Aeroelasticity in Dynamically Pitching Wind Turbine Airfoils

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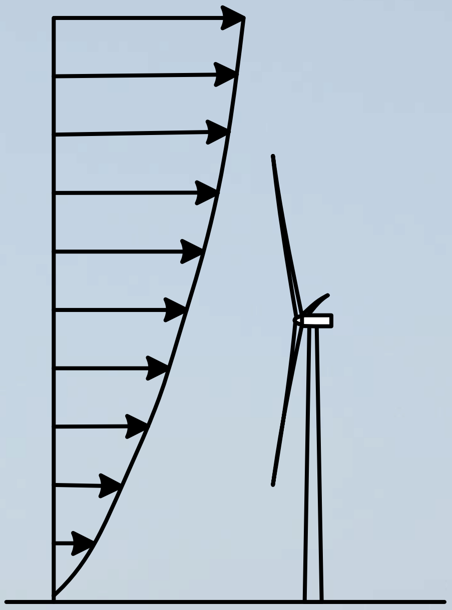
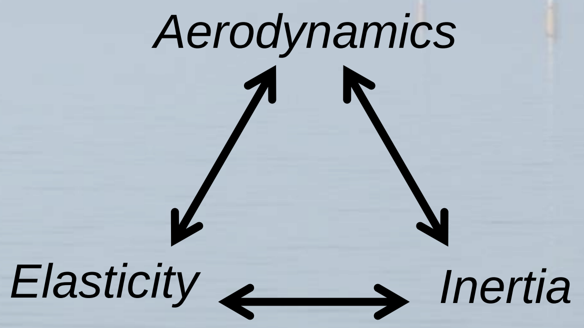
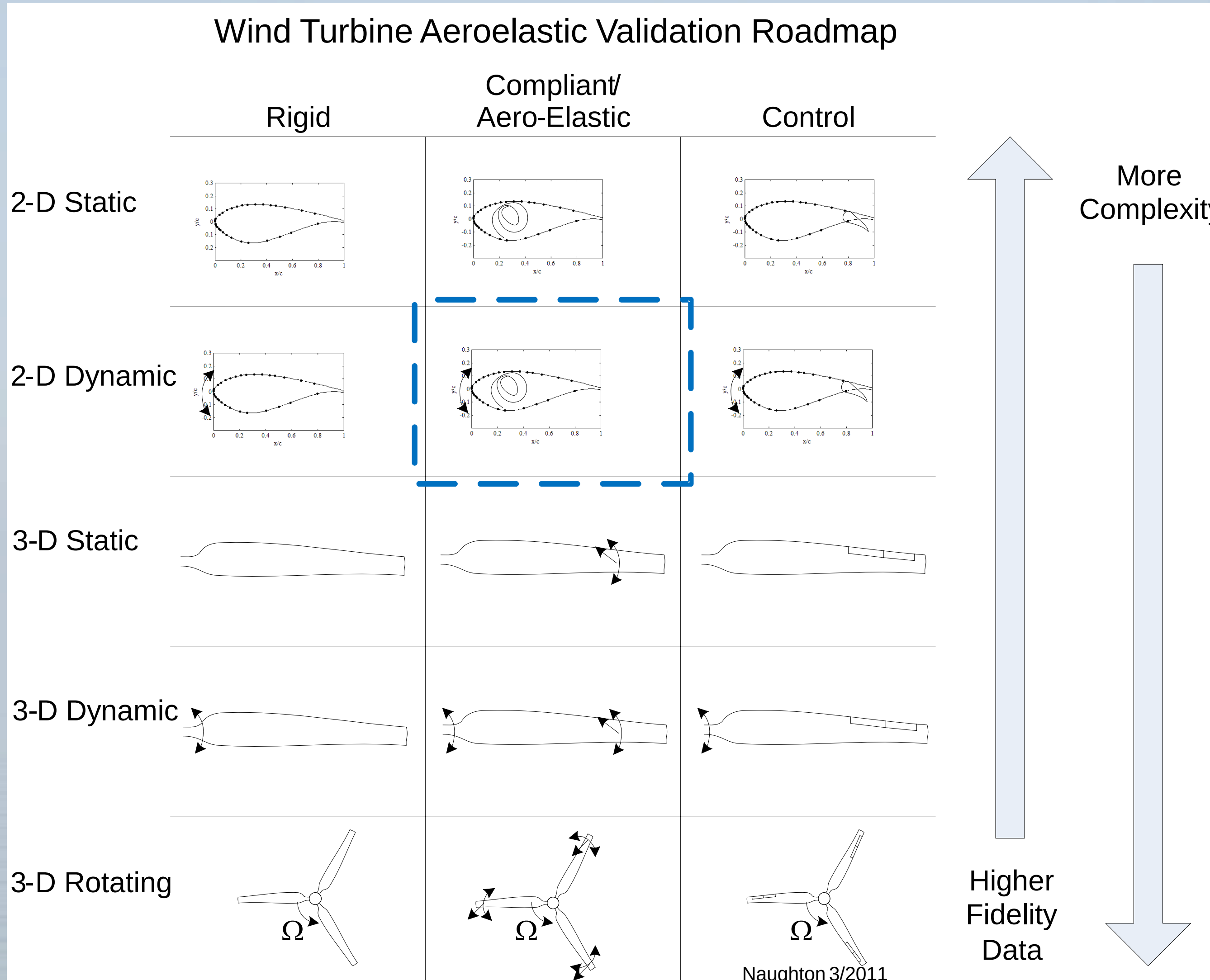
Motivation



- **Wind turbines are growing larger**
  - Market demands cheaper energy
  - Increased blade size (blades proposed ~100 m)
    - **Decreased relative stiffness**
    - **Aeroelasticity becomes major concern**
- **Varying inflow conditions produce well-known unsteady aerodynamics**
  - Shear & turbulence in Atmospheric Boundary Layer
  - Yawed operating conditions
- **Aeroelastic system comprised of nonlinear components**
  - Complex & difficult to understand
  - Tough to numerically model
  - Need for experimental investigation
    - **Validation of models**



Motivation
Validation & Verification



Objectives & Approach

Research Goals

- Investigate and characterize the effects of elastic compliance
  - Airfoil Response
  - Aerodynamics
- Understand how compliance affects the wind turbine system
  - Dynamic Loading
  - Stall Flutter, LCOs?

Experimental Means

- Single d-o-f system considered
  - $I\ddot{\alpha} + b\dot{\phi} + k_{\phi}\phi = M$
  - All forces ~ Order of Magnitude
- Driven pitch oscillations produce dynamic stall in wind tunnel
- Compliant spring section designed & characterized
- Rigid and compliant systems contrasted

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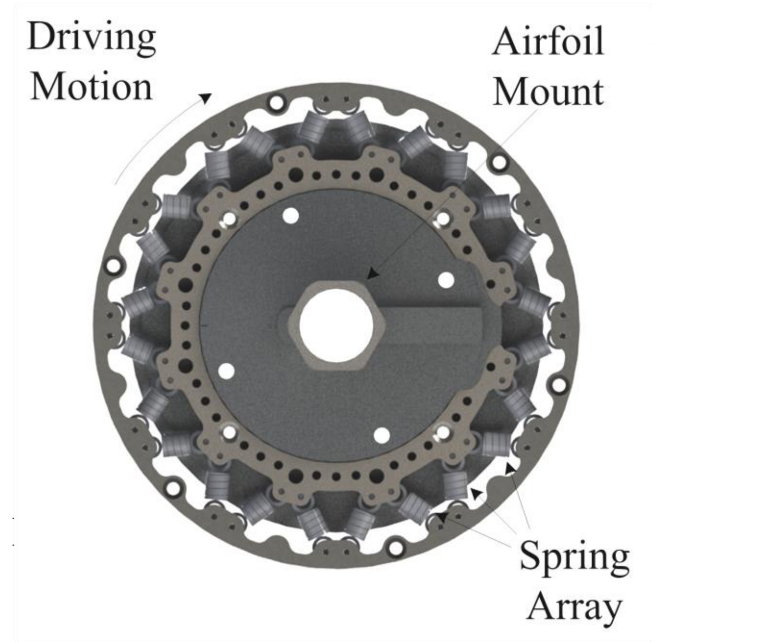
Experimental Setup
Mechanical System

UW's Low Speed Wind Tunnel

- Operational range up to 50 m/s
- 0.61 x 0.61 x 1.22 m test section
- 0.3% free-stream turbulence



Pitching System

- 24V DC driving motor
  - PID algorithm, flywheel, & PWM maintain constant frequency
- Cam & push rod for sinusoidal pitch cycles

Compliance

- Variable Spring Stiffness
  - 16.2 N.m/rad to 389 N.m/rad
- Maximum Allowable Differential
  - $\Phi_{max} = 4.4^o$

Experimental Setup

Instrumentation

Position

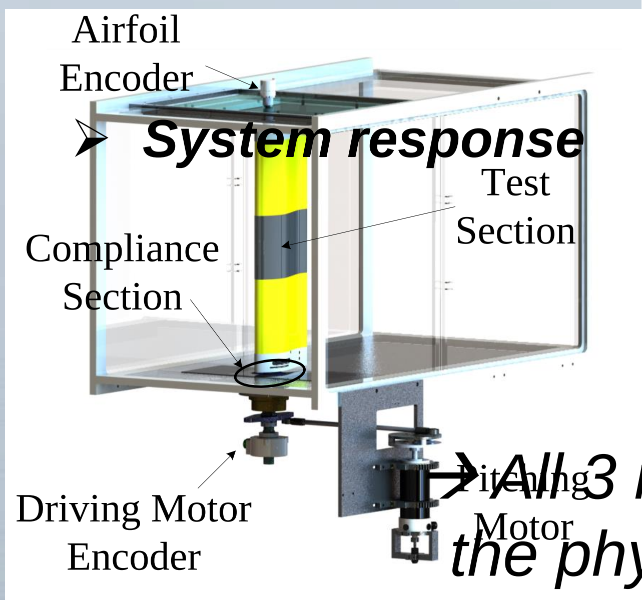
- **Two rotary encoders**
  - Airfoil
  - Driver

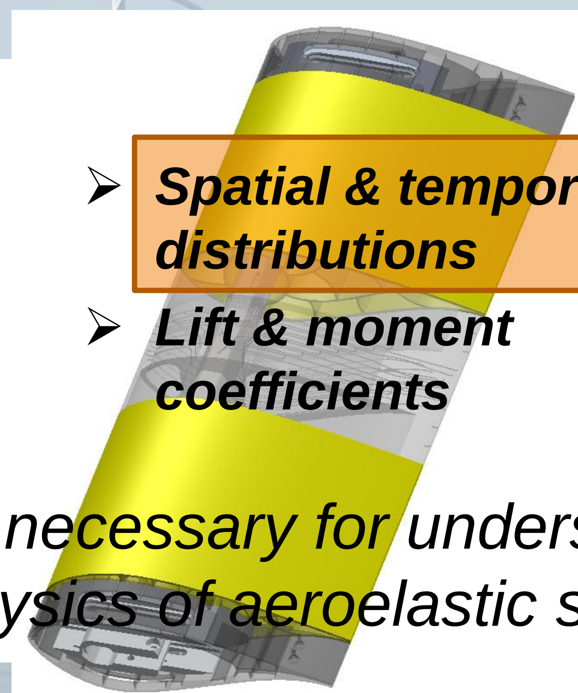
Pressure

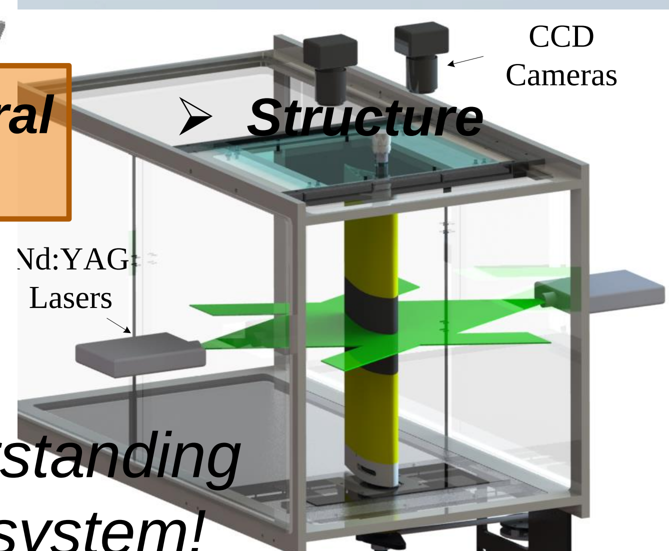
- **Remotely measure unsteady surface pressures**

Flow-field

- **Dual PIV**
- **Vector fields merged & phase-averaged**





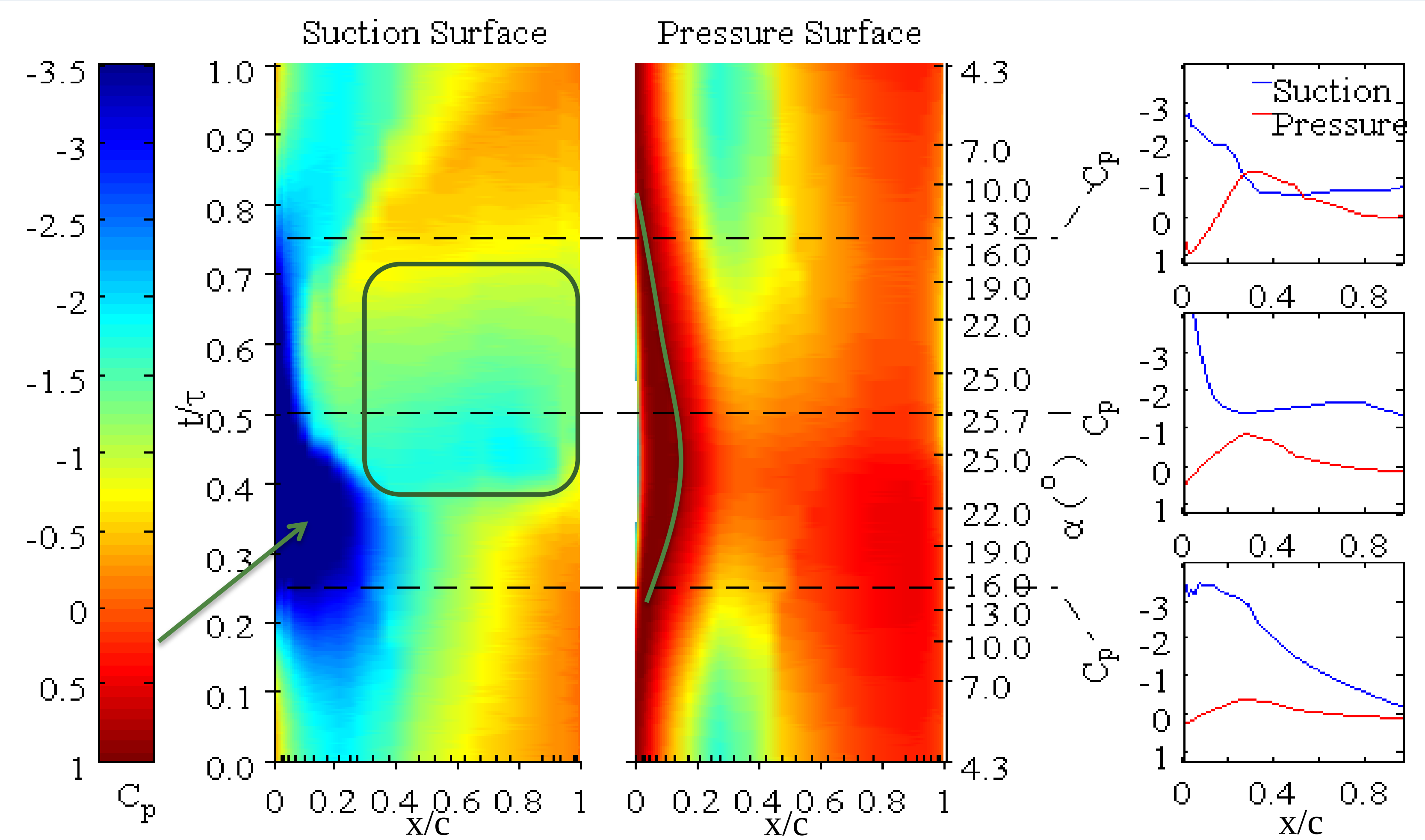


- ***System response***
- ***Spatial & temporal distributions***
- ***Lift & moment coefficients***
- ***Structure***

