer

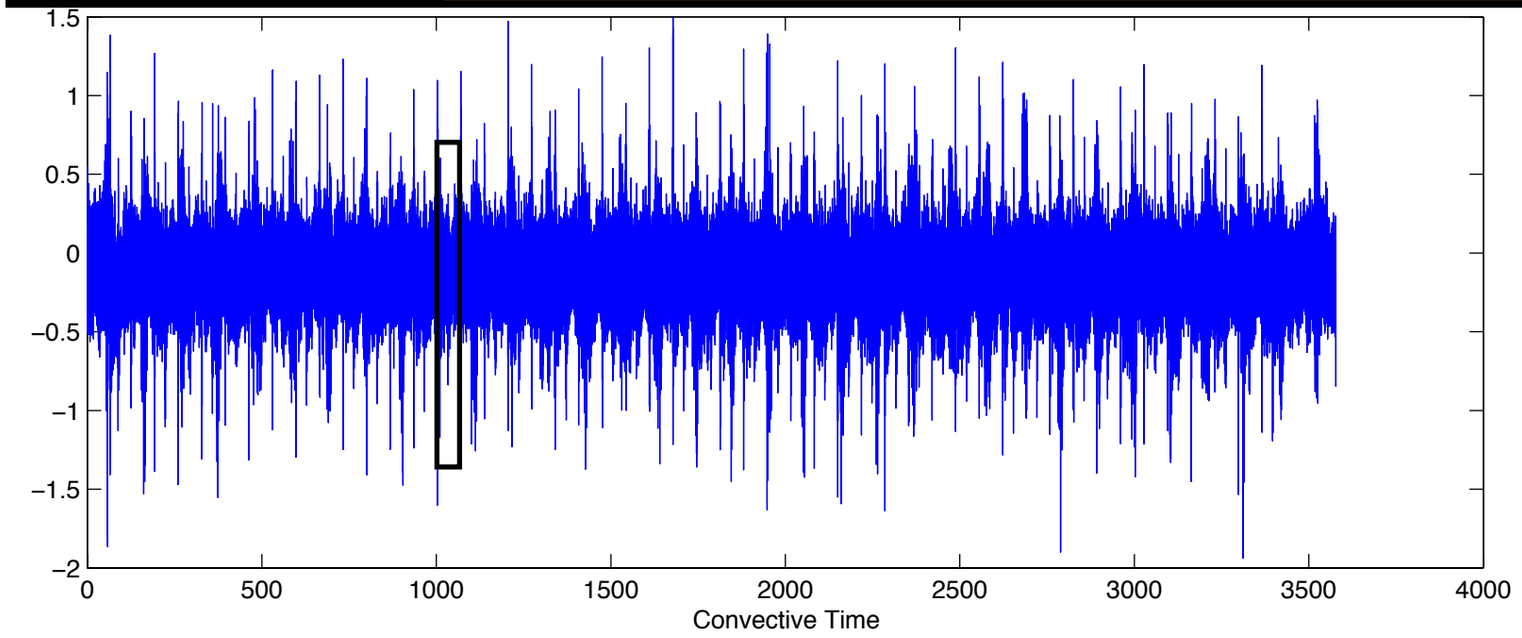
Pushrod position measurement: linear potentiometer