→ *All 3 necessary for understanding the physics of aeroelastic system!*

Experimental Setup

Dynamic Pressure Distribution



Case 9: α = 15°±10° @ 12 Hz (k =0.17) , k_φ= 194.4 N·m/rad

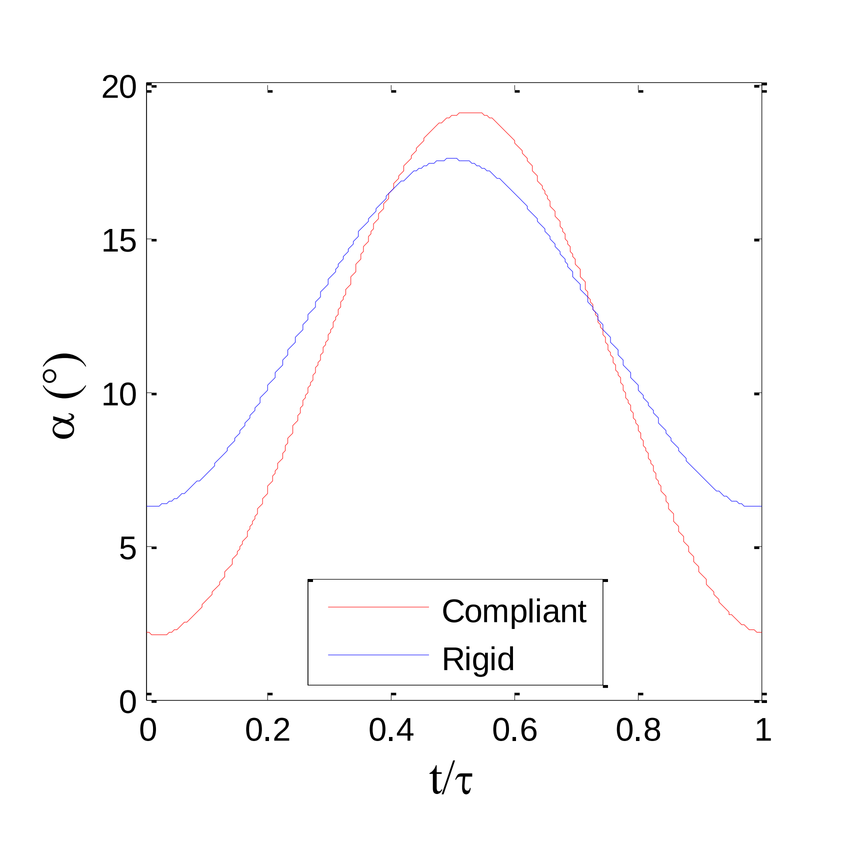
Experimental Setup
Test Cases

- **All cases operated under the following test conditions:**
  - Chord, $C = .203\ m$
  - Reynolds Number, $Re_c = 4.4x10^5$
  - Flexural Axis, $FA = c/4$
  - Moment of Inertia, $I = 6.5x10^{-3} kg \cdot m^2$
- **Spring stiffness was arrived at by maximizing the differential angle while oscillating**
- **Rigid & compliant data taken for each case**
- **Cases 2 - 4 suggested flow structure may start to deviate**
- **Focus on Case 5:** ***$\alpha = 10^o \pm 5^o$ @ 15 Hz → $\alpha = 12^o \pm 5^o$ @ 15 Hz***

	Fully Attached	Moderate Stall				Deep Stall			
Case	1	2	3	4	5	6	7	8	9
α_{mean} (°)	8	10	10	10	12	15	15	15	15
α_{amp} (°)	4	5	5	5	5	10	10	10	10
k	.21	.12	.16	.21	.21	.07	.11	.14	.17
k_ϕ ($\frac{N \cdot m}{rad}$)	113.4	65.6	129.6	129.6	129.6	81.0	97.2	145.8	194.4

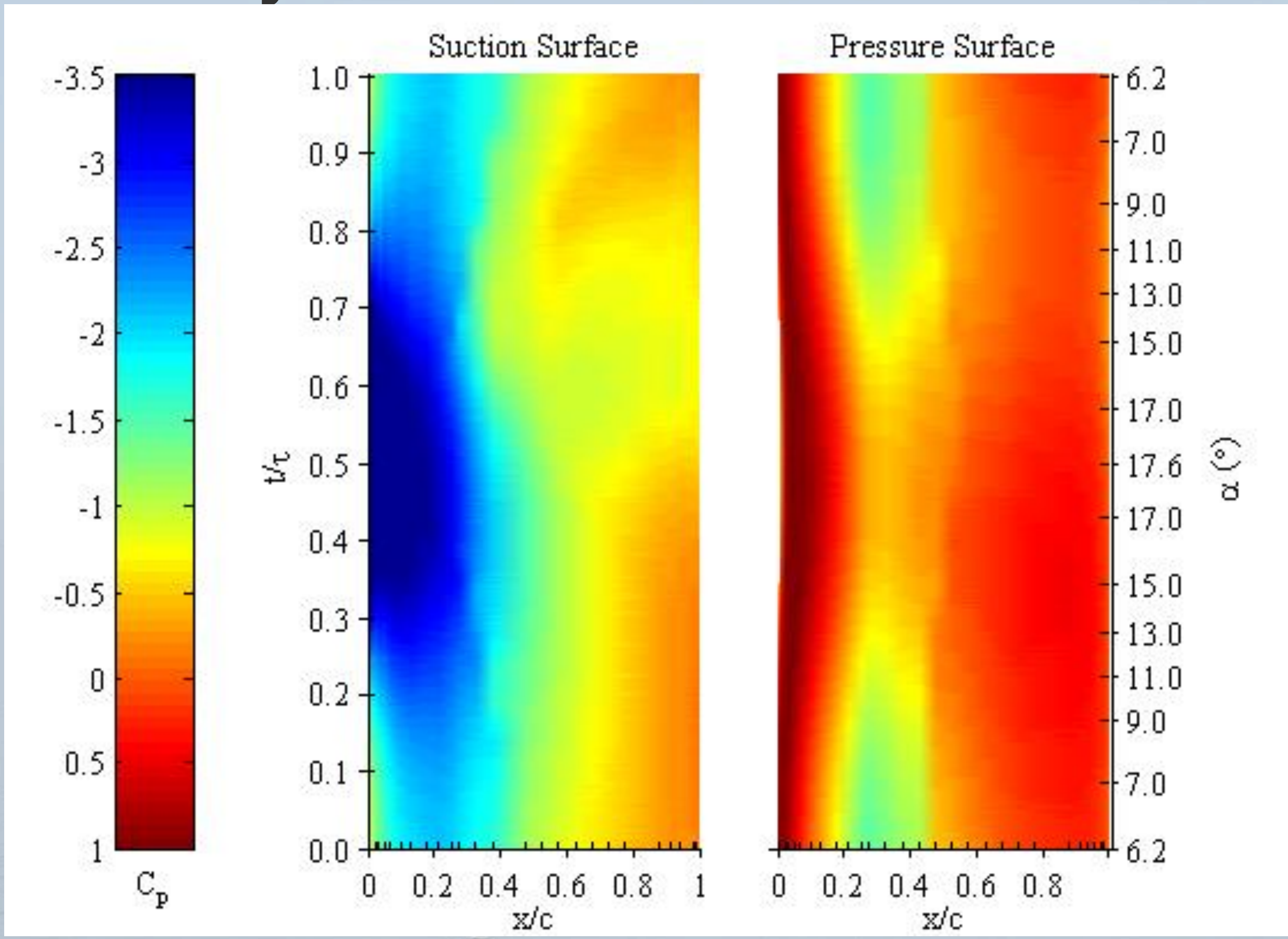
Results
Aeroelastic Airfoil Response

- **Static Equilibrium**
  - Mean AoA shifts
- **Inertial & Elastic Interactions**
  - More extreme AoAs experienced
  - Peak lag
  - Classic harmonic oscillator
- **Aerodynamic Influence**
  - Departure from sinusoidal curve
  - Falling slope is steeper than rising
  - Requires further investigation



Results

Dynamic Pressure Results

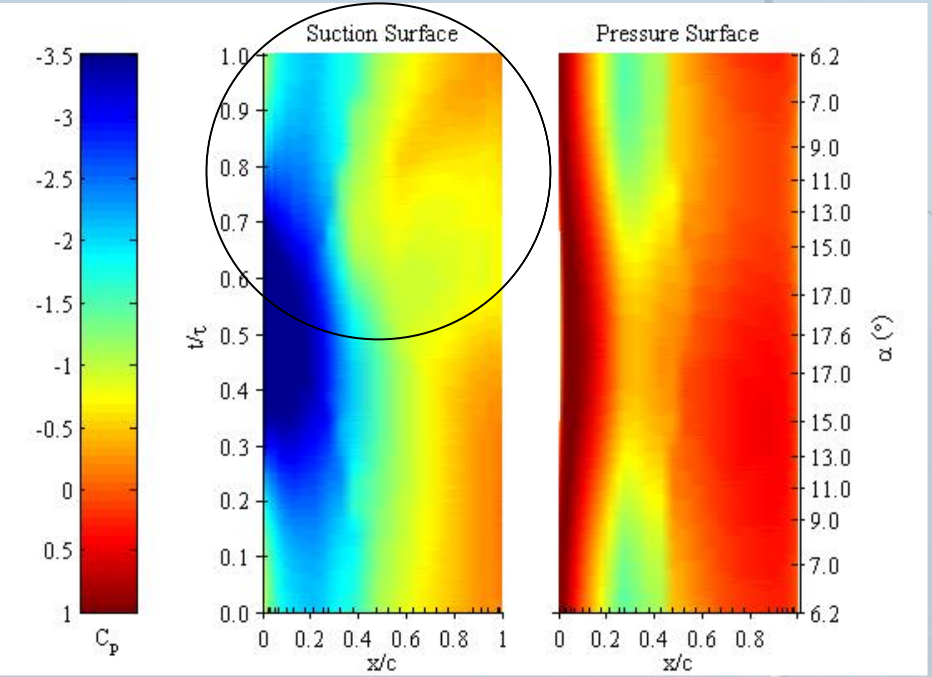


Case 5: $\alpha = 12^{o} \pm 5^{o}$ @ 15 Hz ($k = 0.21$), $k_{\varphi} = 129.6$ N·m/rad

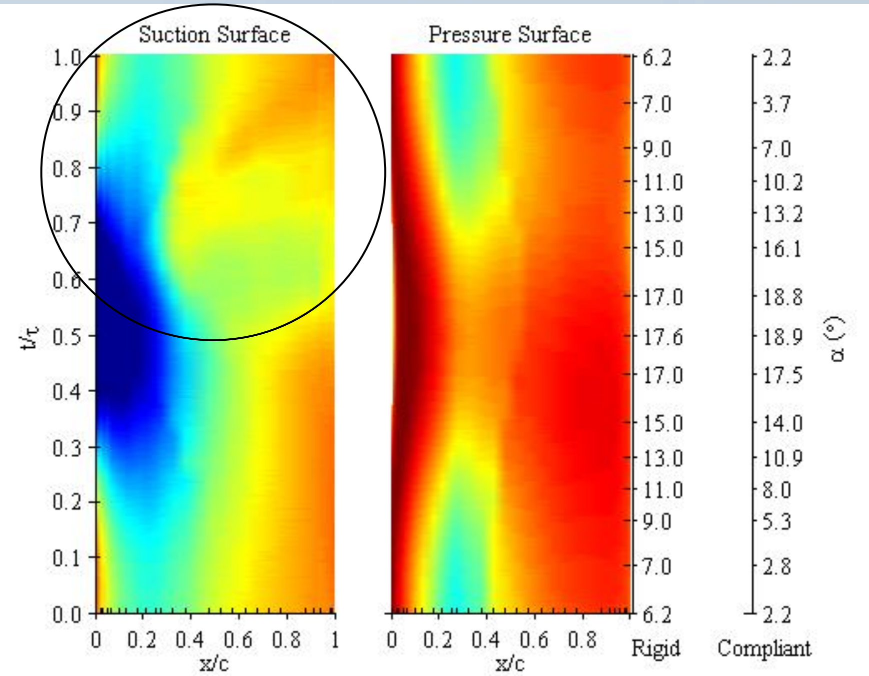
Results

Dynamic Pressure Results

Rigid Results



Compliant Results



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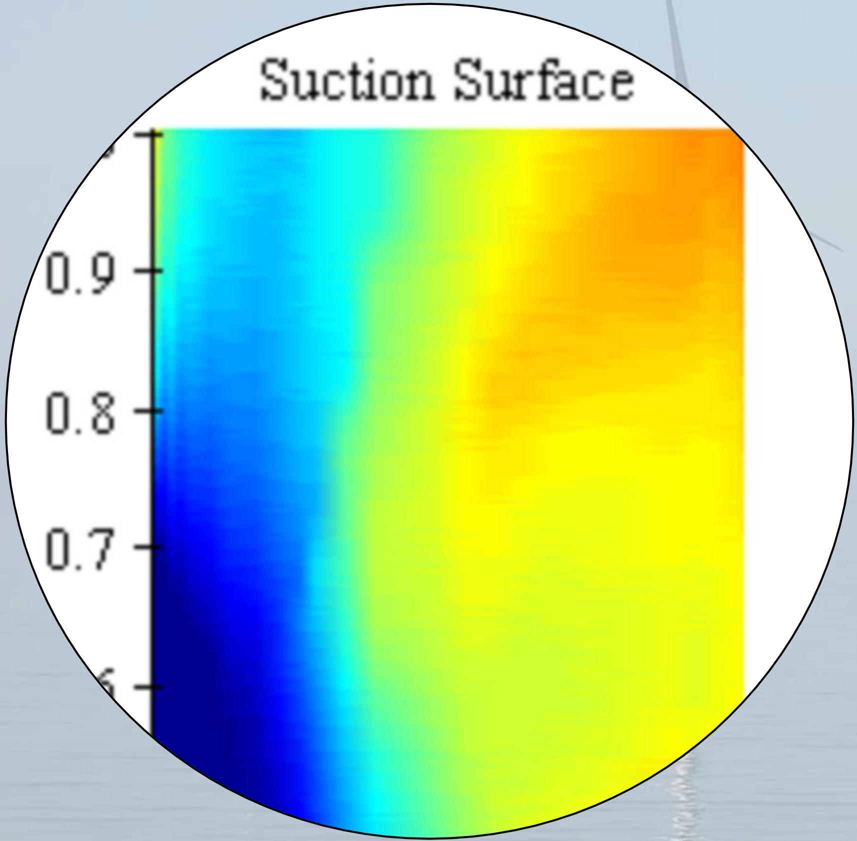
Results
Dynamic Pressure Results

Rigid Results



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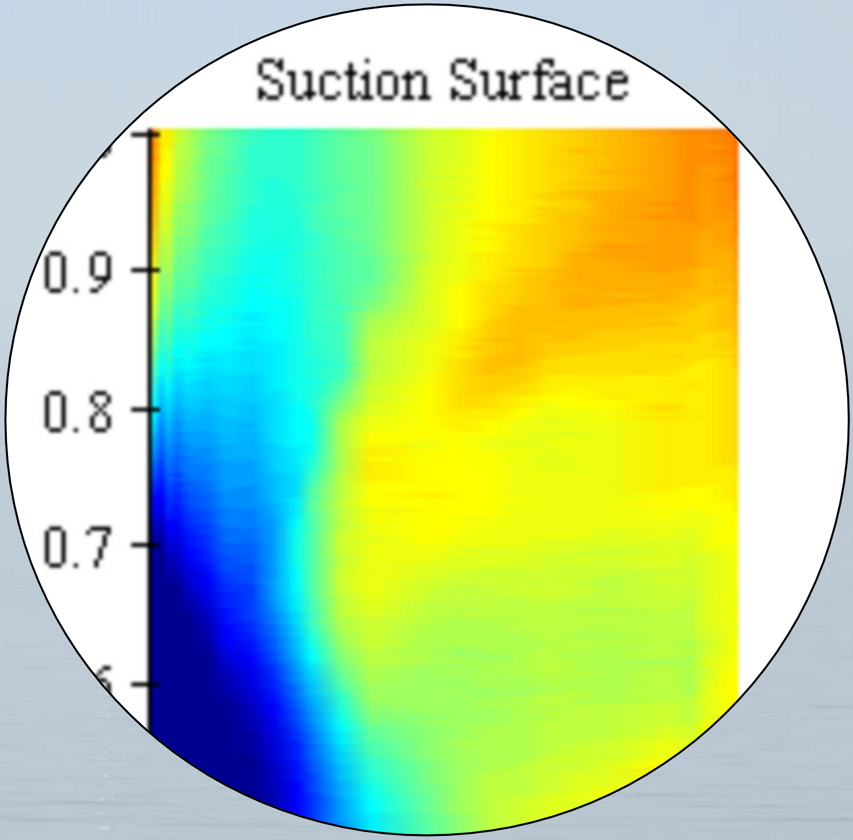

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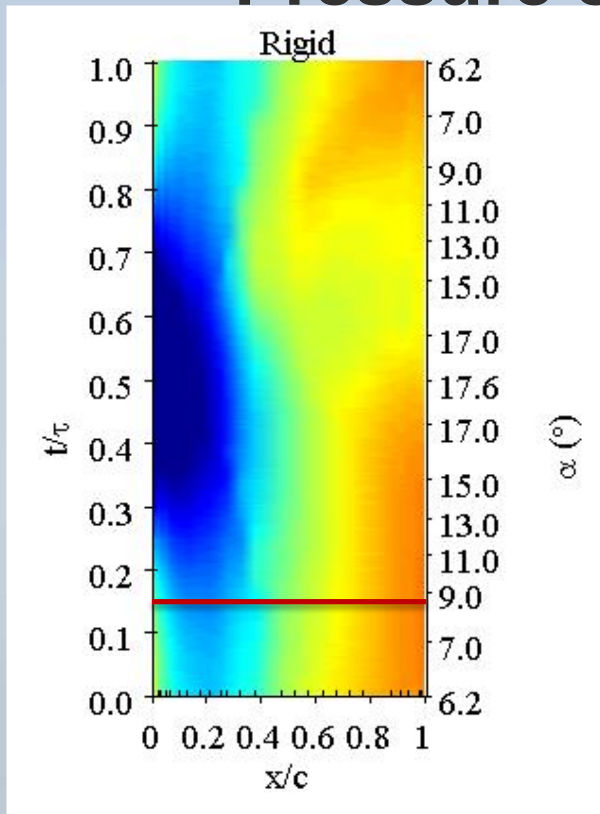
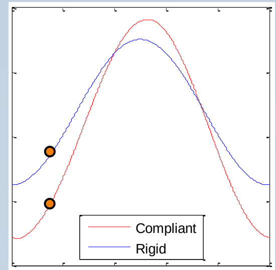
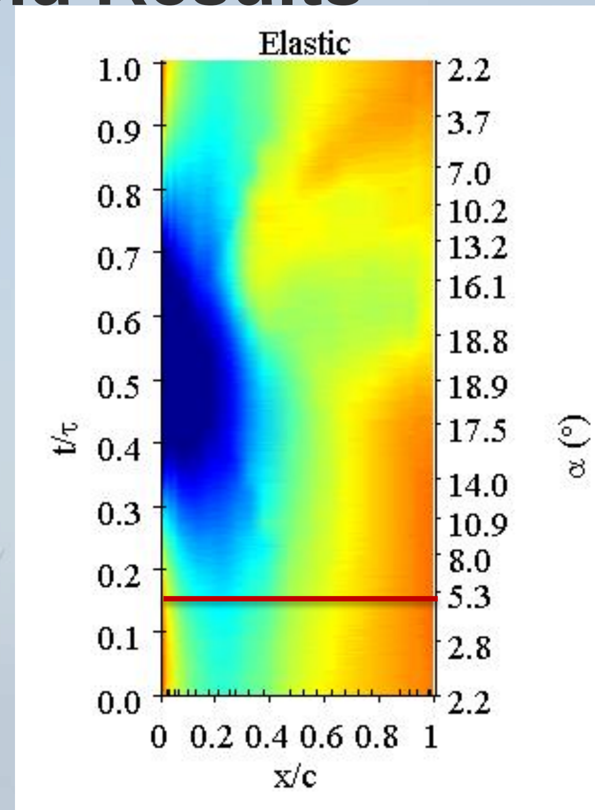
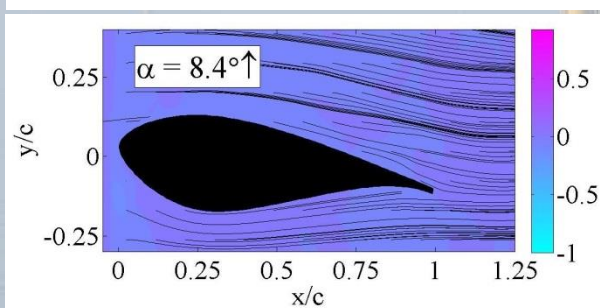
Results

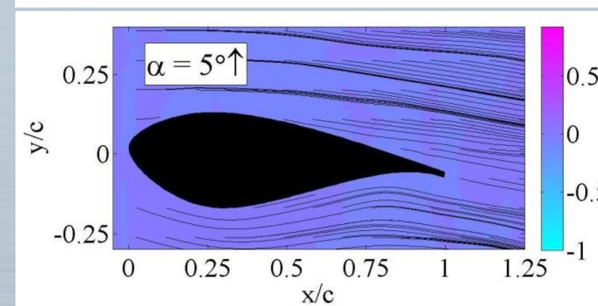
Pressure & Flow-field Results











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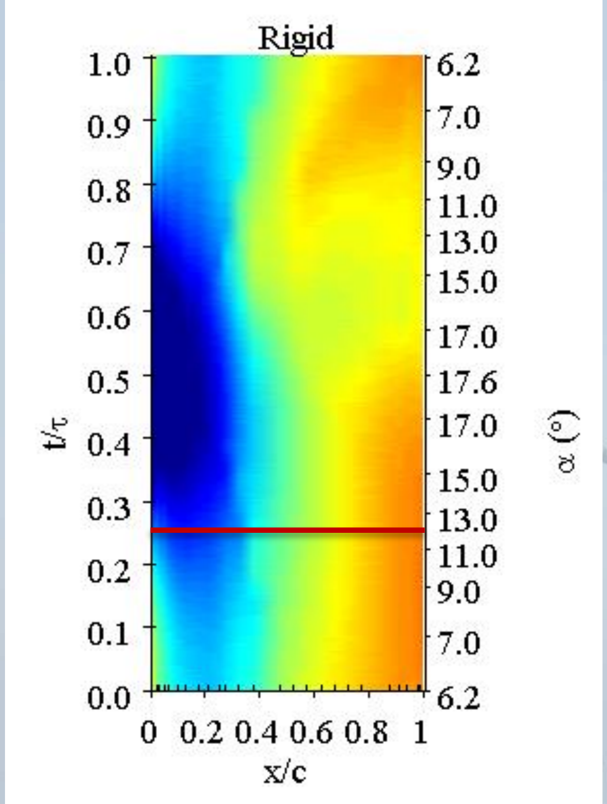
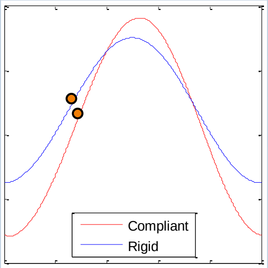
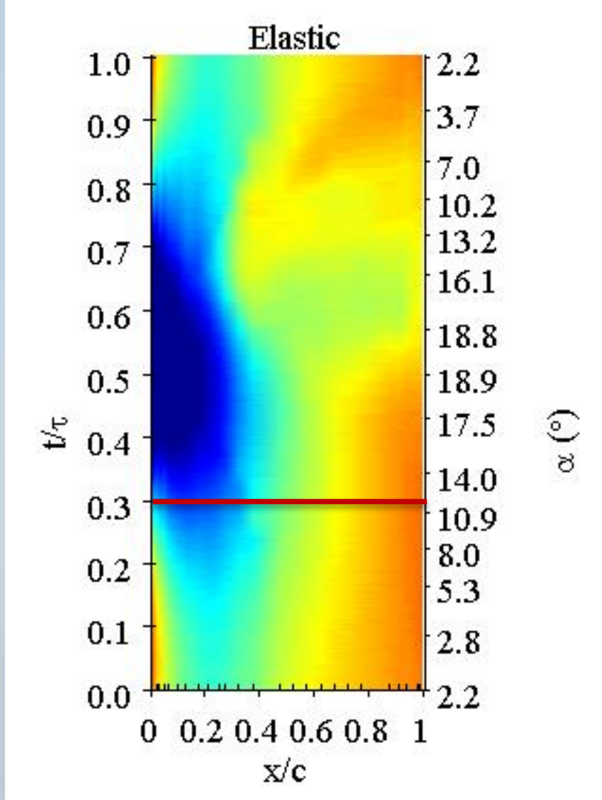
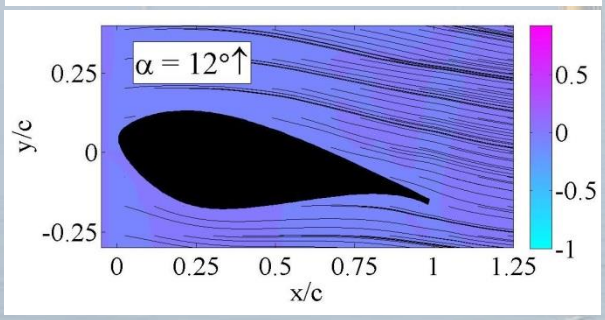
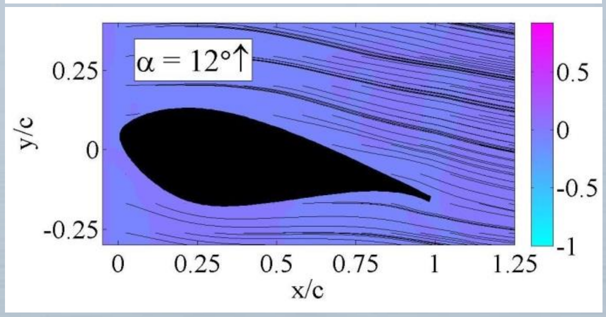
Pressure & Flow-field Results











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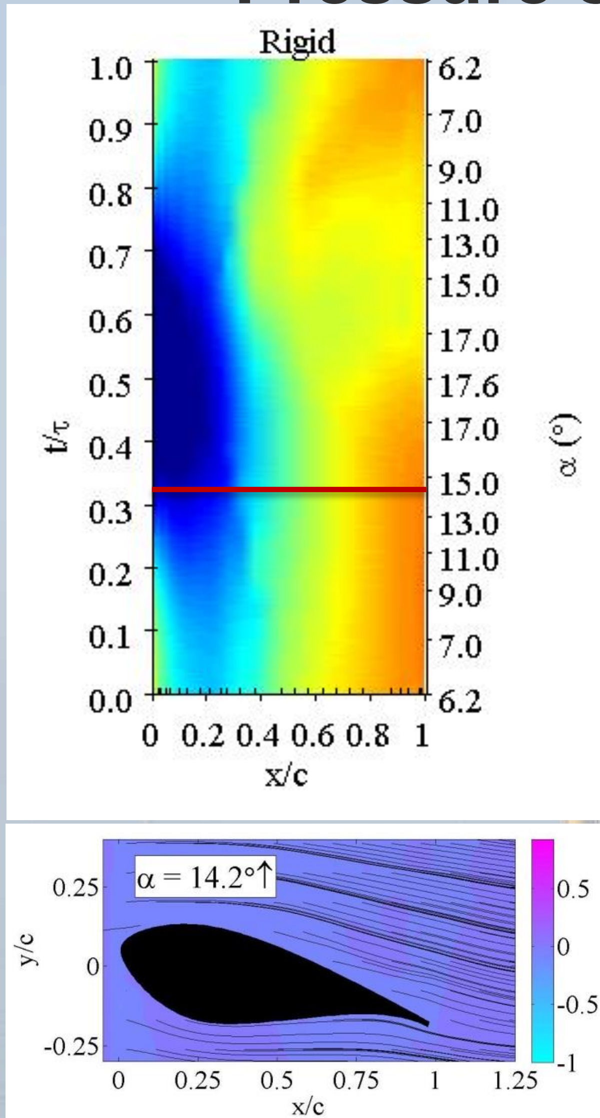
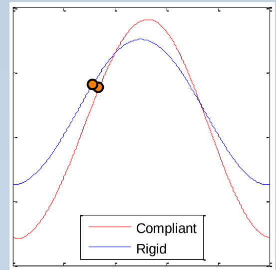
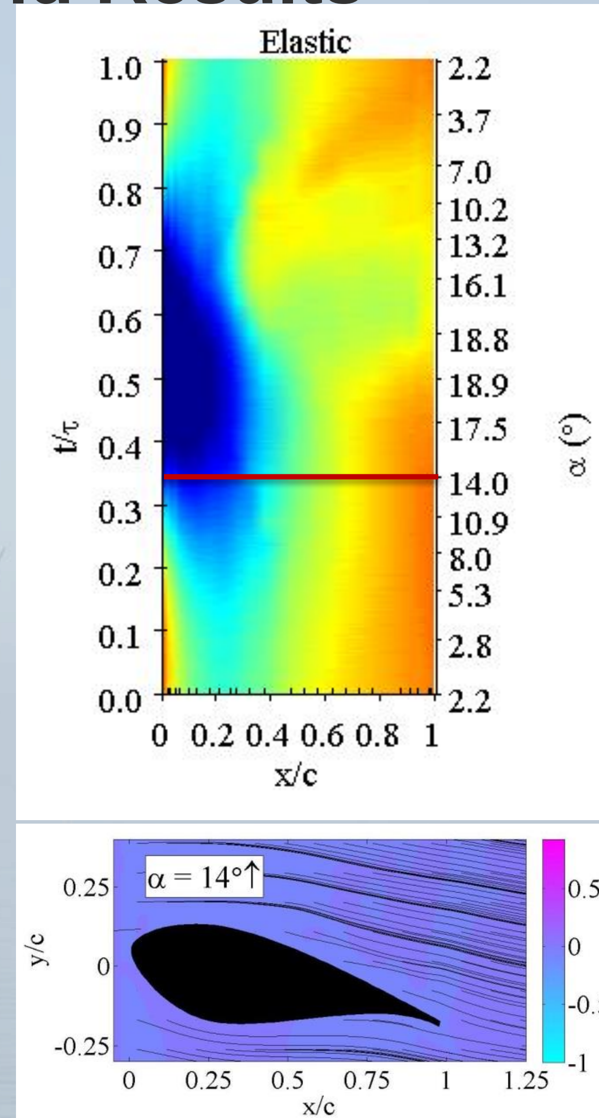
Results

Pressure & Flow-field Results







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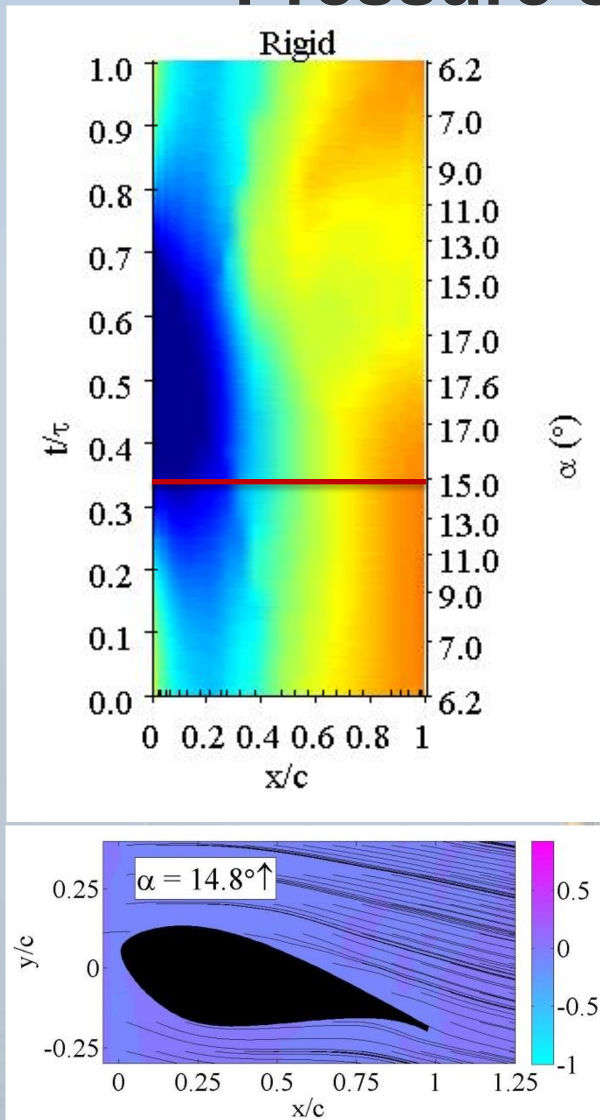