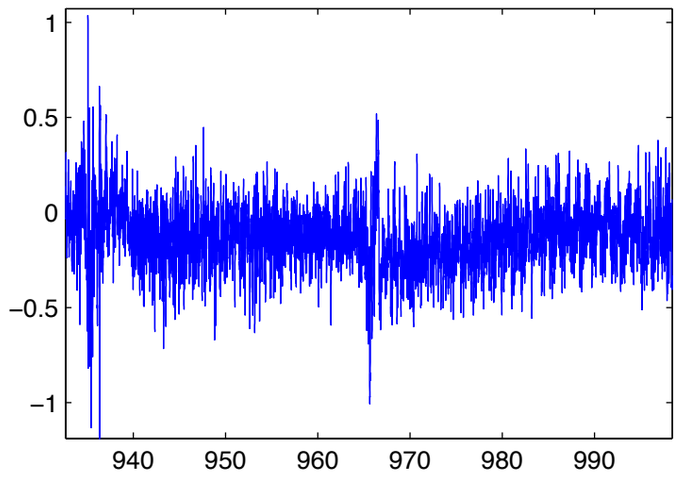
Pushrod actuation: Copley servo tubes

Acknowledgments: Professor David Williams

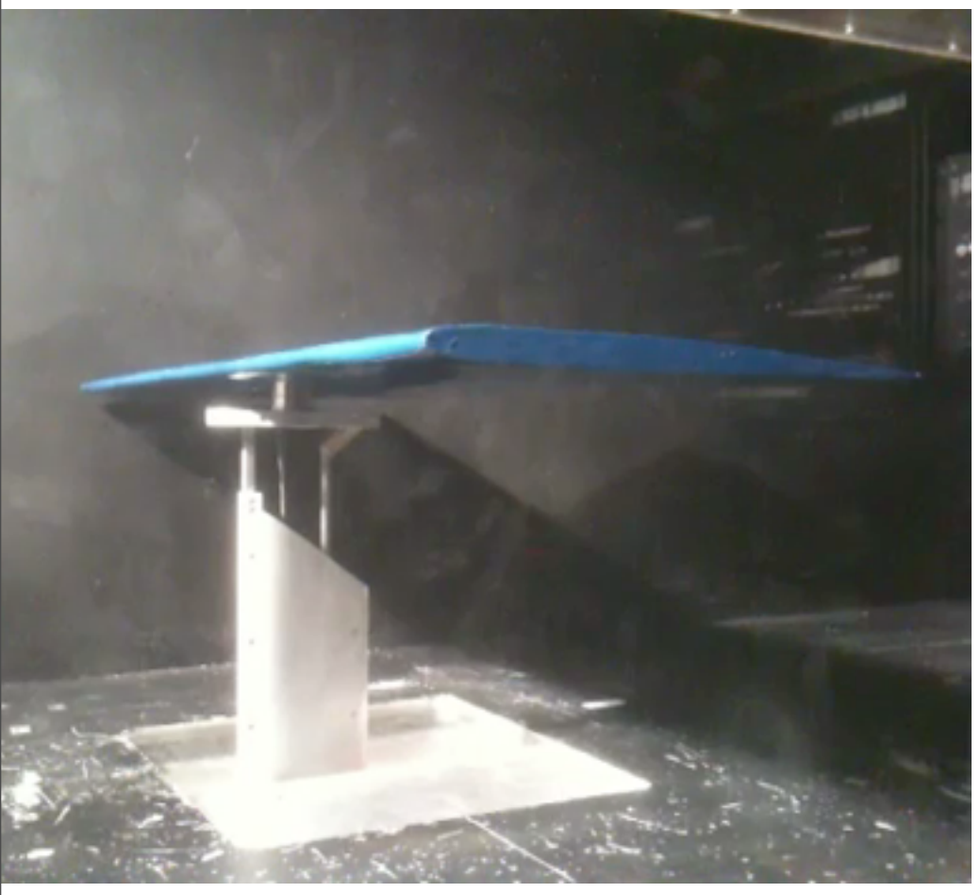
Seth Buntain and Vien Quatch

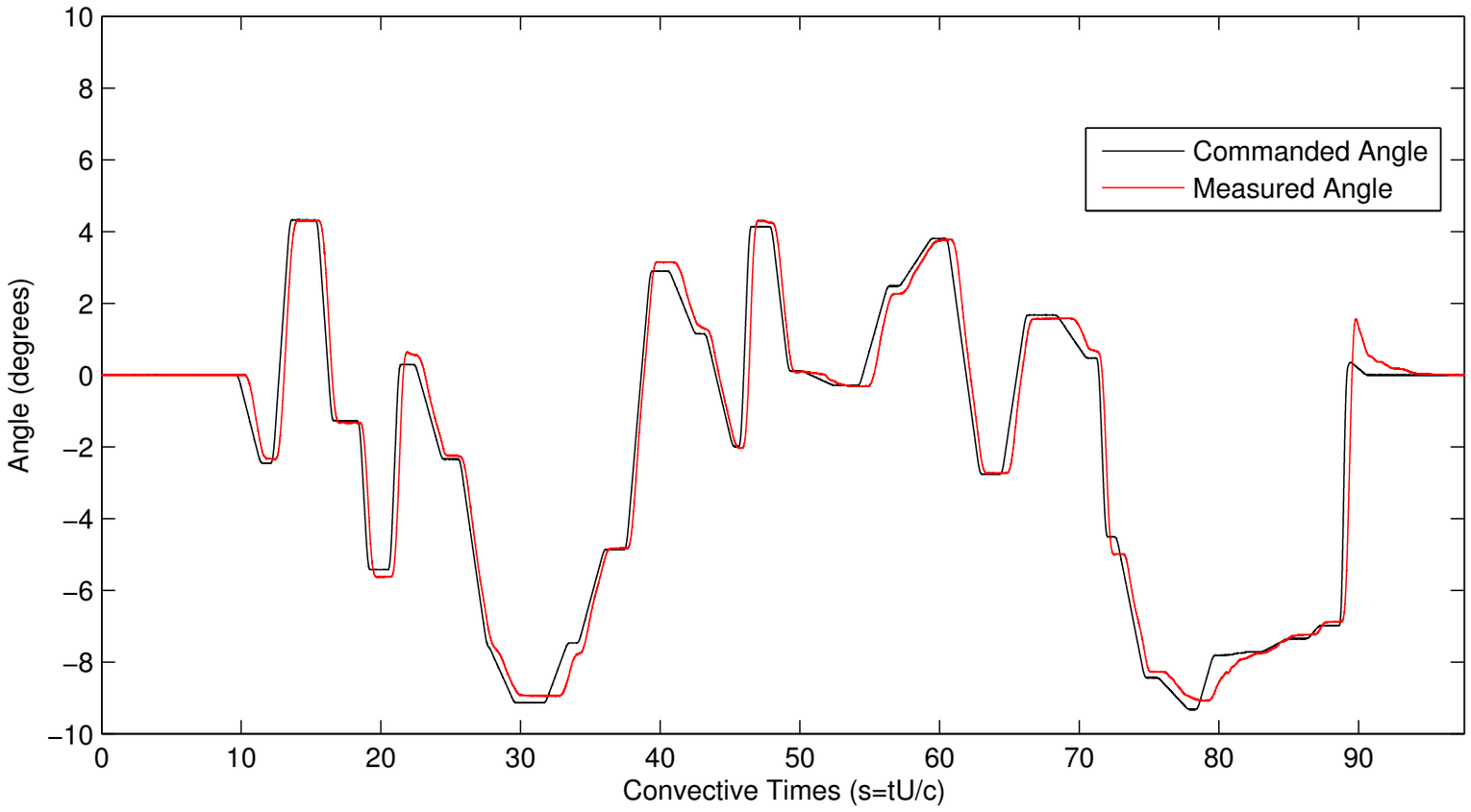
Phase Averaged Data



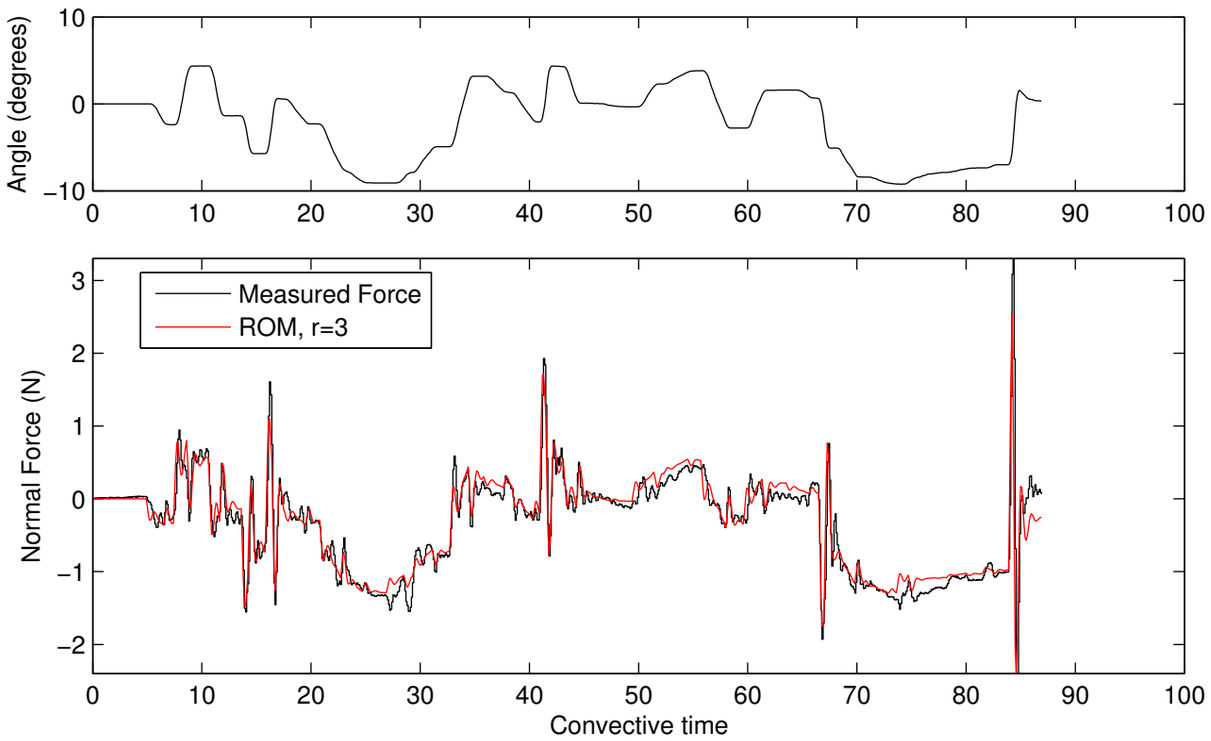


Wing Maneuver

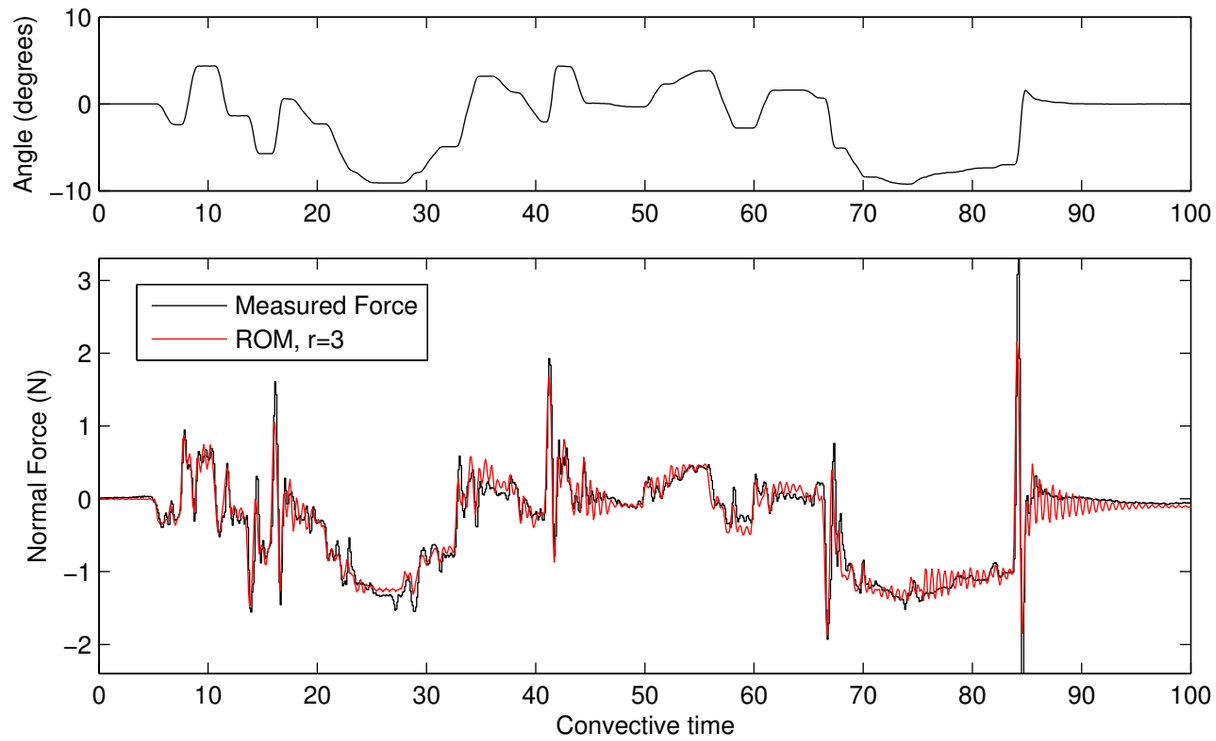




What are we modeling?