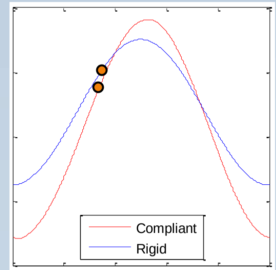

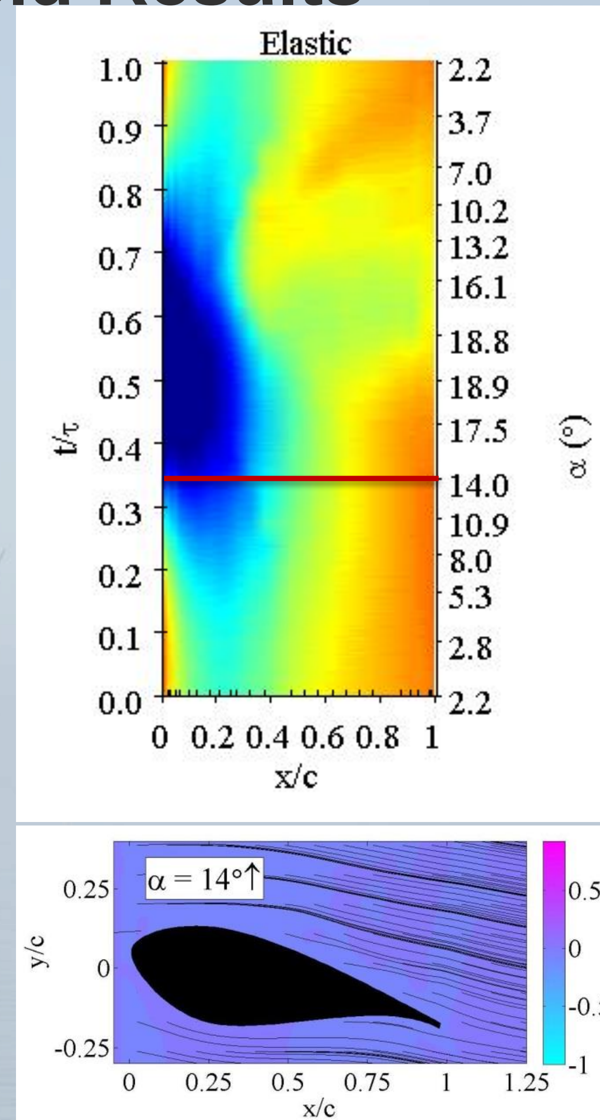

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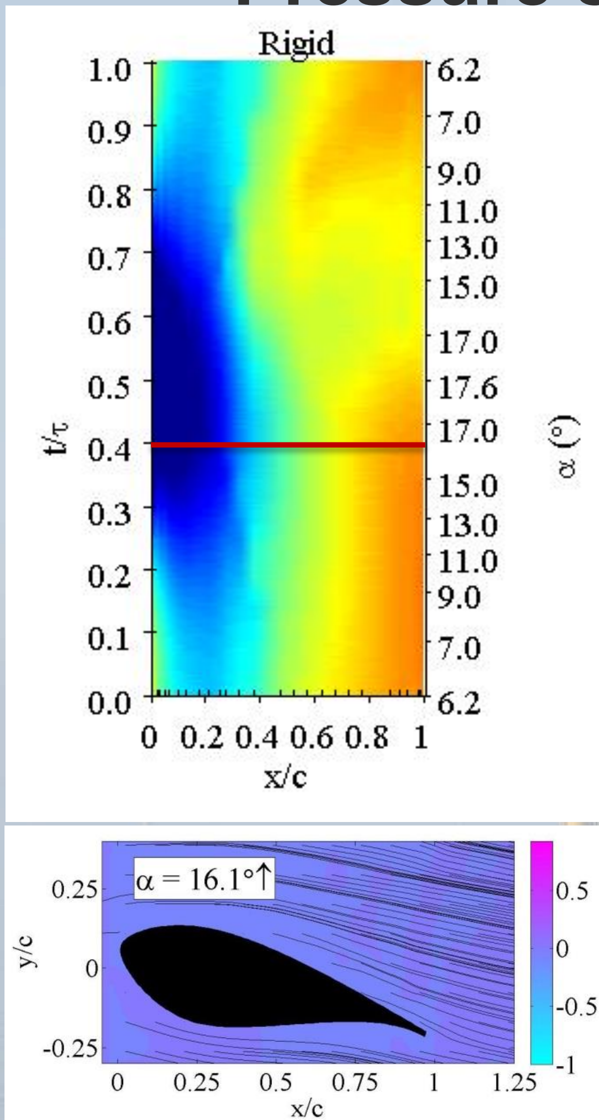
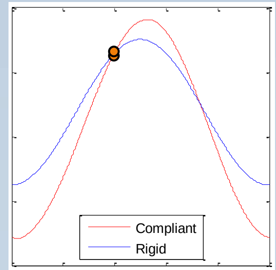
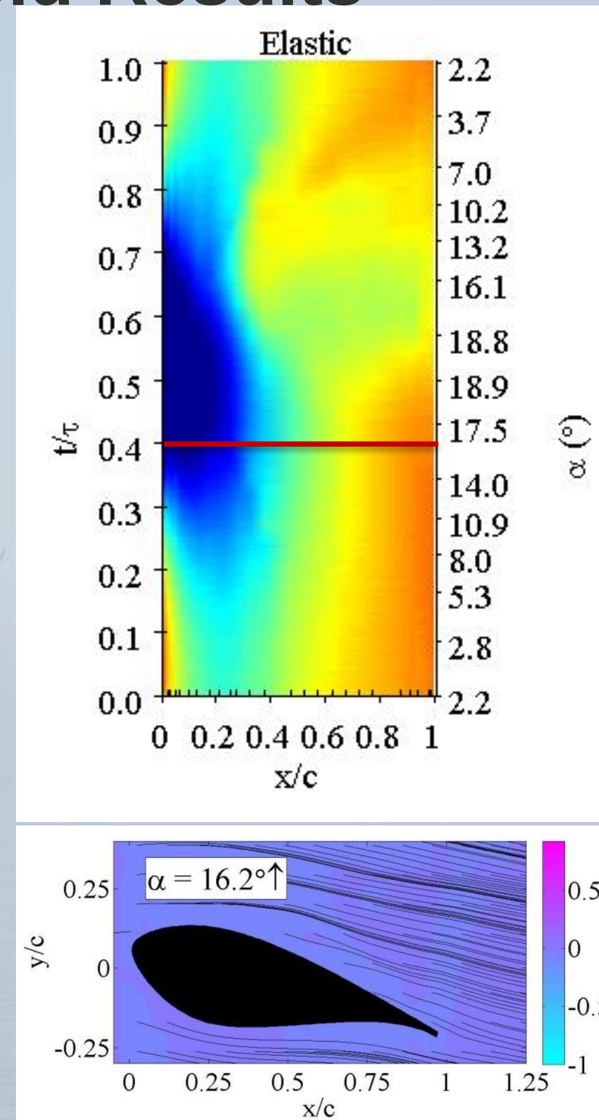
Pressure & Flow-field Results







Case 5: α = 12°±5° @ 15 Hz (k =0.21) , k_φ= 129.6 N·m/rad

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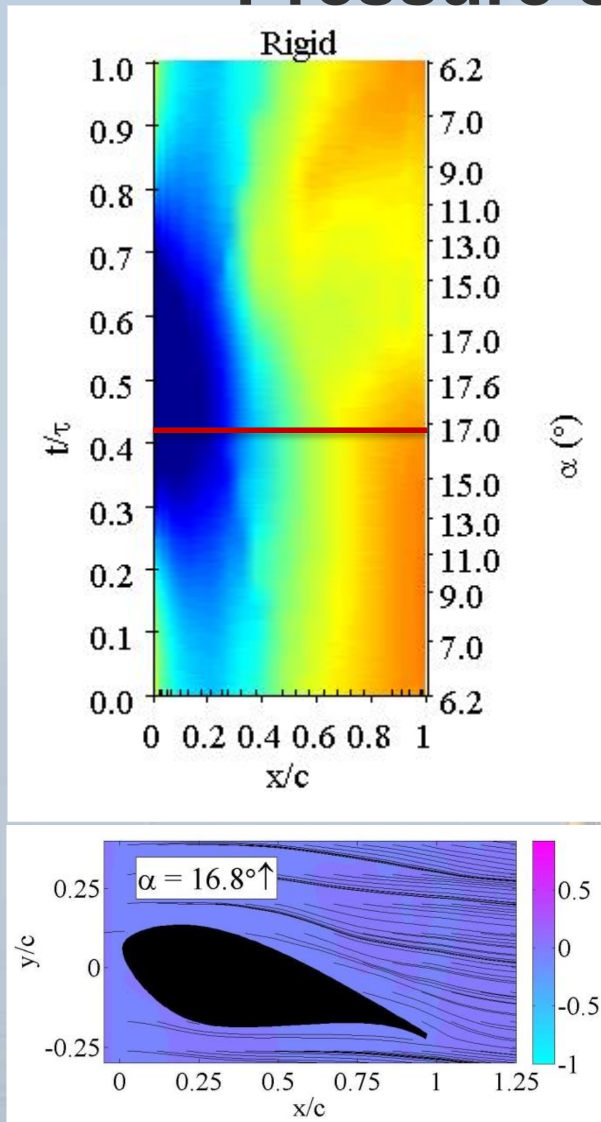
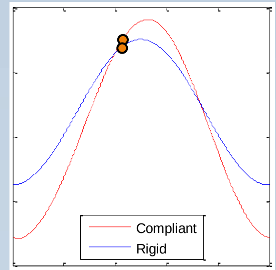
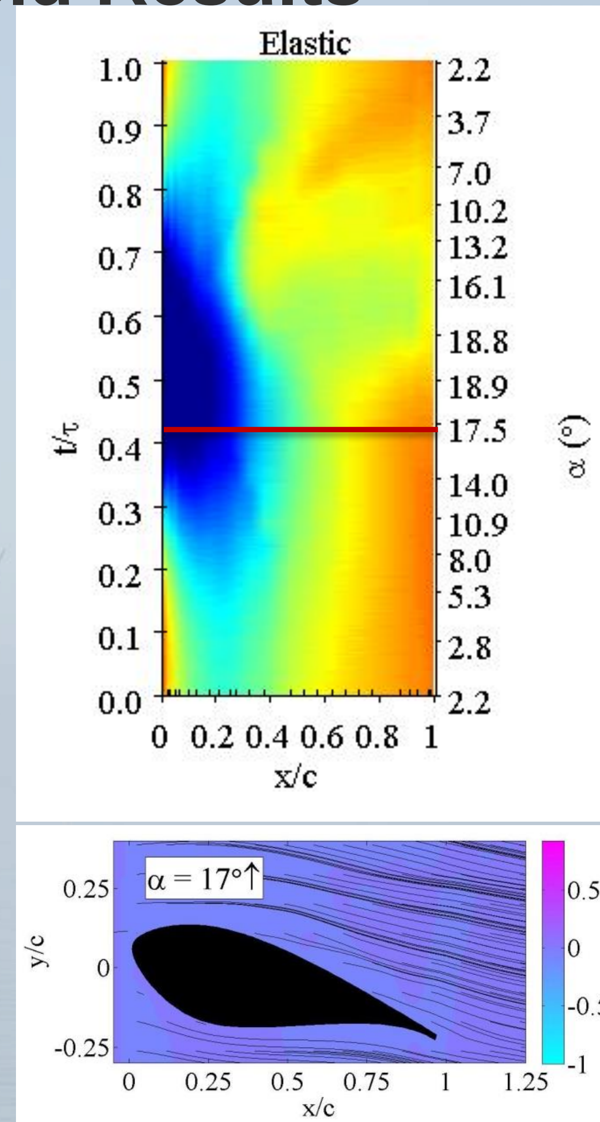
Pressure & Flow-field Results







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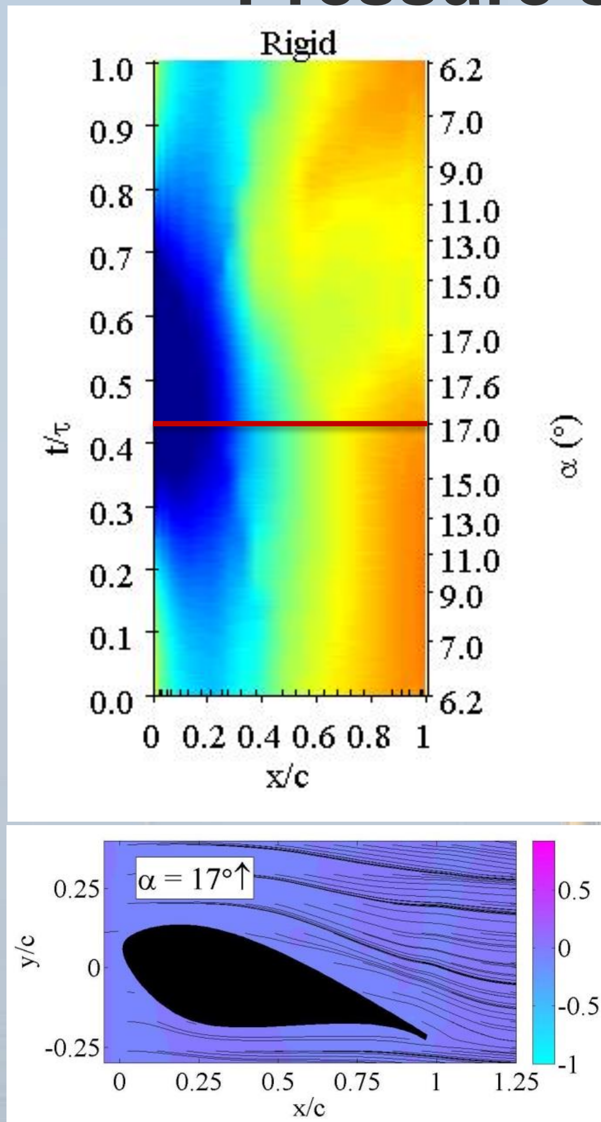

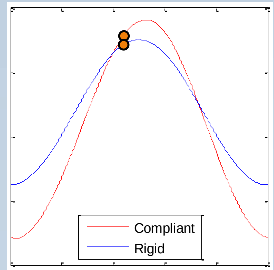

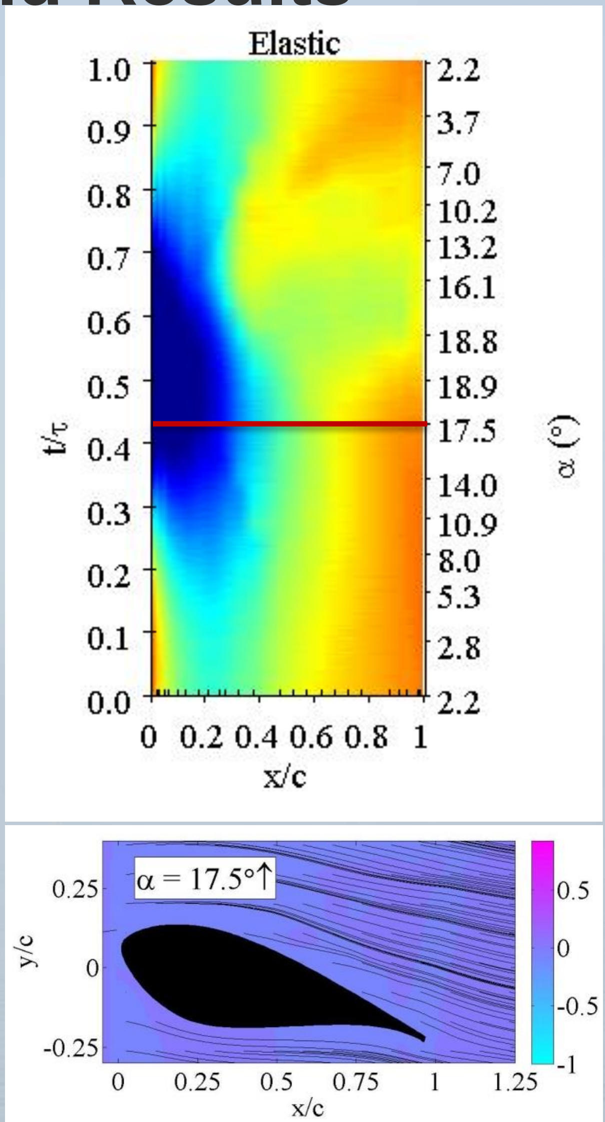

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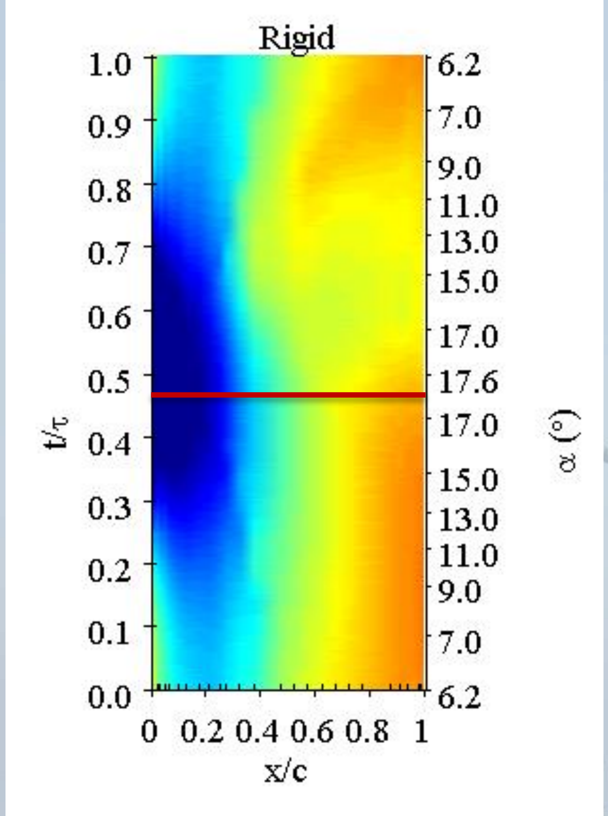
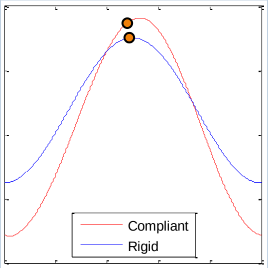
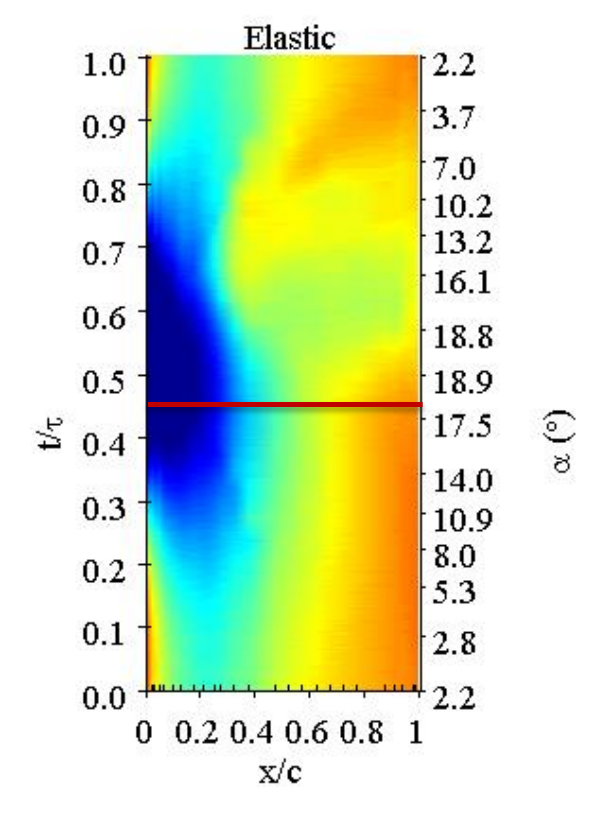
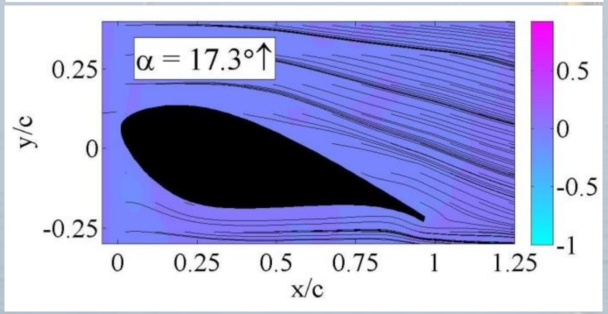
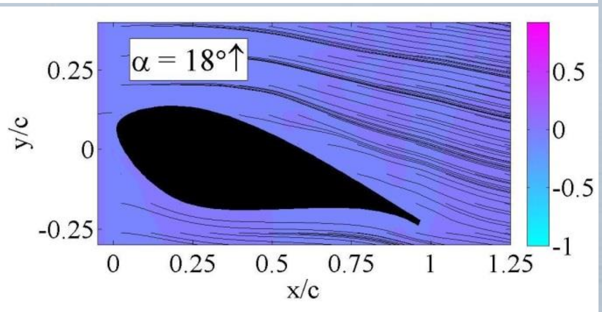
Pressure & Flow-field Results











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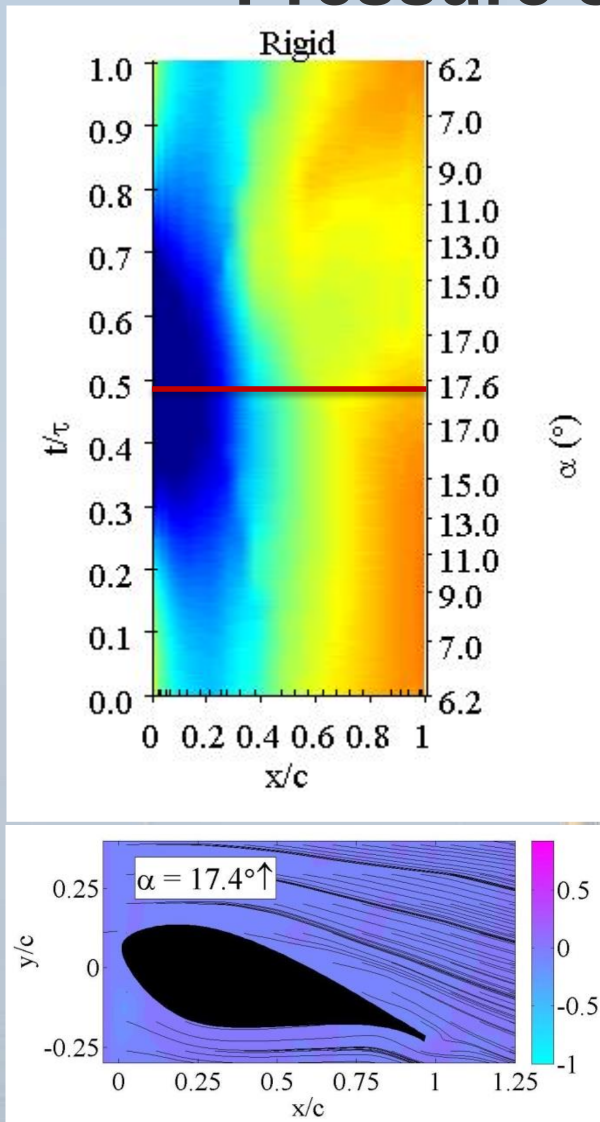
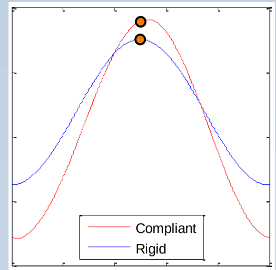
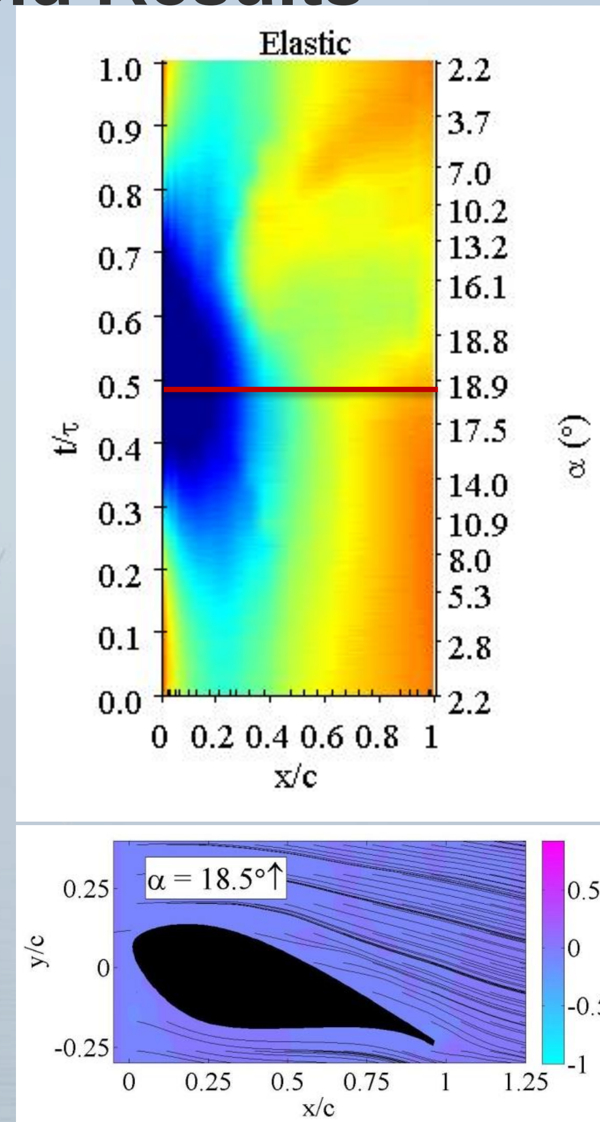
Pressure & Flow-field Results







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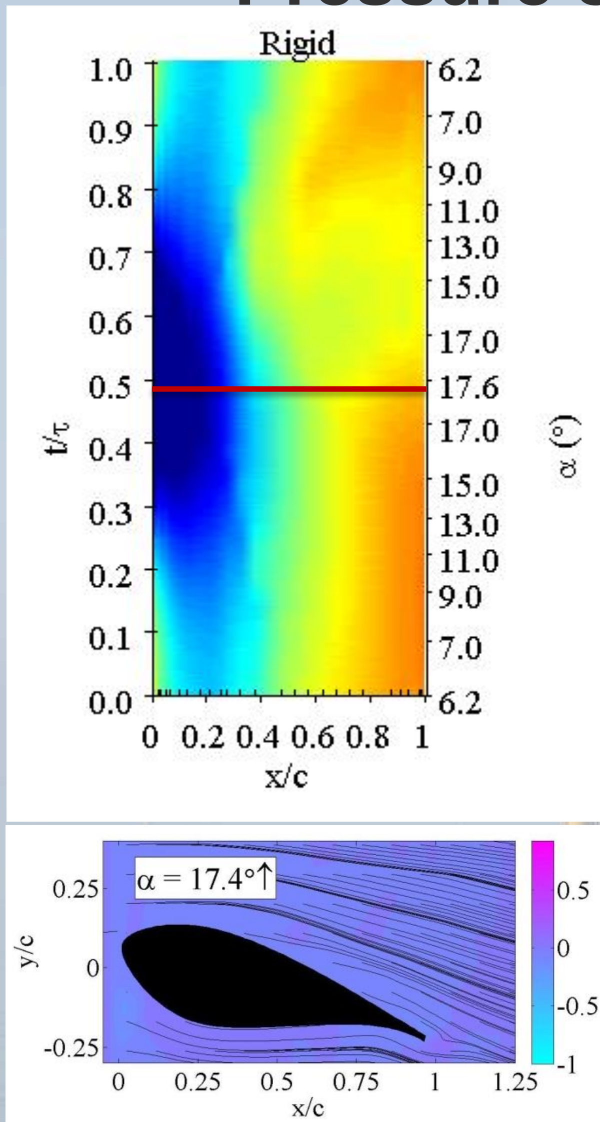
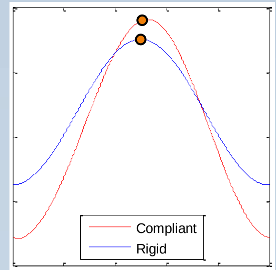
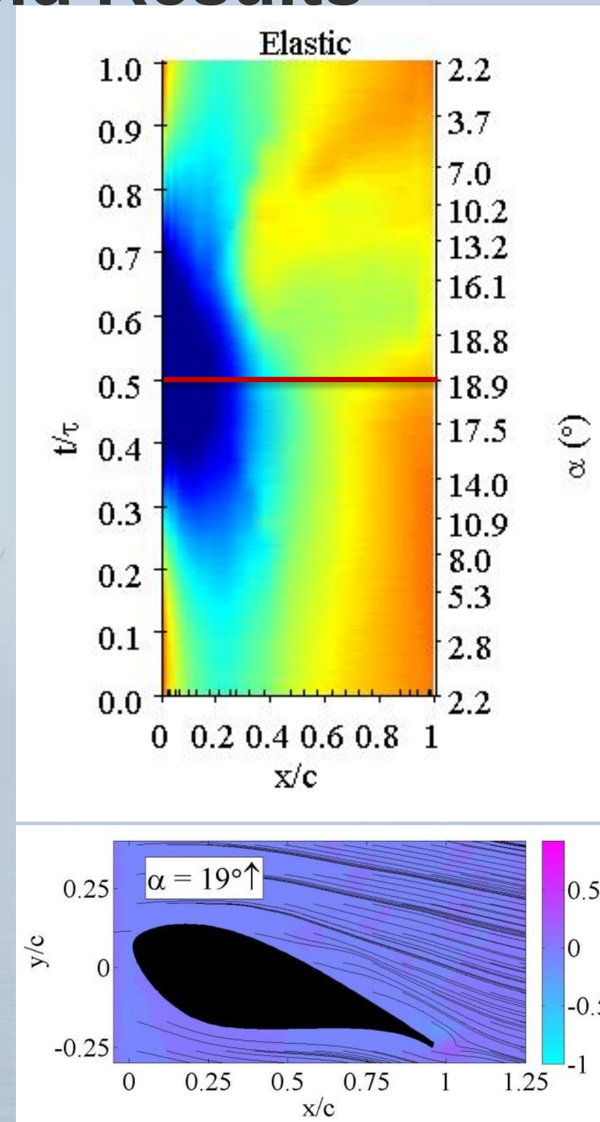
Pressure & Flow-field Results







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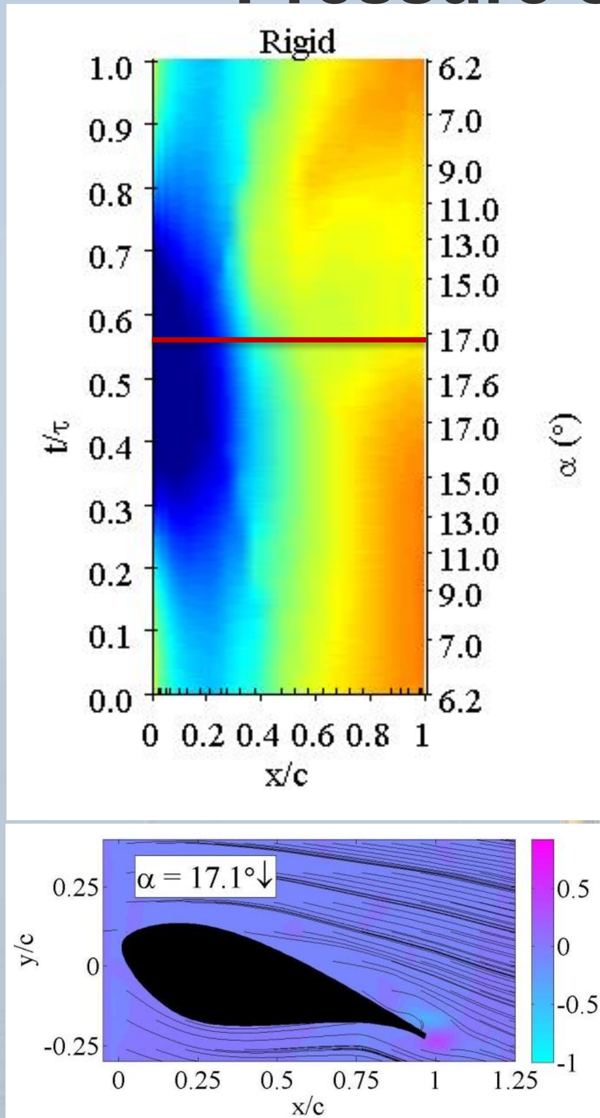
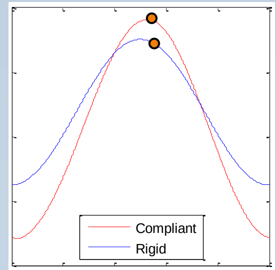
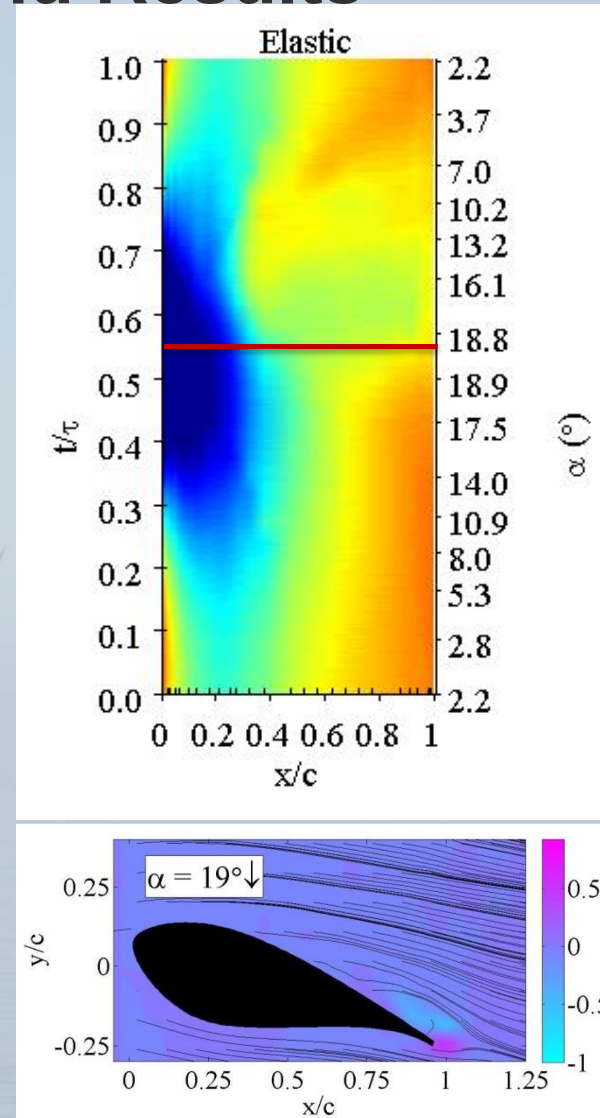