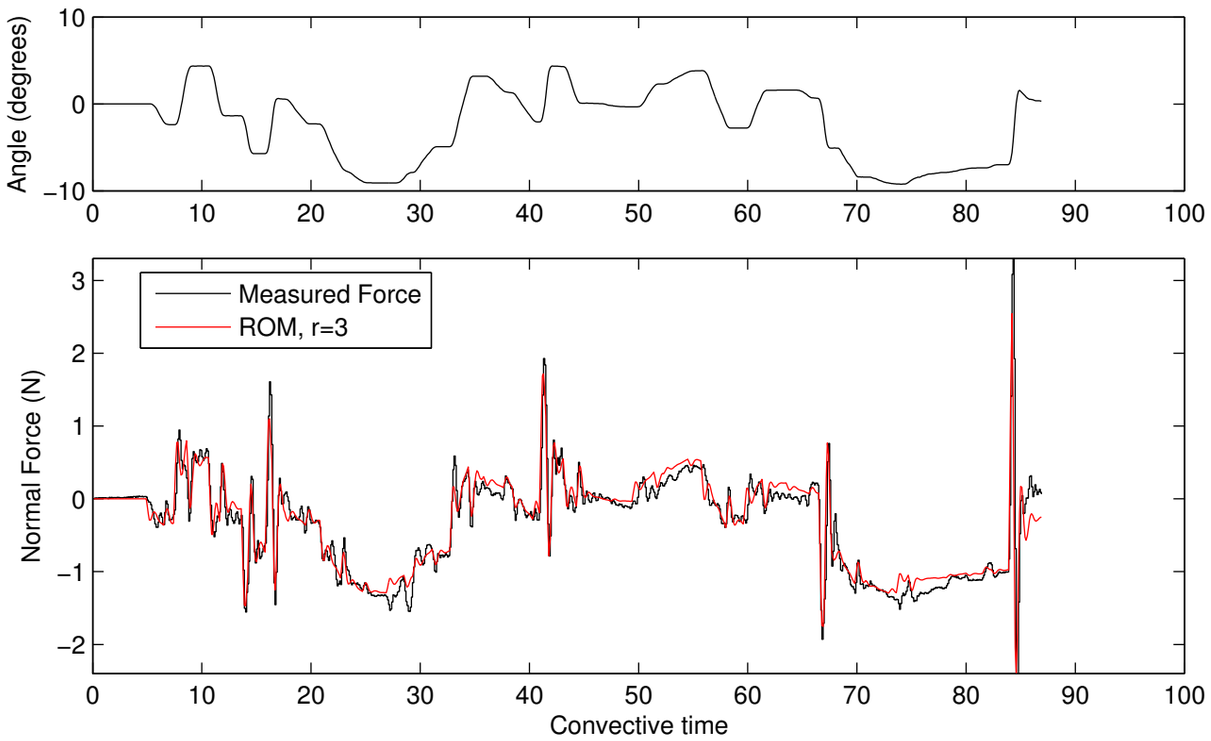


Model using command acceleration

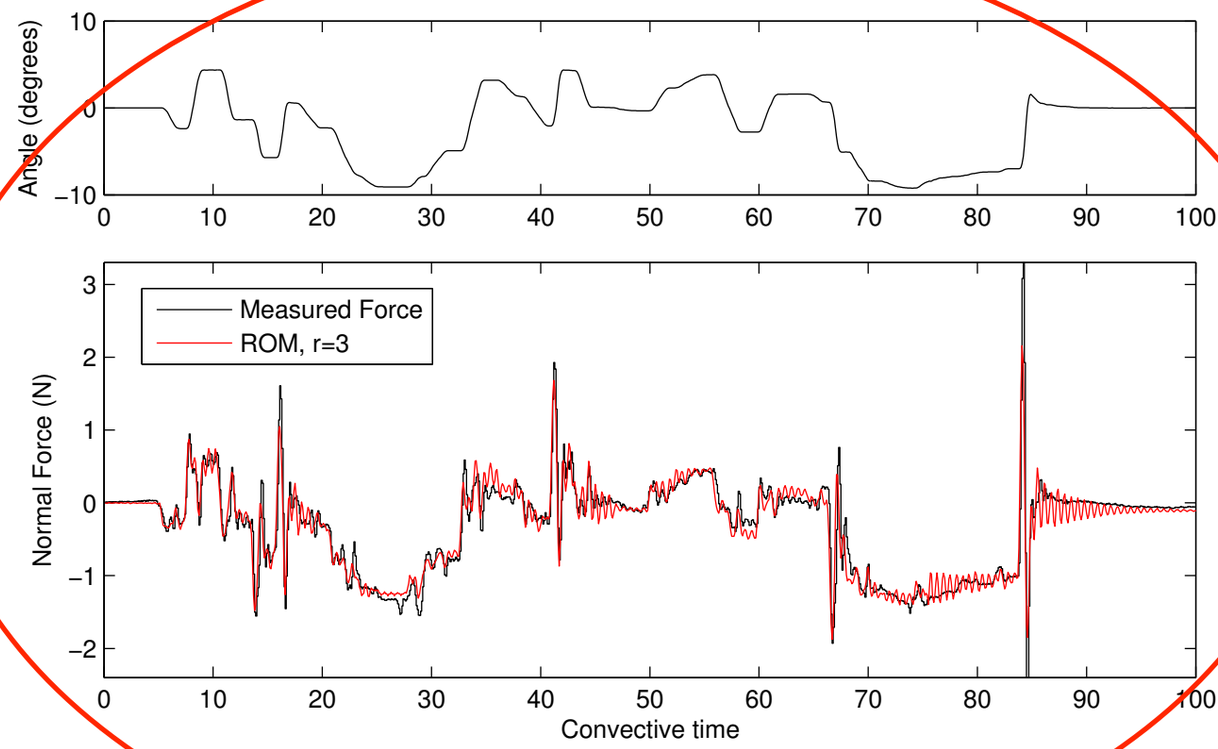


Model using measured acceleration

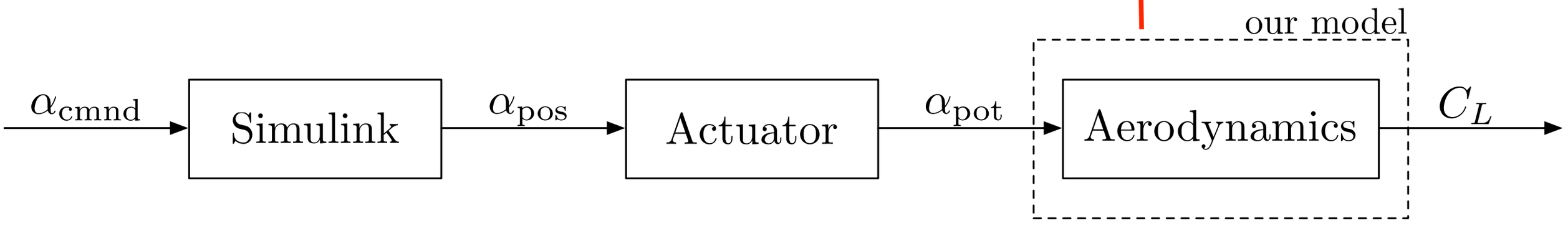
What are we modeling?



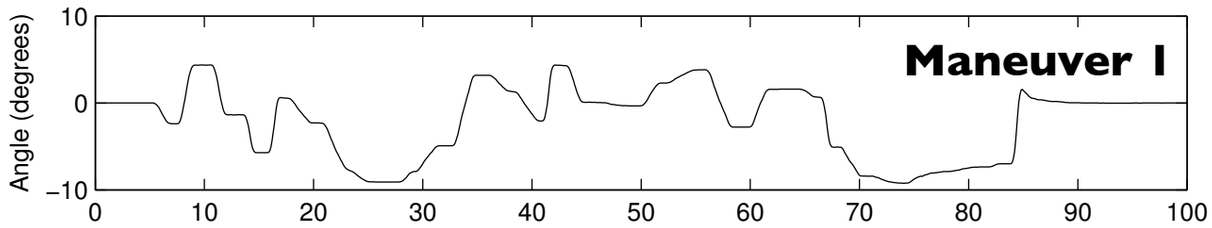
Model using command acceleration

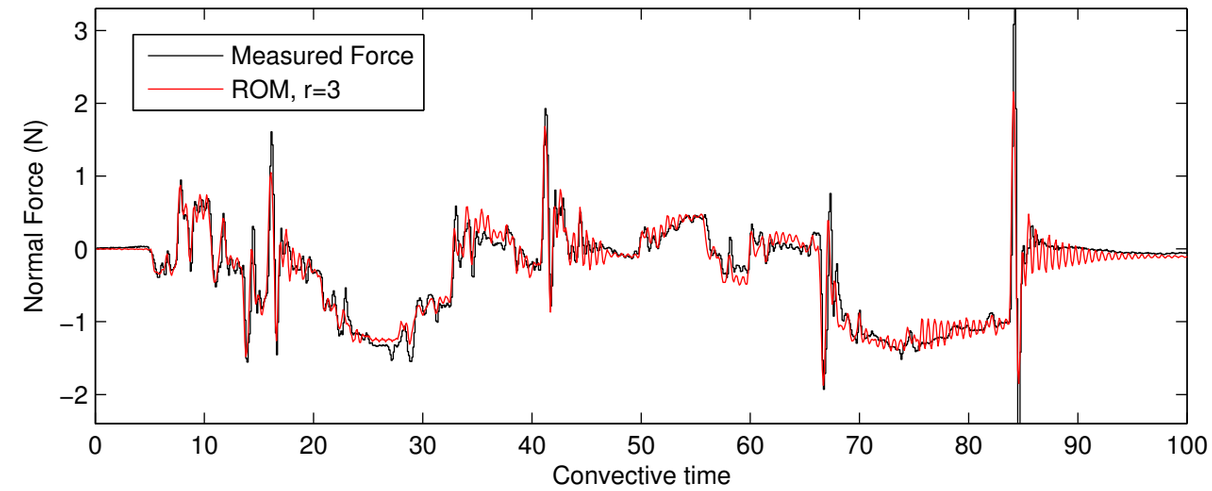


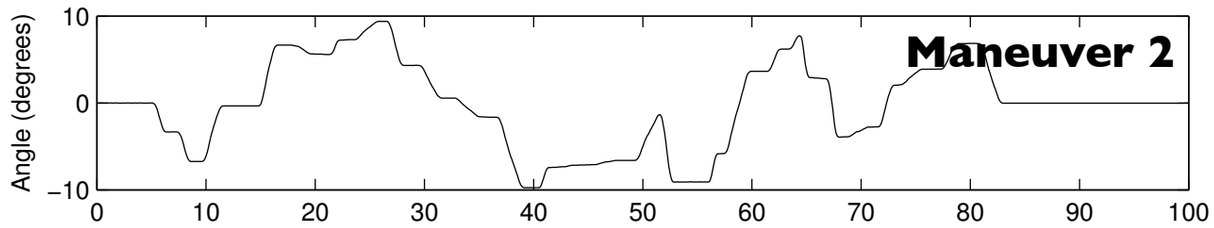
Model using measured acceleration

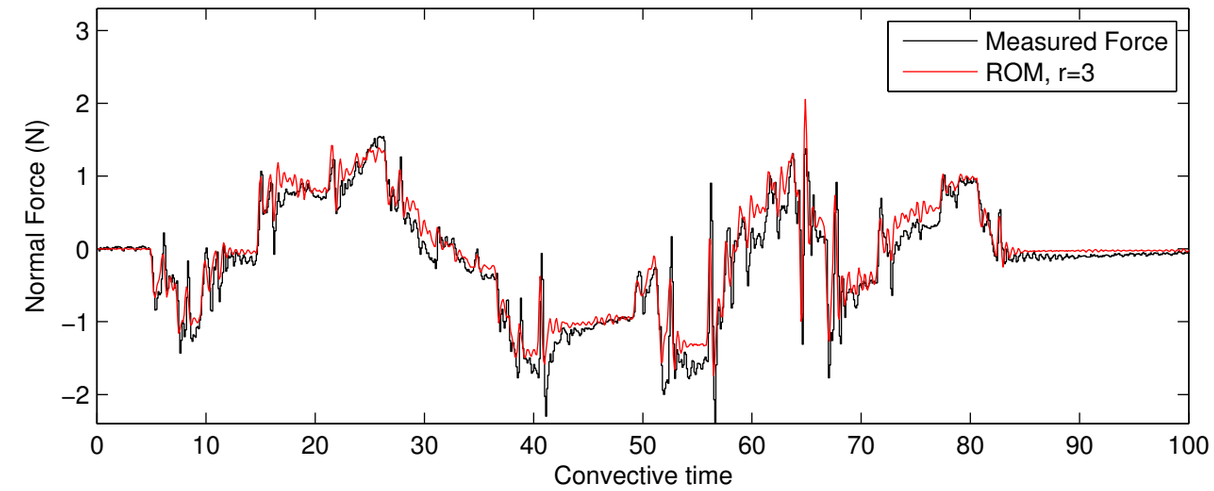