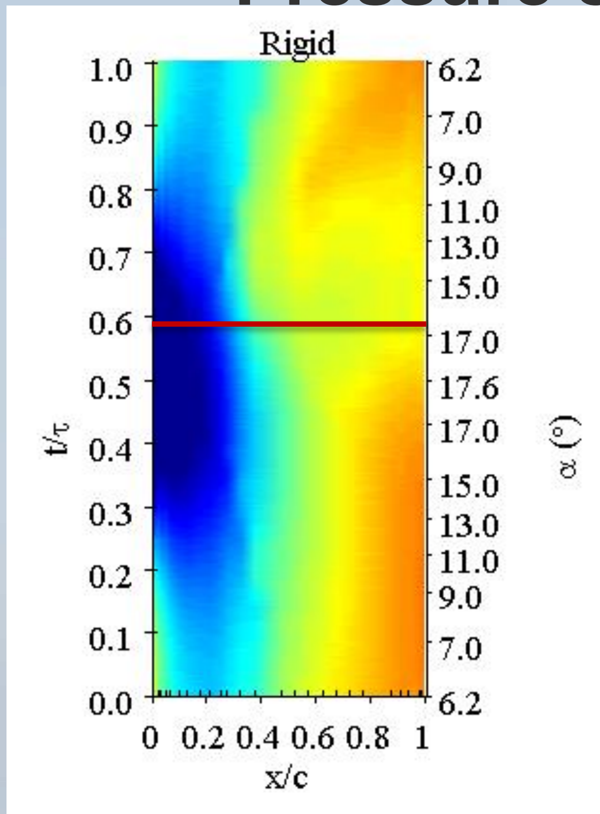


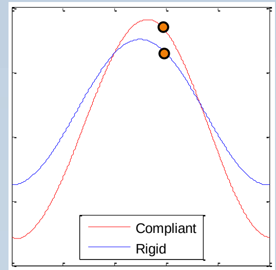


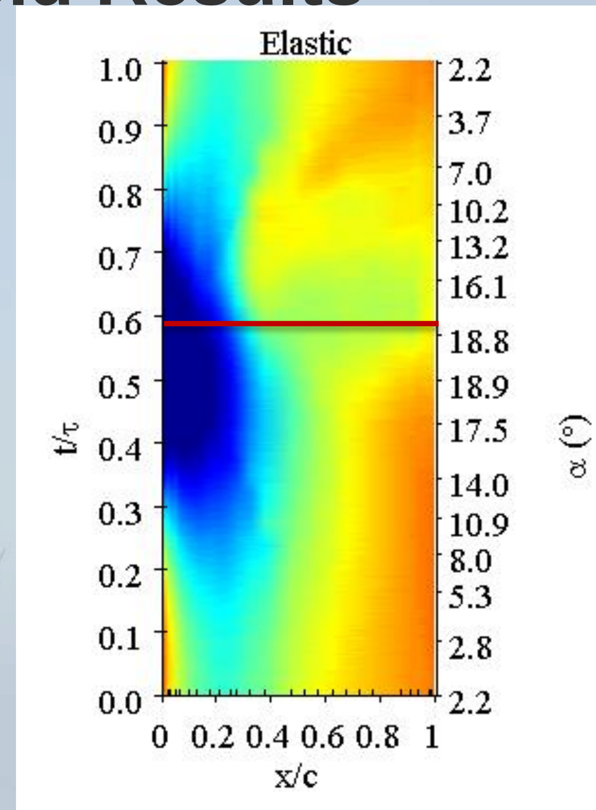
Case 5: $\alpha = 12^o \pm 5^o$ @ 15 Hz ($k = 0.21$), $k_\varphi = 129.6$ N·m/rad

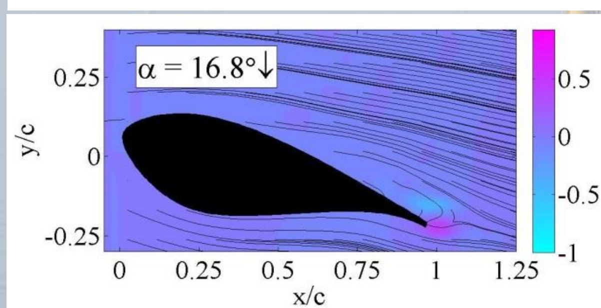
Results

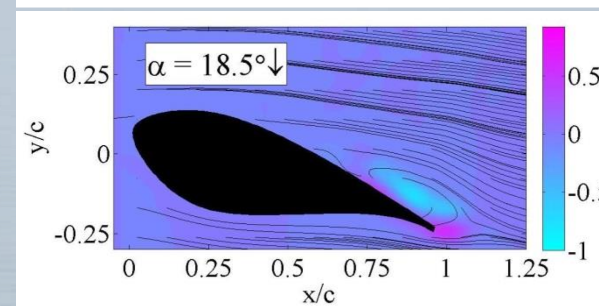
Pressure & Flow-field Results











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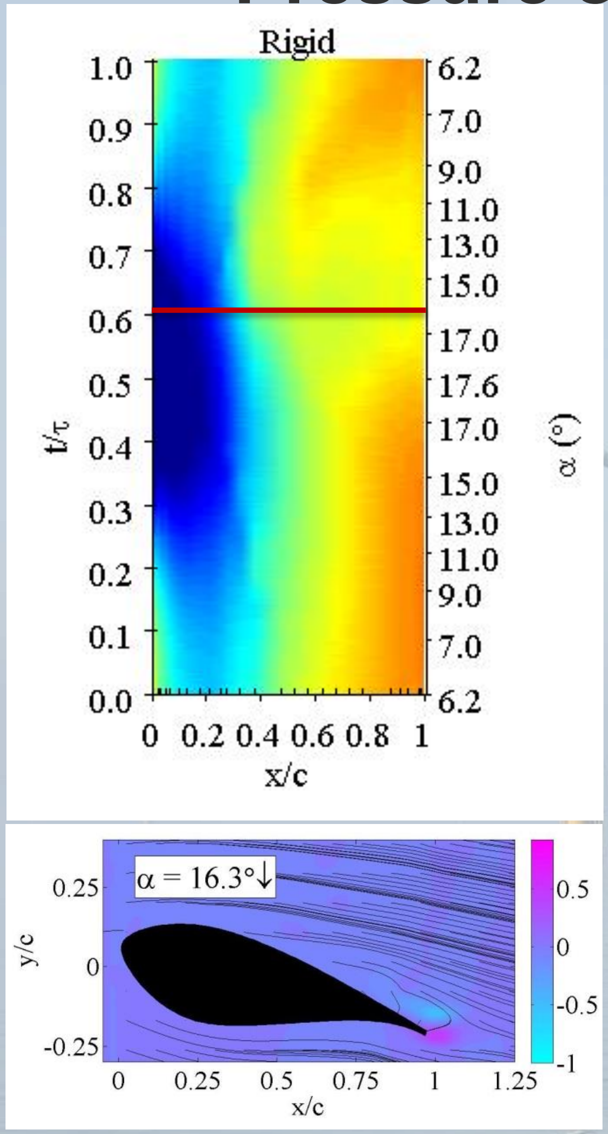
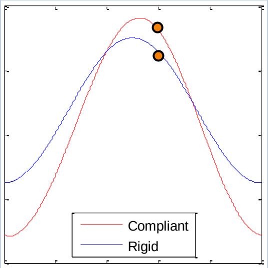
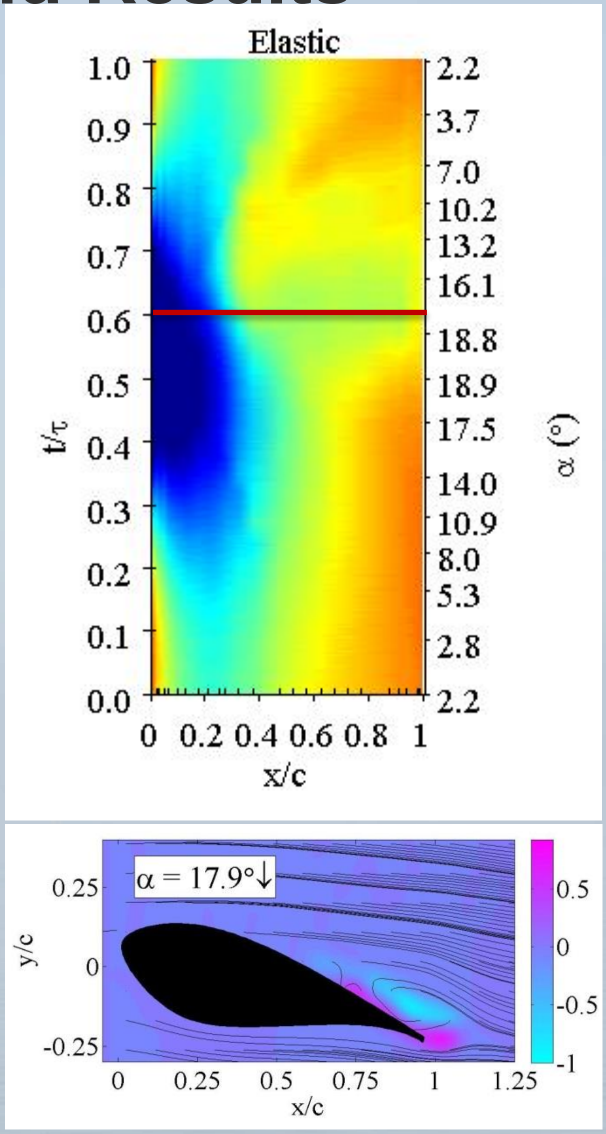
Pressure & Flow-field Results



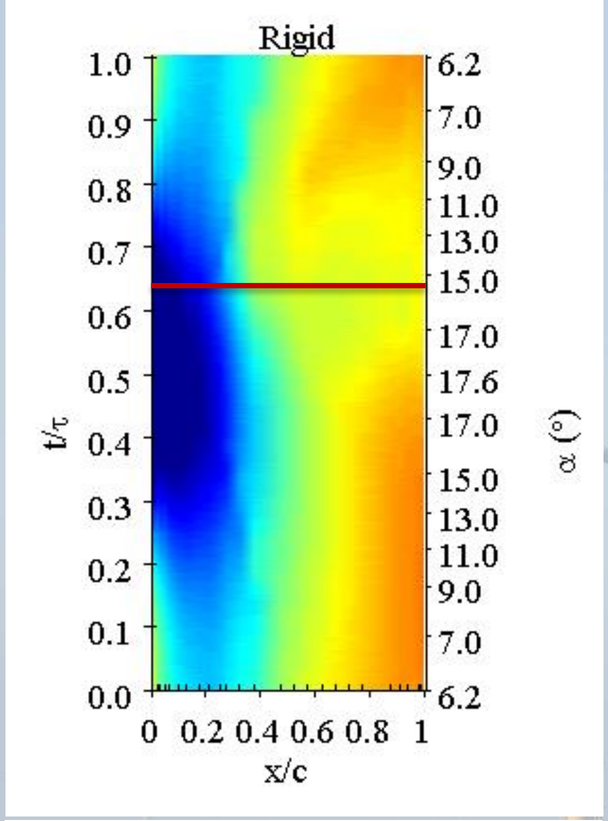


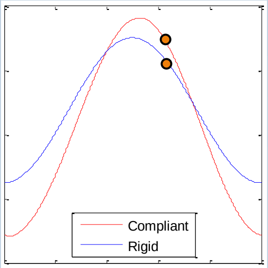


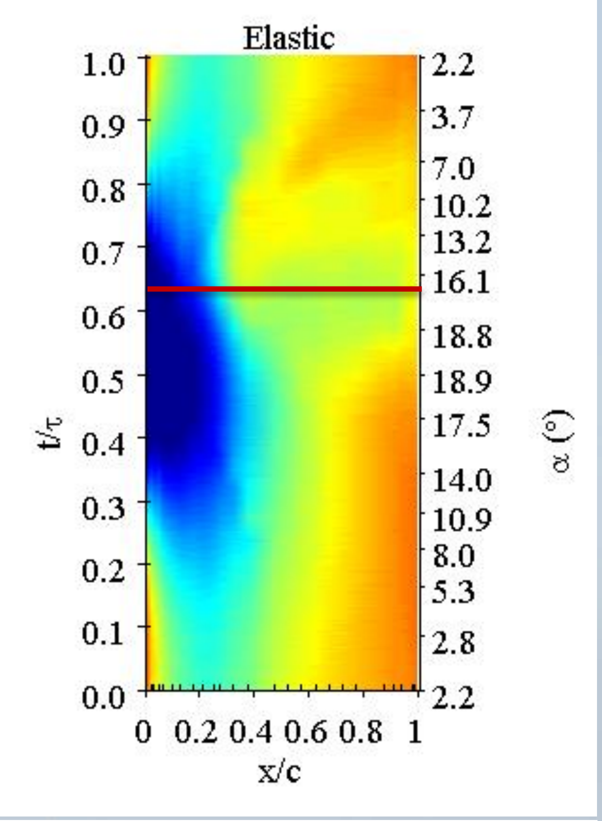
Case 5: α = $12^o \pm 5^o$ @ 15 Hz (k =0.21) , k_φ= 129.6 N·m/rad

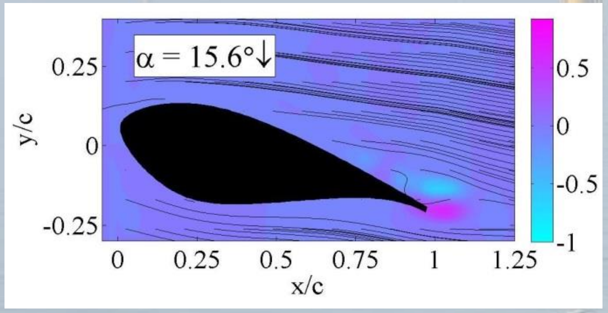
Results

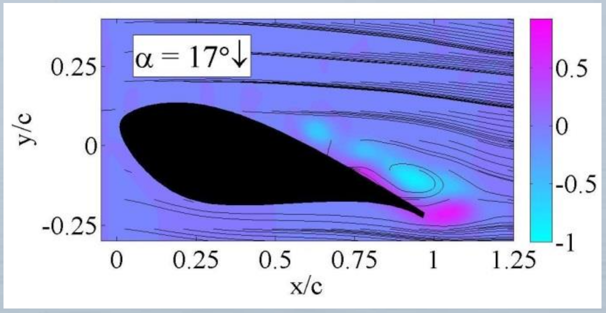
Pressure & Flow-field Results











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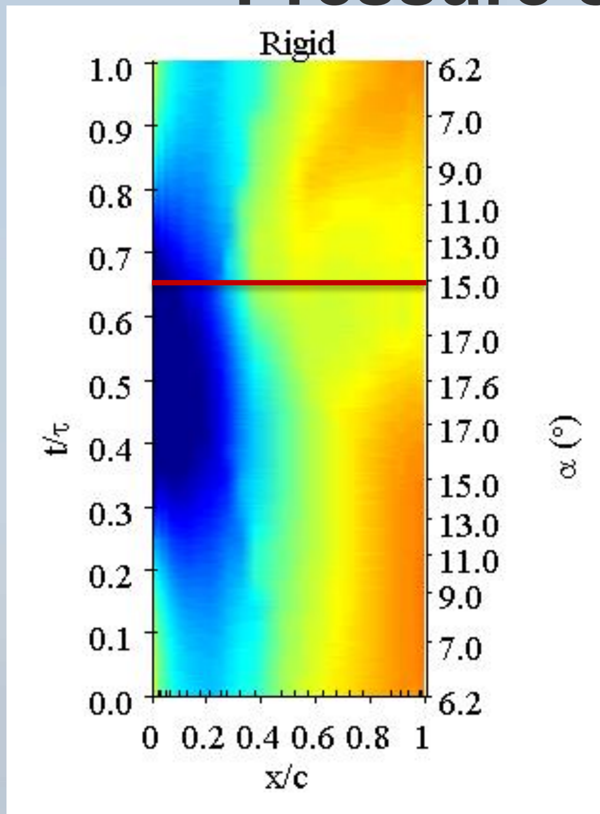
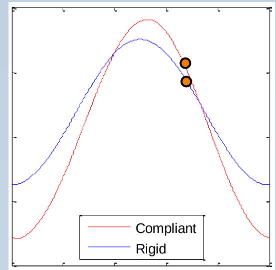
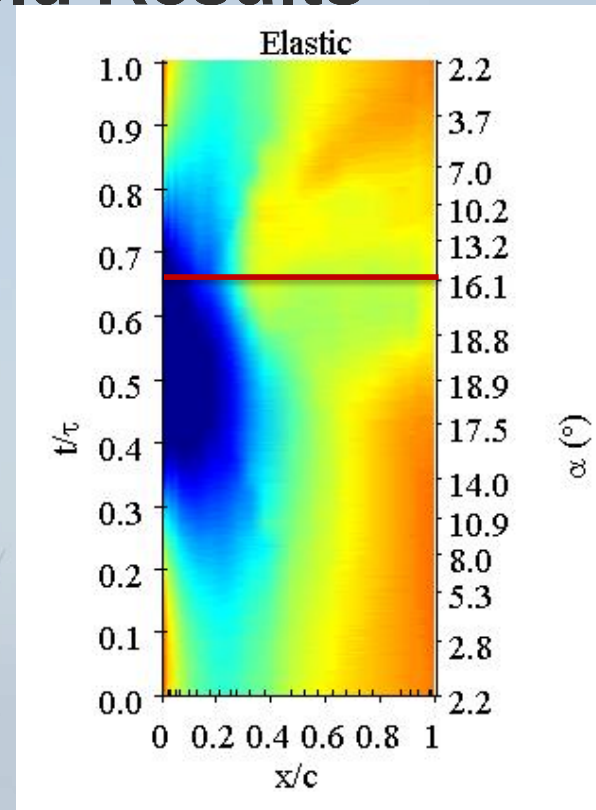
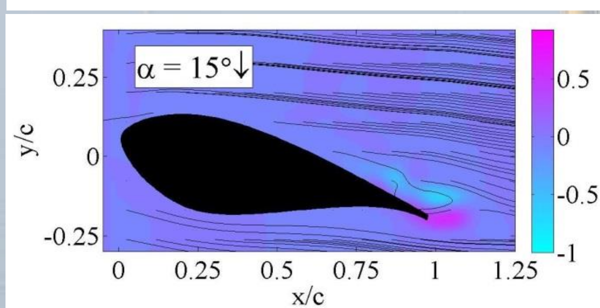
Results