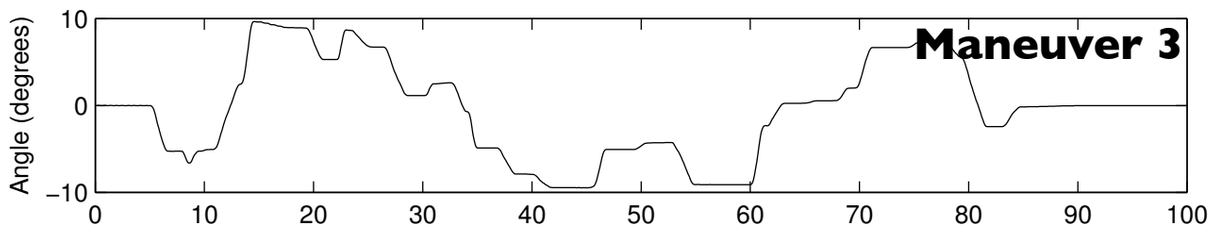
Four Test Maneuvers

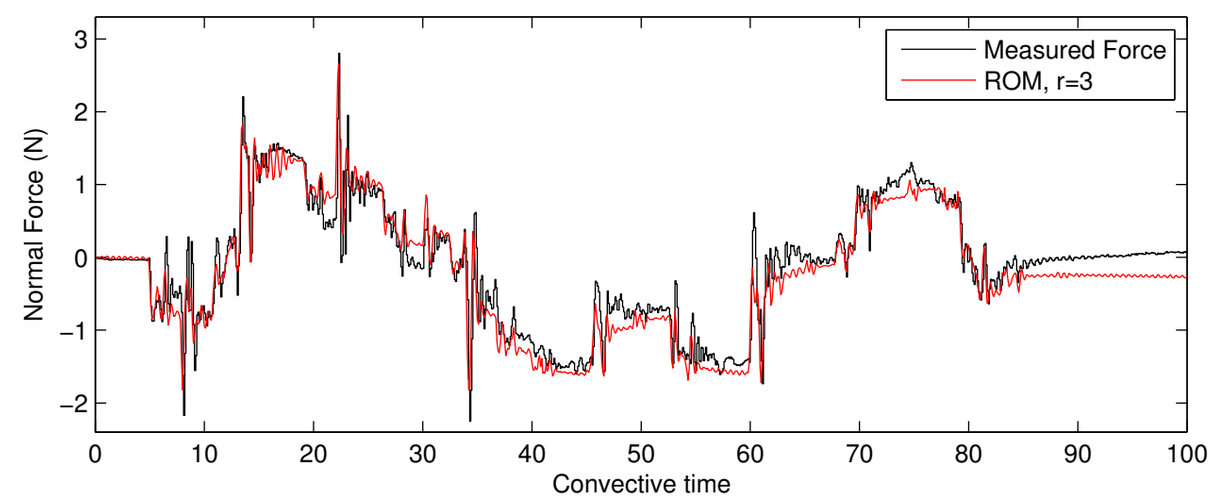


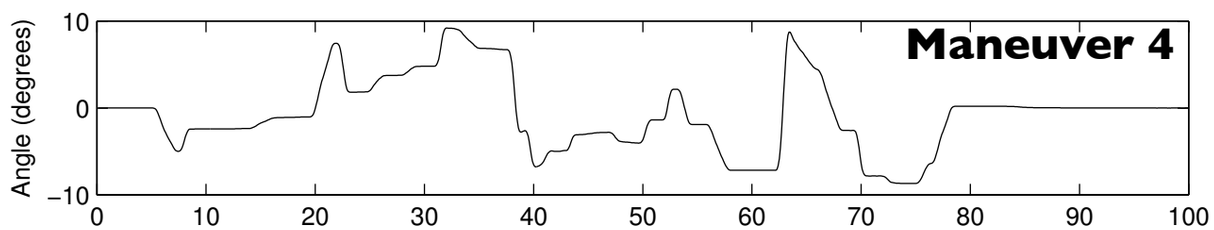


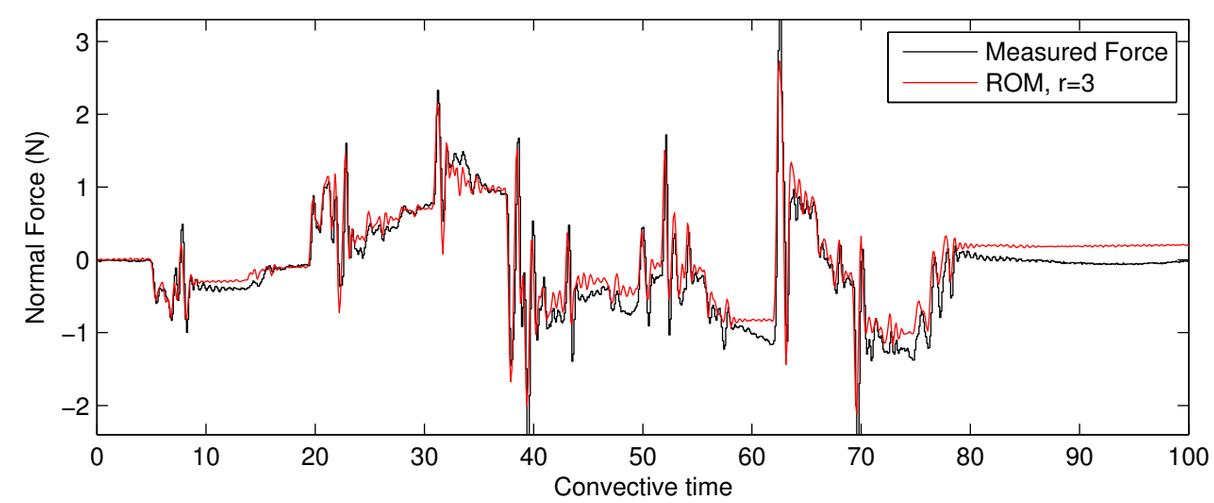




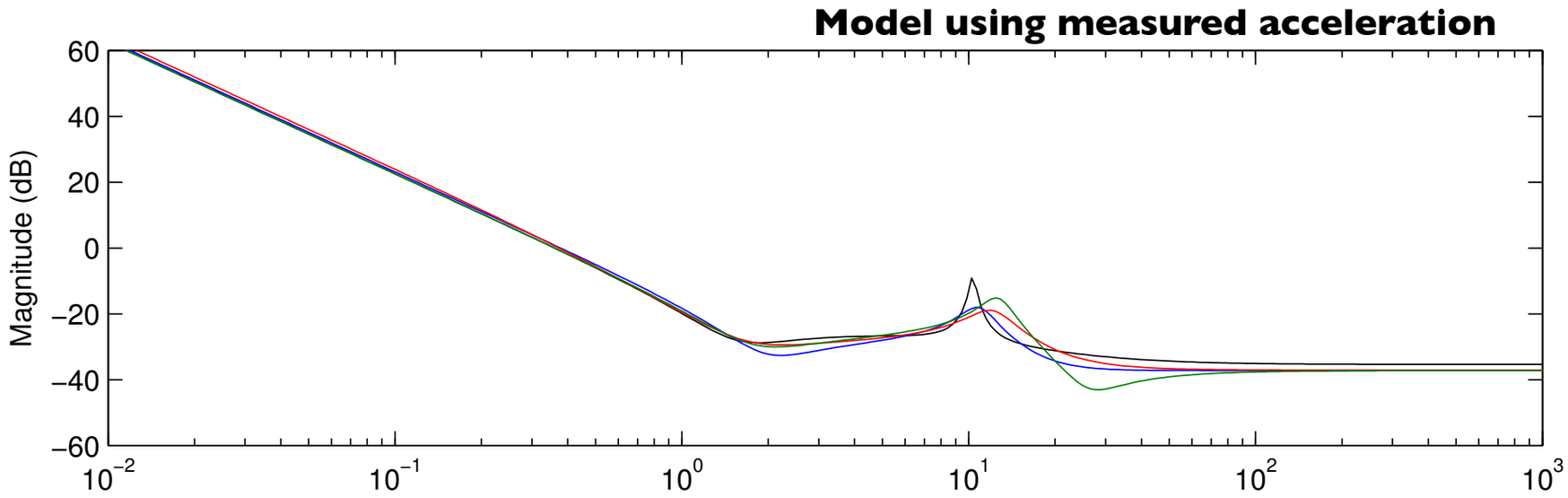


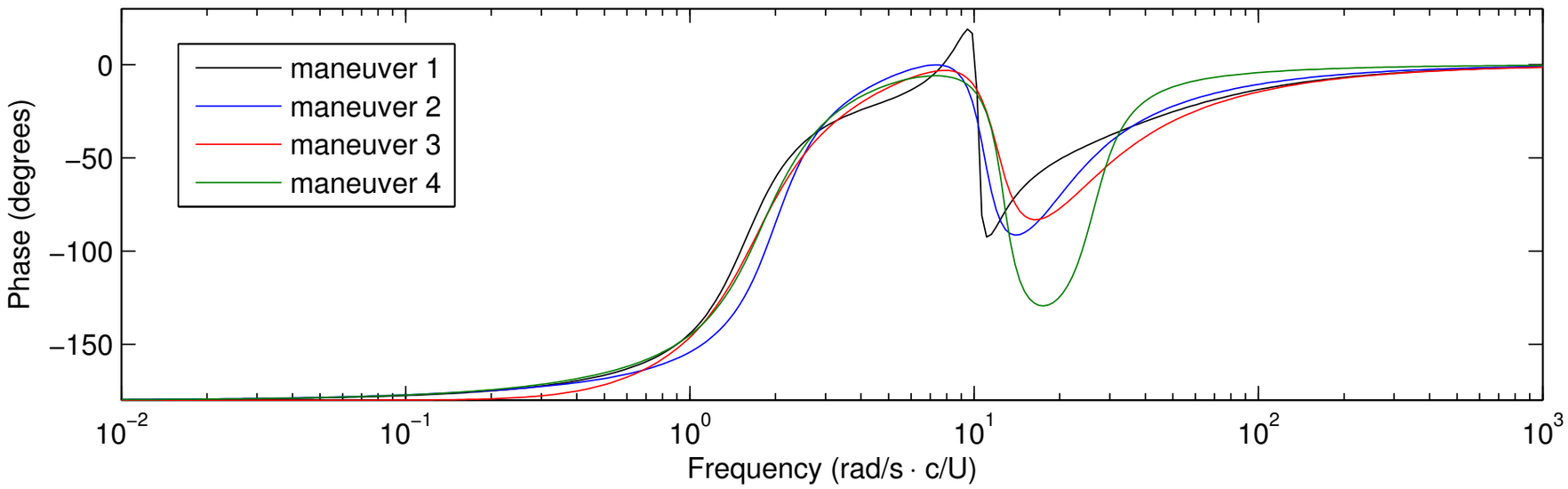






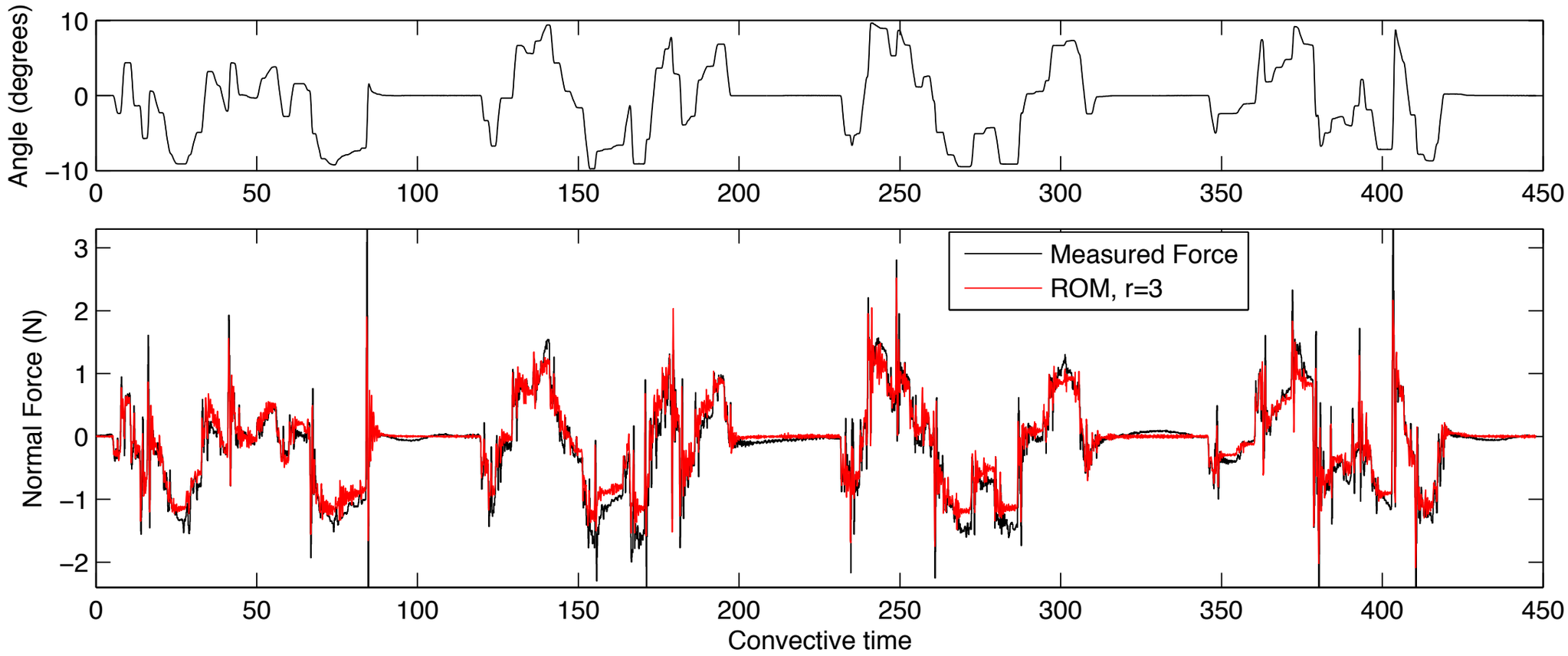
Bode Plots for AoA=0

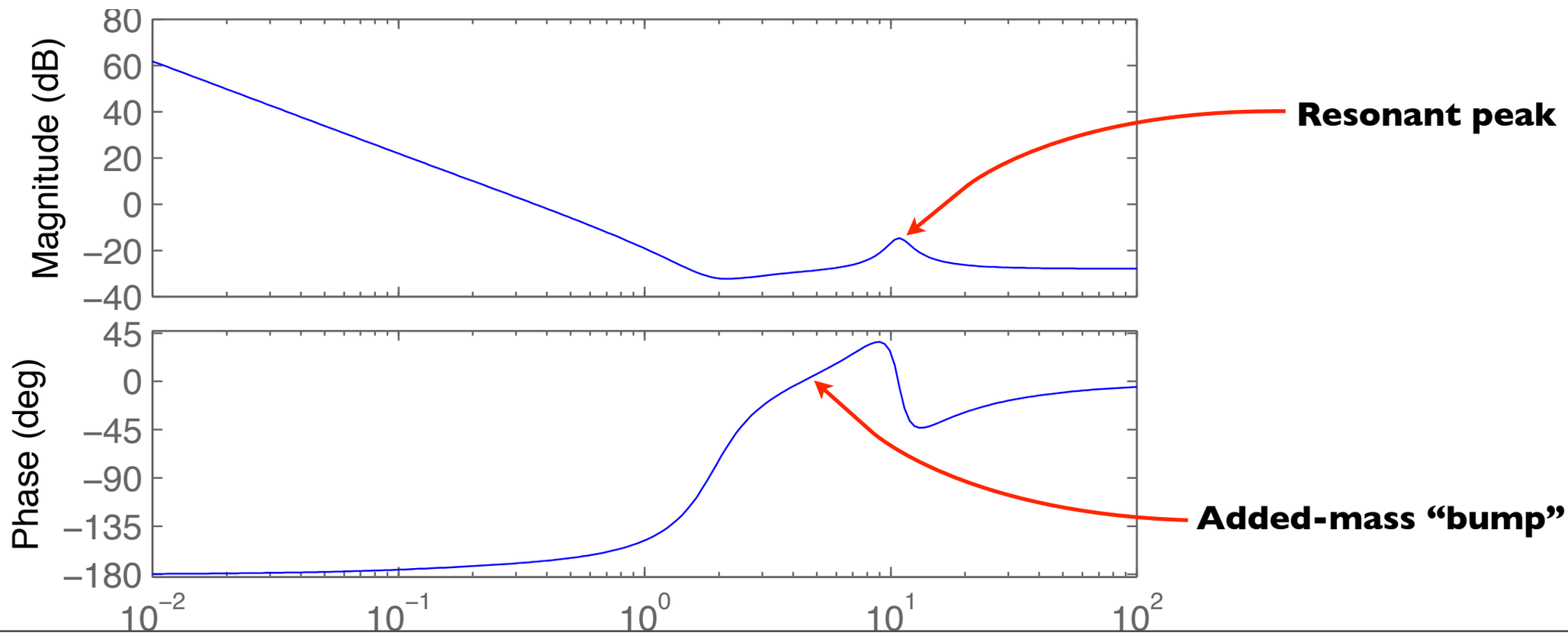




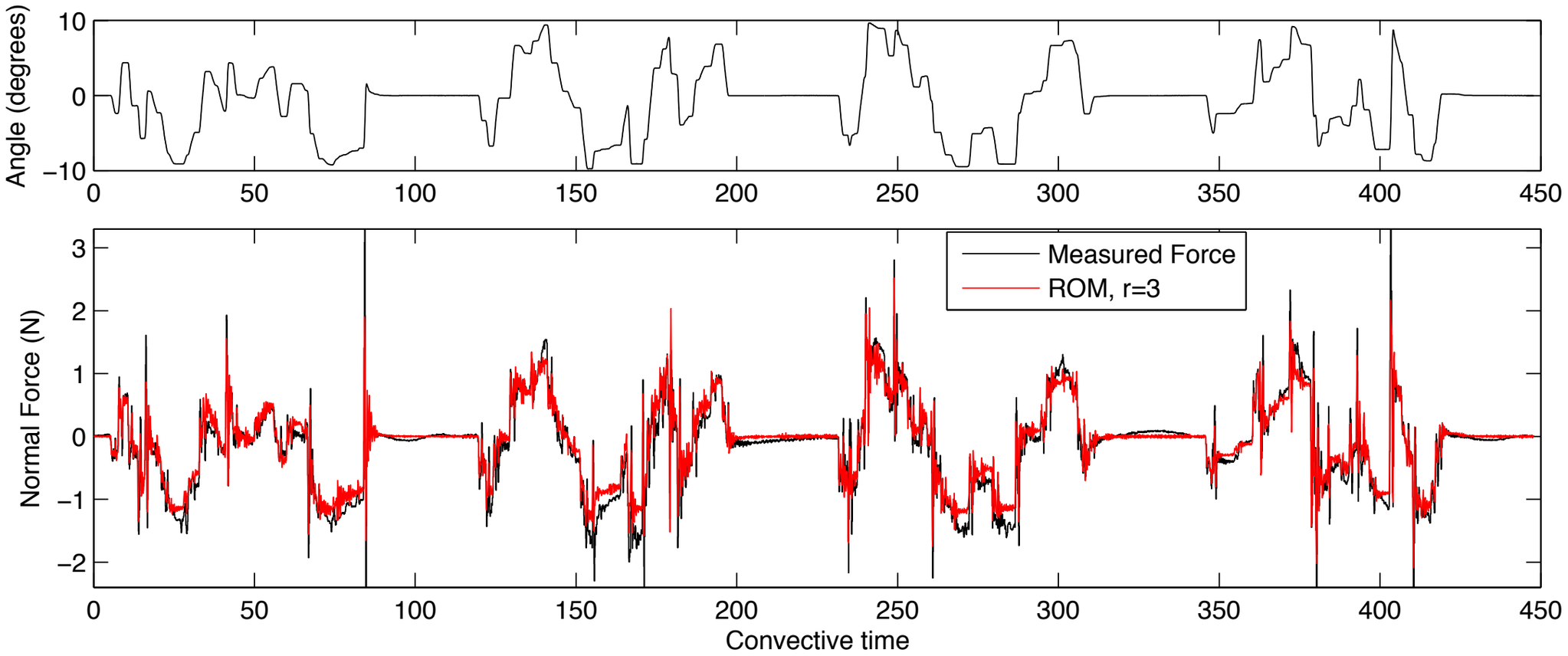
Idea: lets combine all maneuvers into one large system ID maneuver!