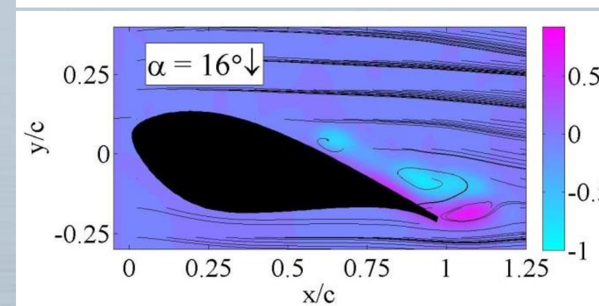
Pressure & Flow-field Results











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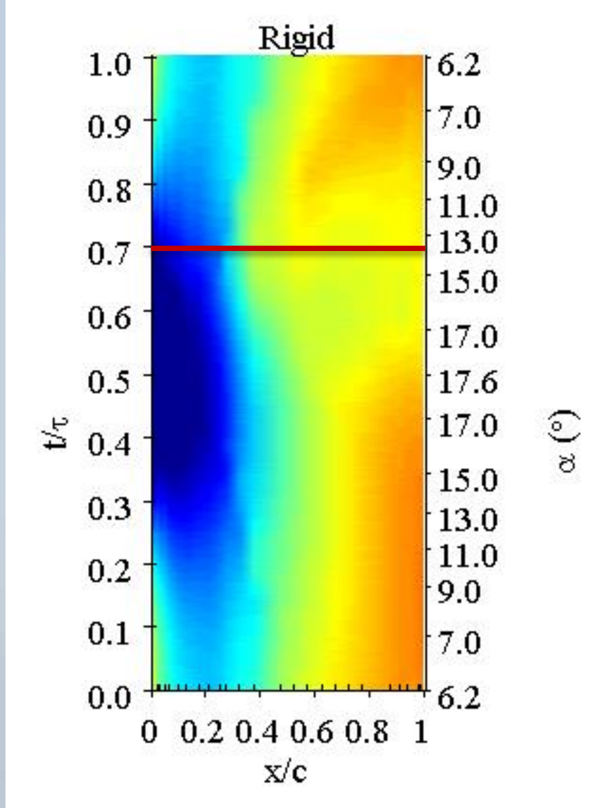
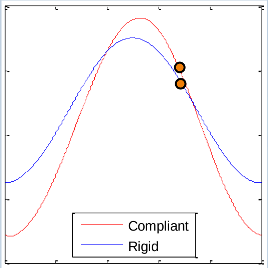
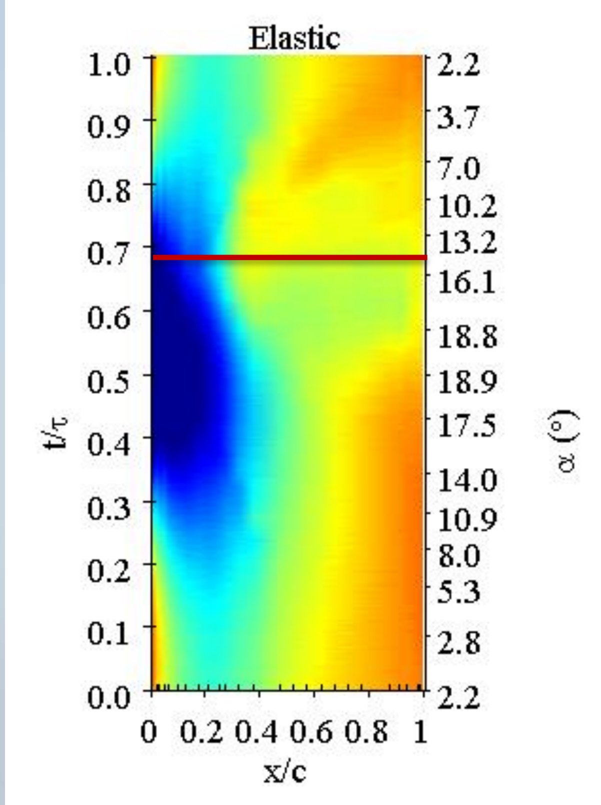
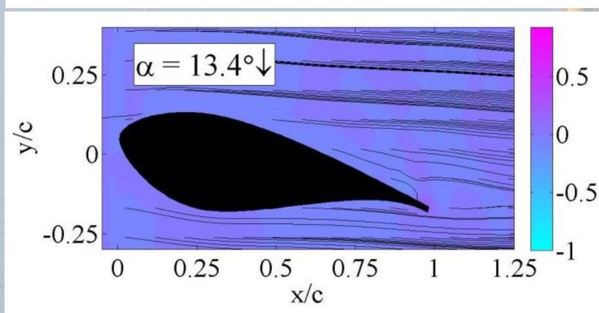
Results

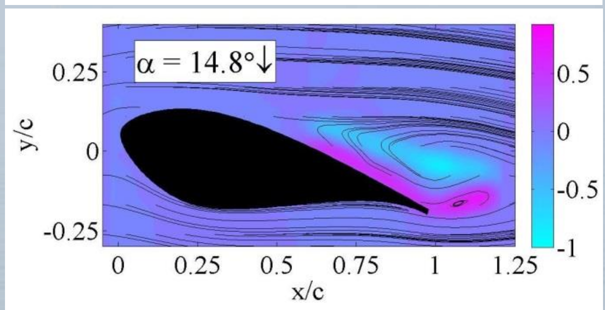
Pressure & Flow-field Results







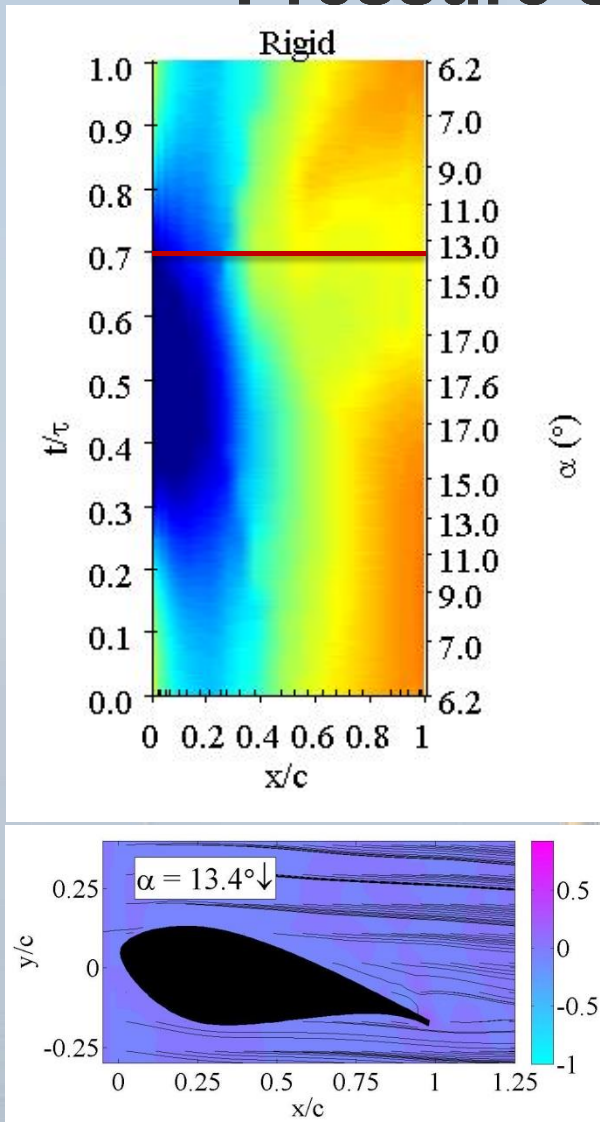


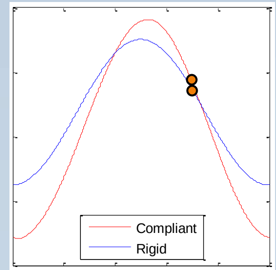


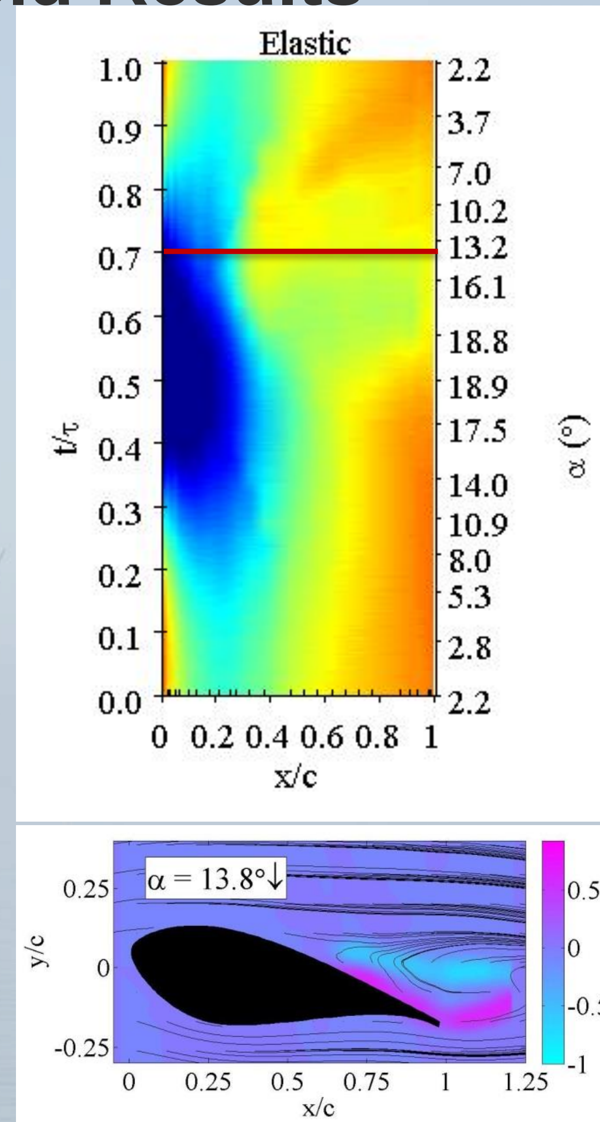
Case 5: α = 12°±5° @ 15 Hz (k =0.21) , k_φ= 129.6 N·m/rad

Results

Pressure & Flow-field Results



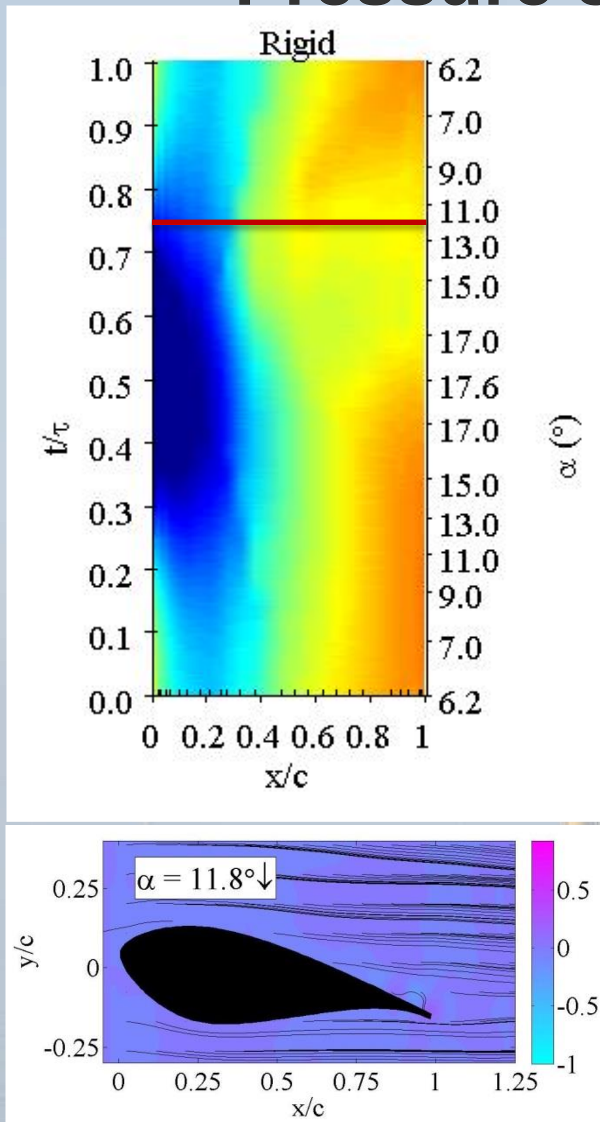


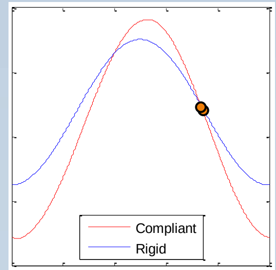


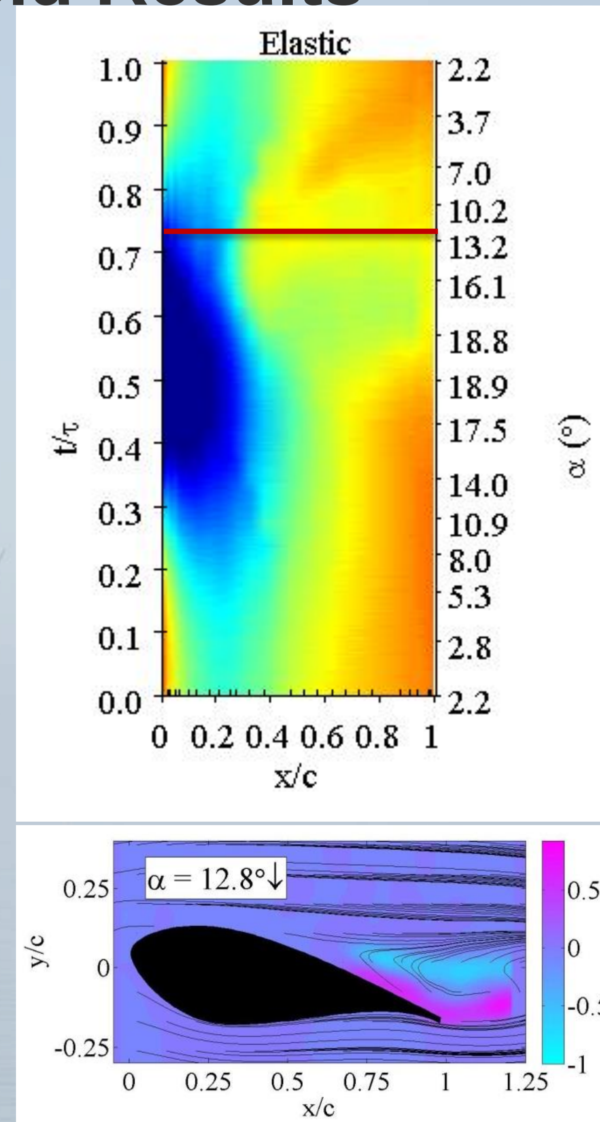
Case 5: α = 12°±5° @ 15 Hz (k = 0.21), k_φ = 129.6 N·m/rad