Bode Plot for AoA=0

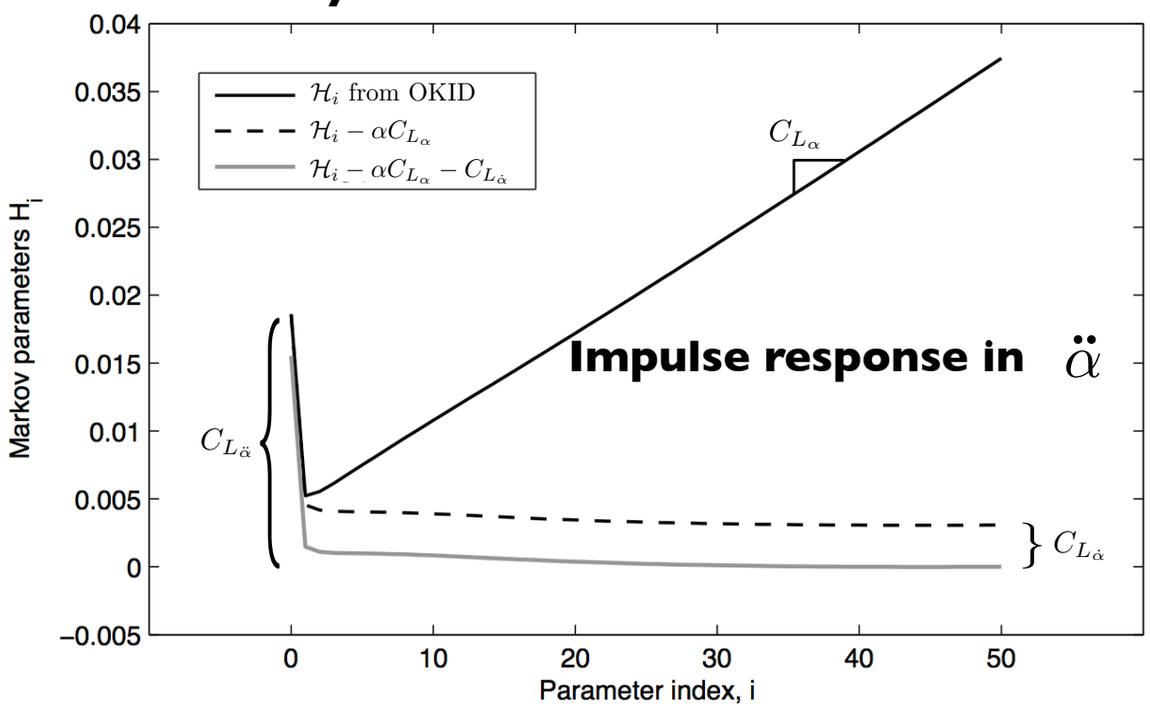




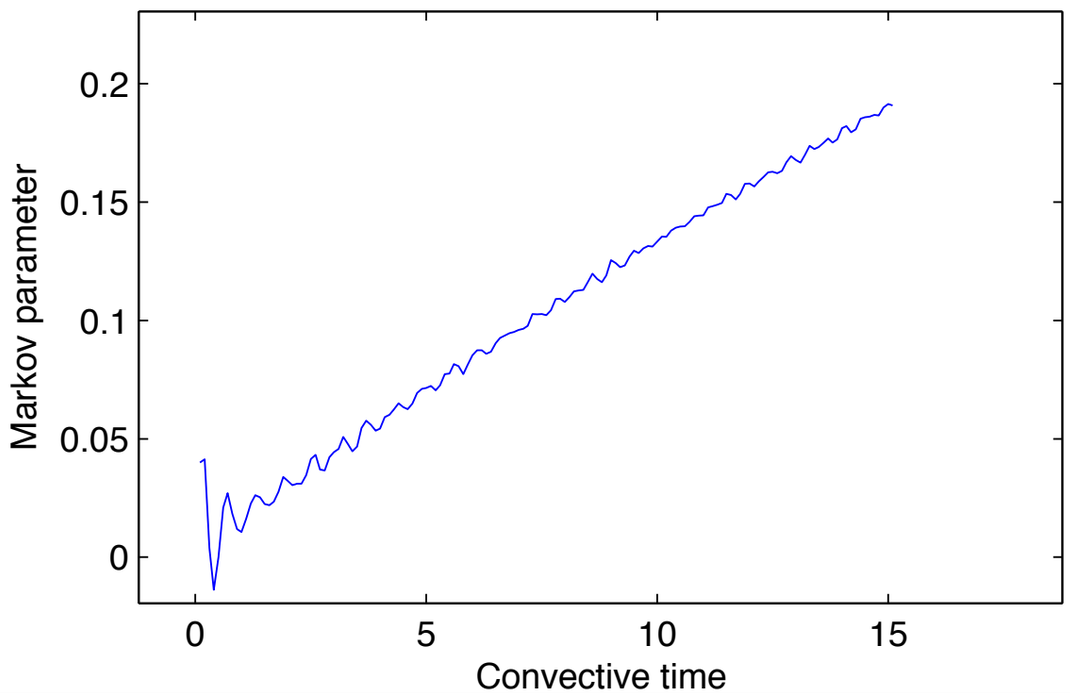
Model using ALL data



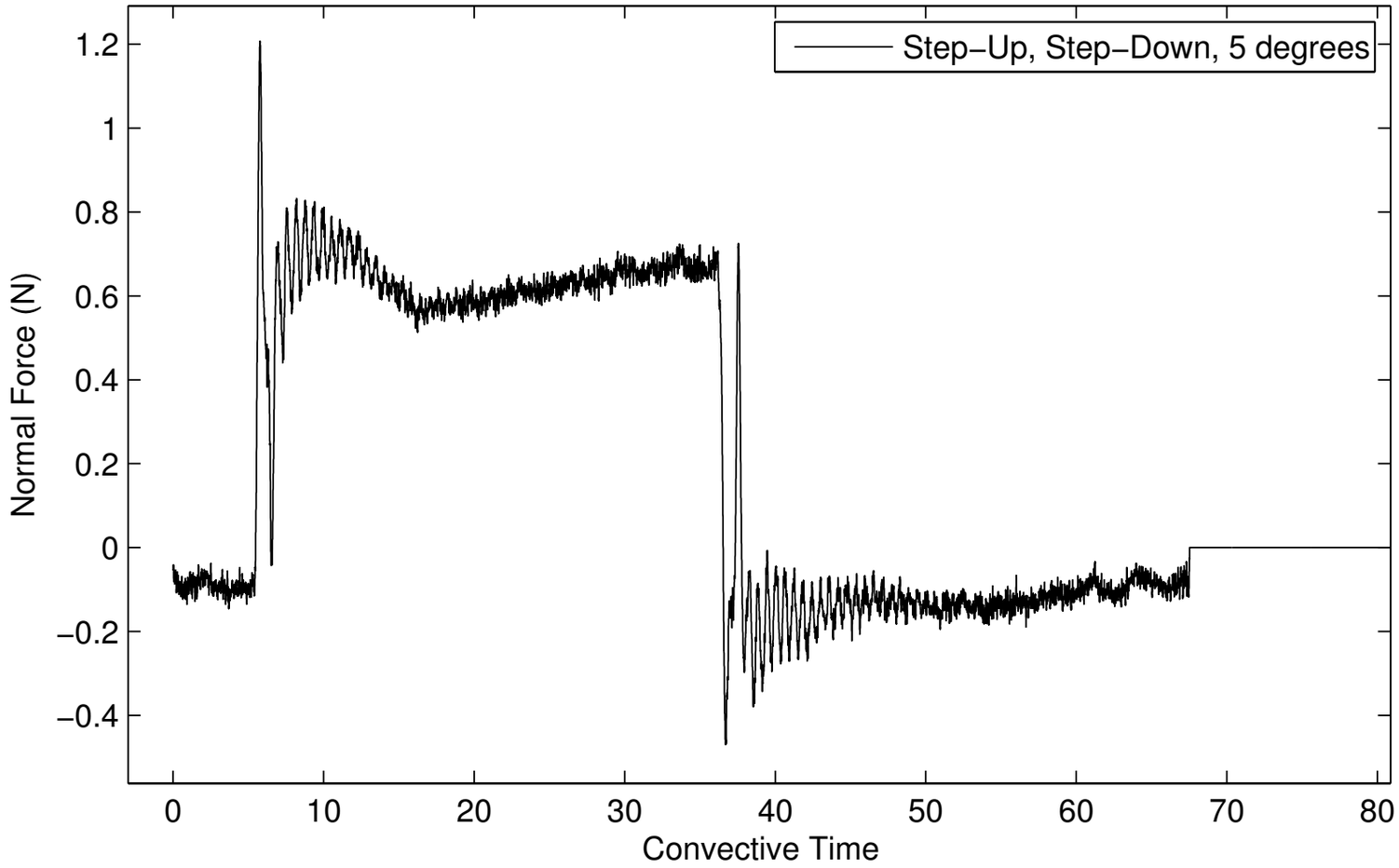
Theory



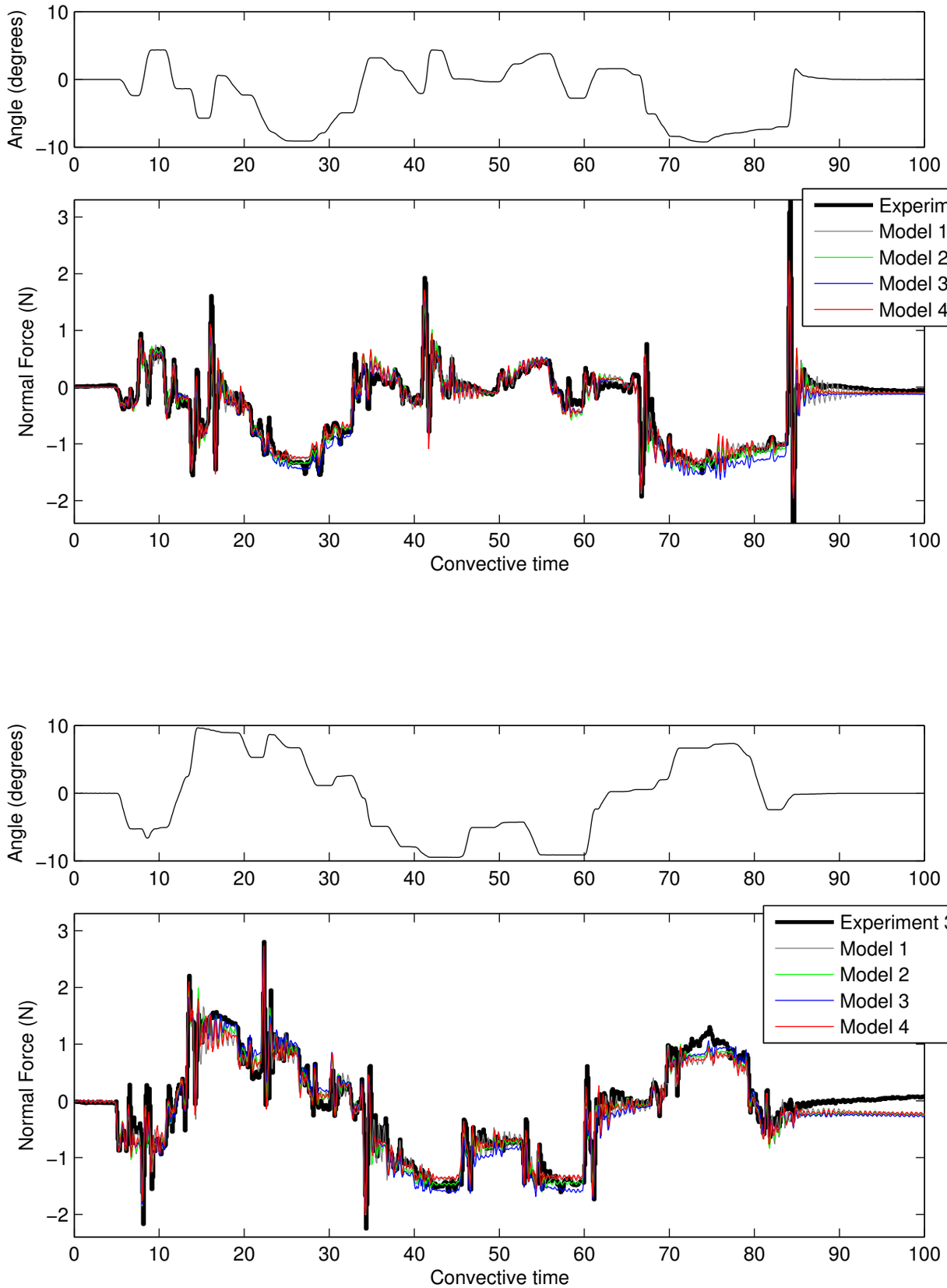
Experimental

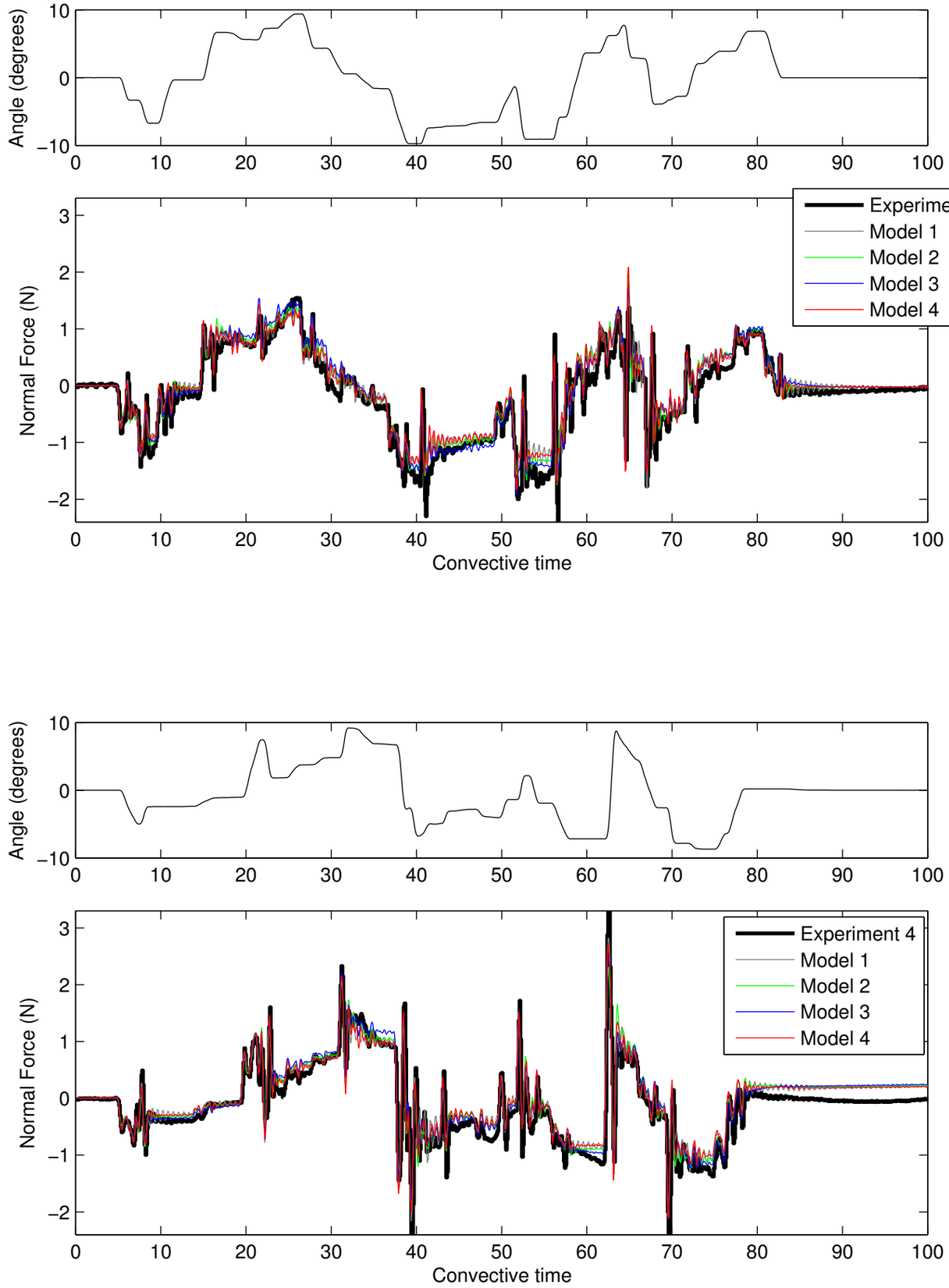


30Hz Mechanical Oscillation

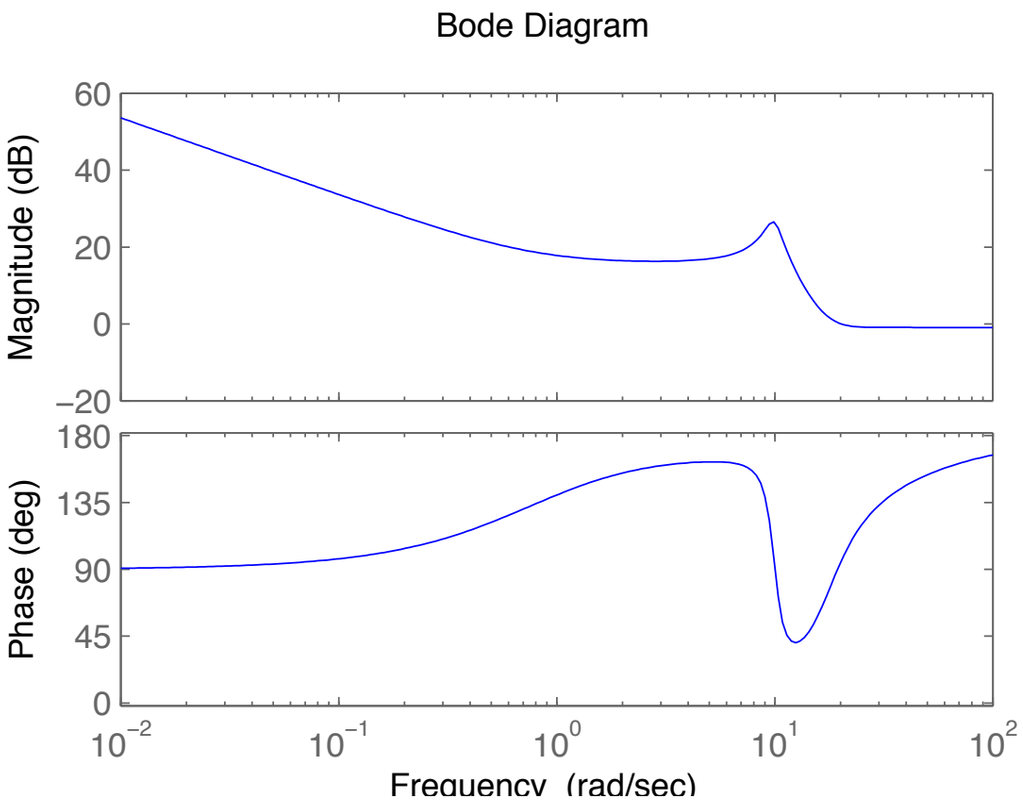


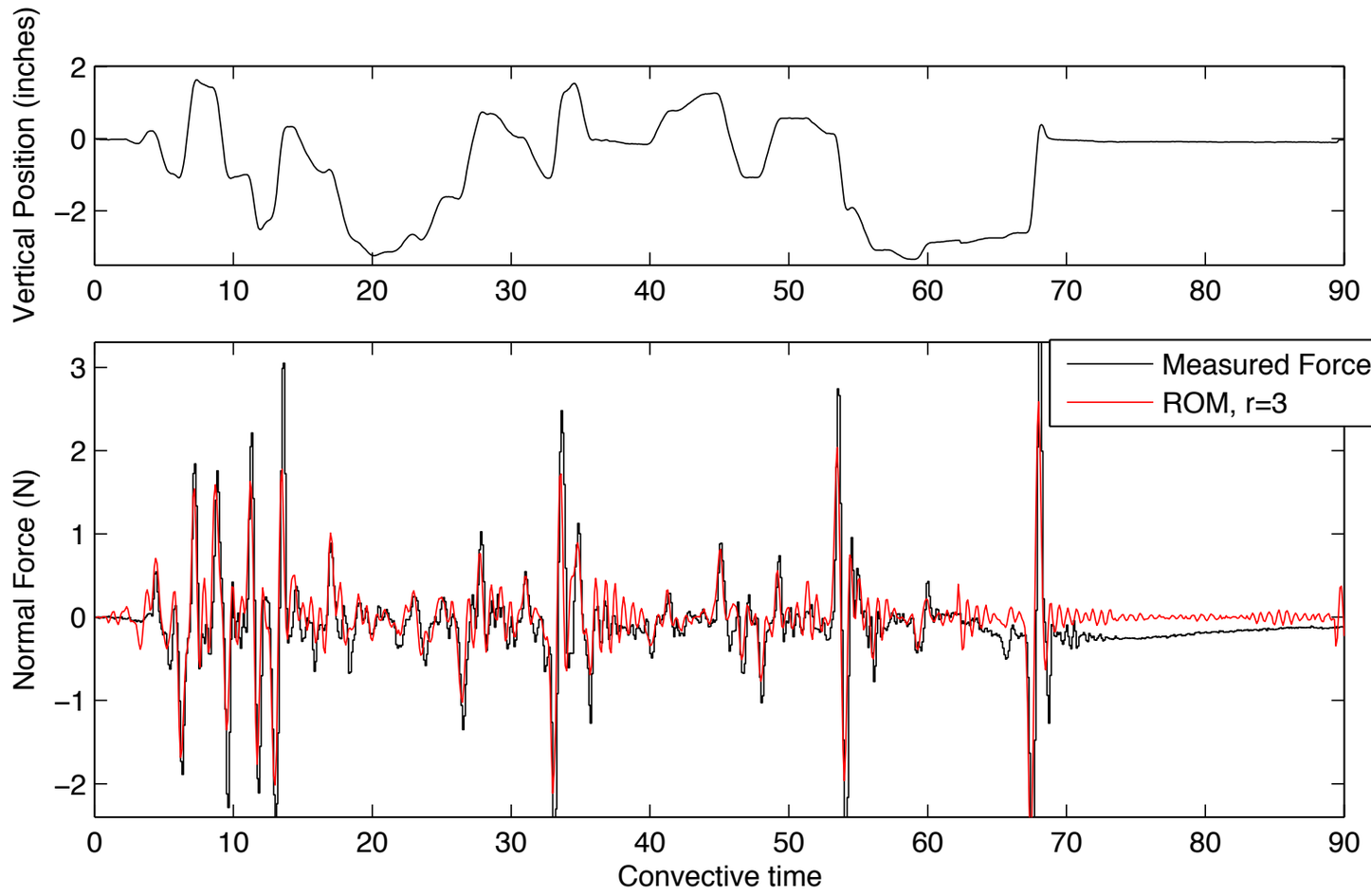
Models agree with data





Model for Plunging





Conclusions

Reduced order model based on indicial response at non-zero angle of attack

- Based on eigensystem realization algorithm (ERA)
- Models appear to capture dynamics up to Hopf bifurcation

Observer/Kalman Filter Identification with more realistic input/output data

- Efficient computation of reduced-order models
- Ideal for simulation or experimental data

Confirmation with experimental data

- Tested modeling procedure in Dave Williams' wind tunnel experiment
- Flexible procedure works with various geometry, Reynolds number

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Wagner, 1925.

Theodorsen, 1935.

Leishman, 2006.

OL, Altman, Eldredge, Garmann, and Lian, 2010

Brunton and Rowley, AIAA ASM 2009-2011

Juang and Pappa, 1985.

Ma, Ahuja, Rowley, 2010.

Juang, Phan, Horta, Longman, 1991.