Results

Pressure & Flow-field Results







Case 5: $\alpha = 12^o \pm 5^o$ @ 15 Hz (k =0.21) , k_φ= 129.6 N·m/rad

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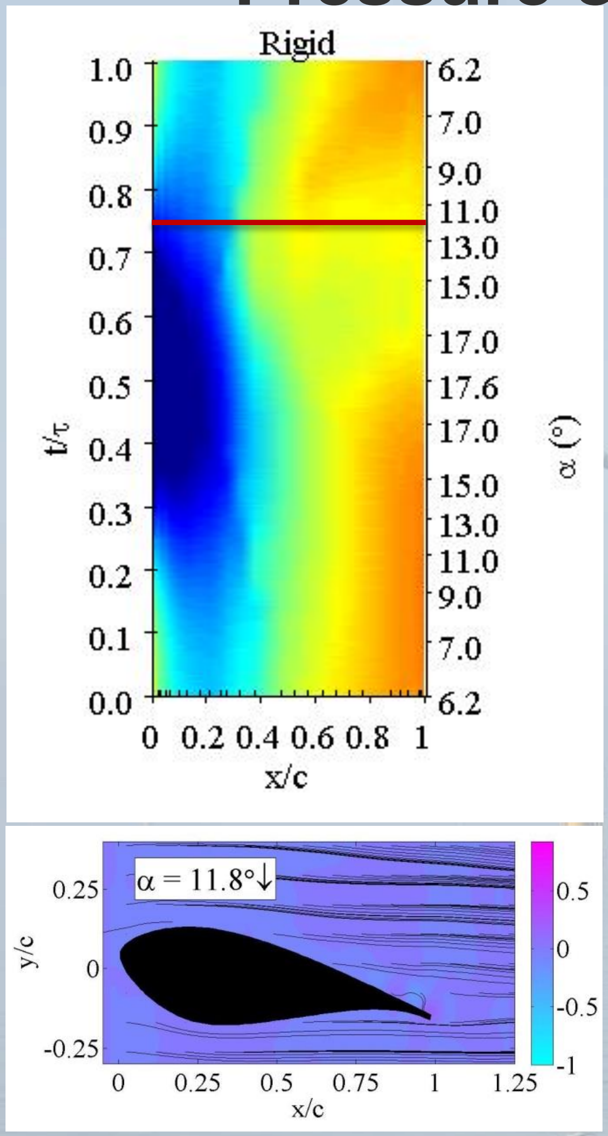
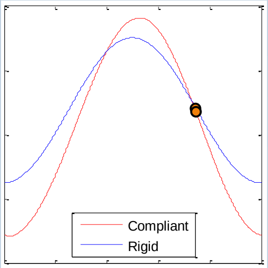
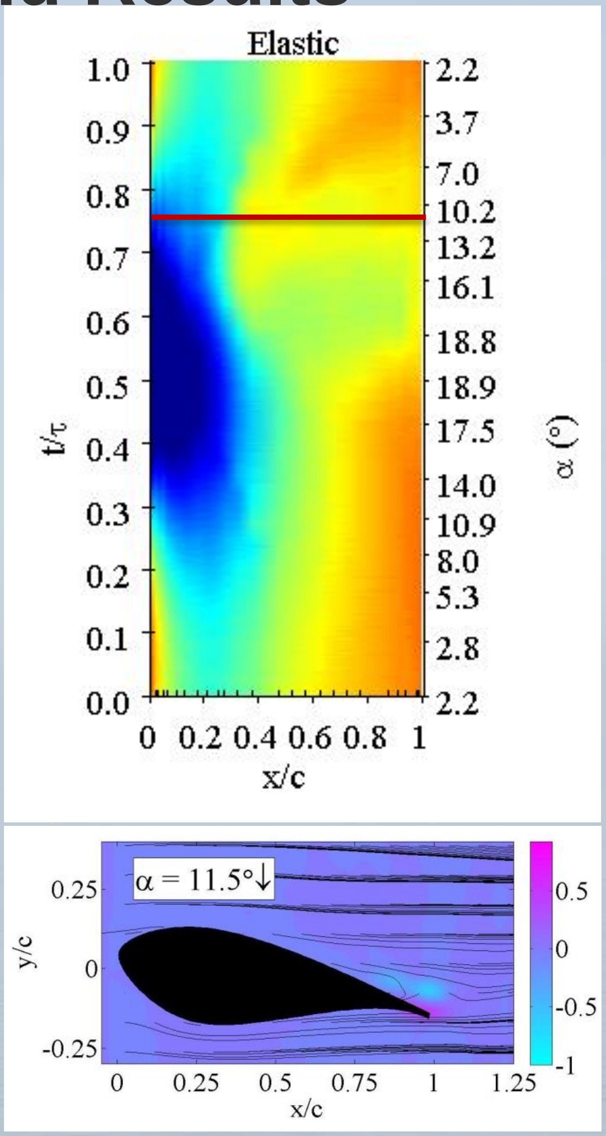
Pressure & Flow-field Results







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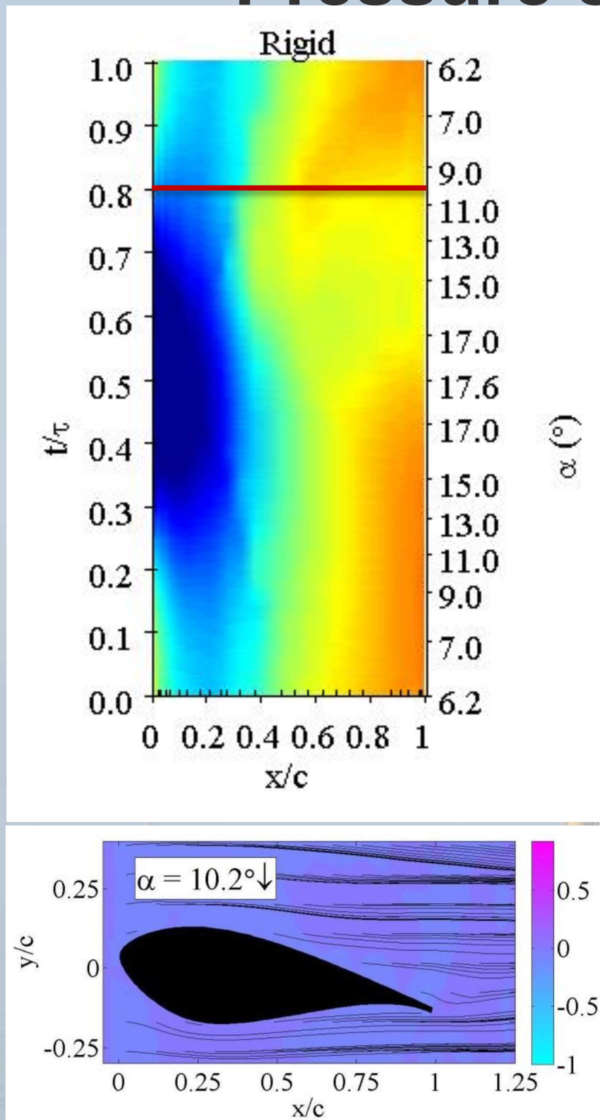
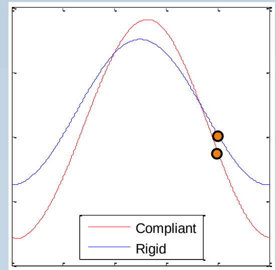
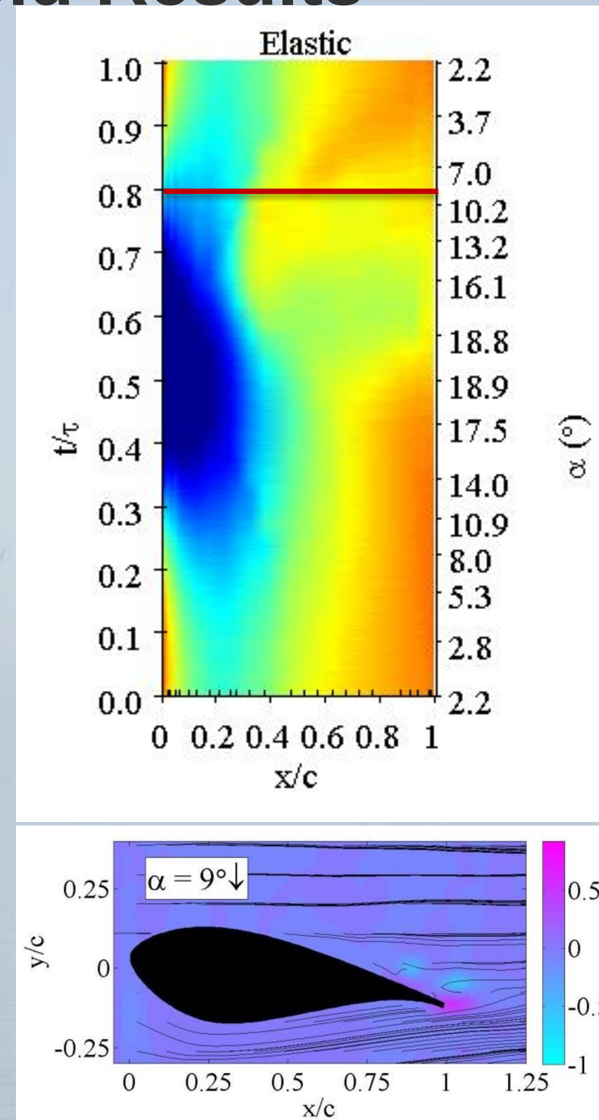
Results

Pressure & Flow-field Results







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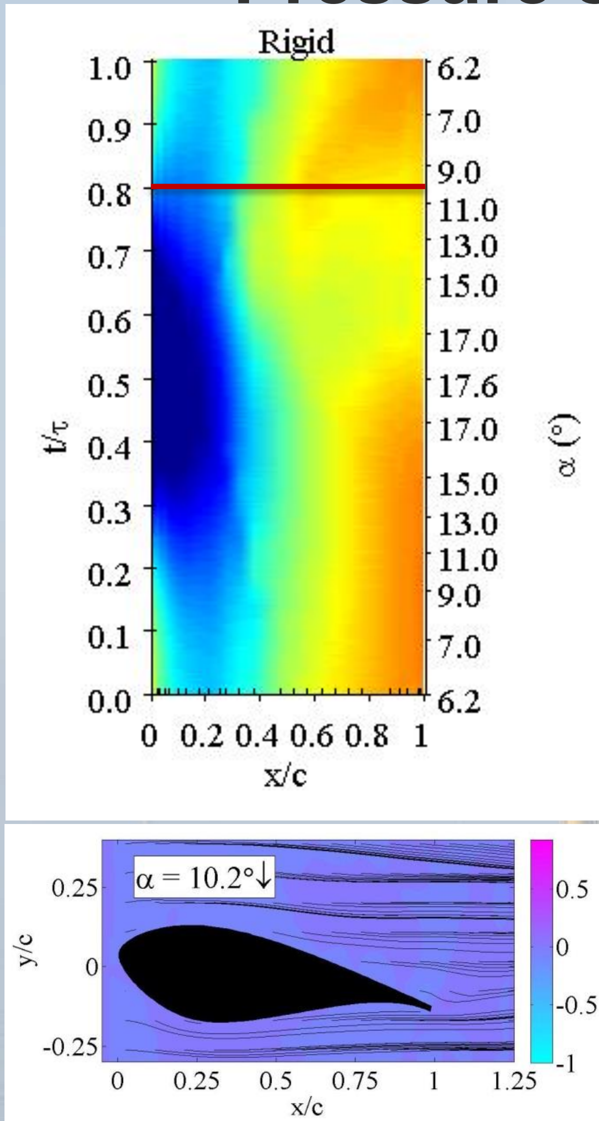
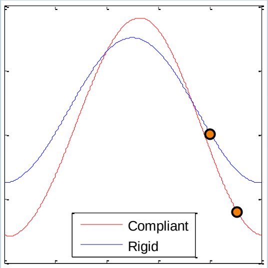
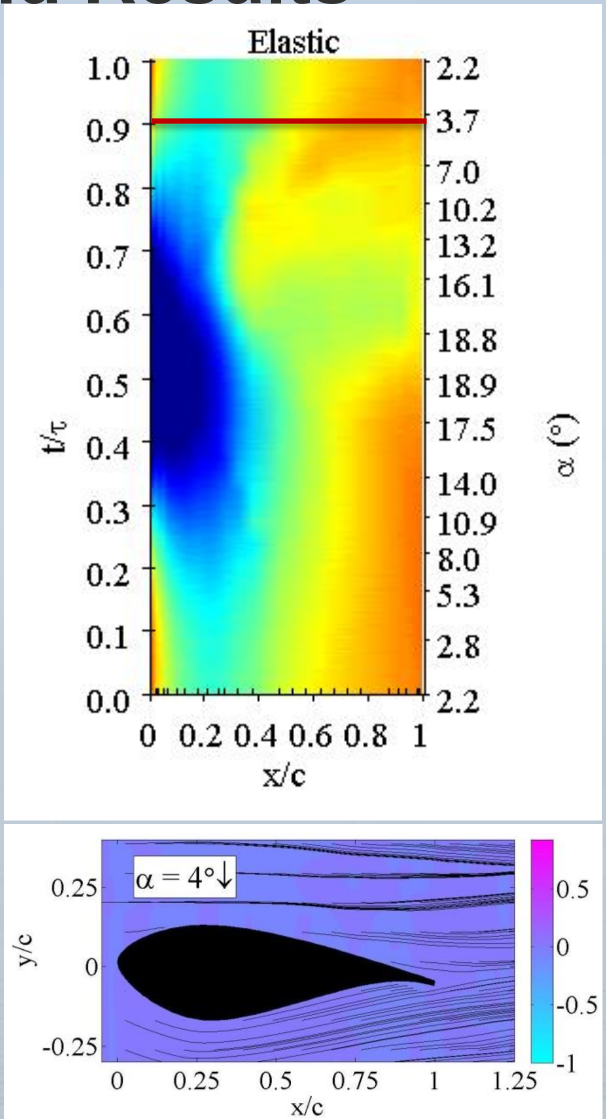
Pressure & Flow-field Results





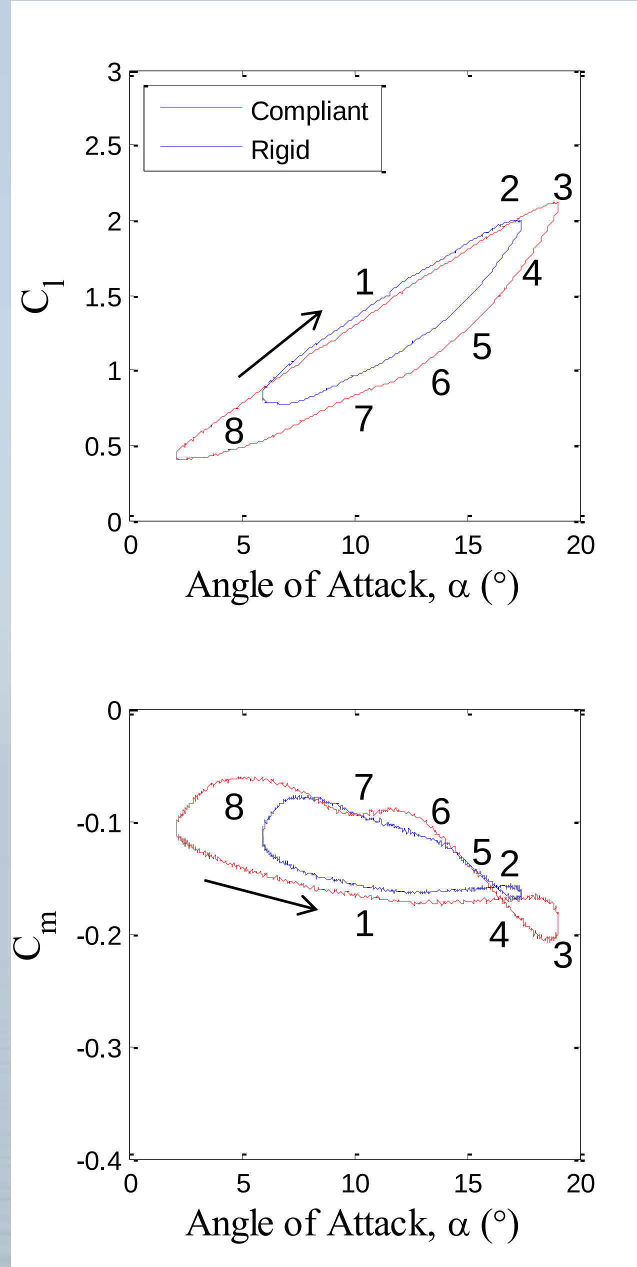


Case 5: α = $12^o \pm 5^o$ @ 15 Hz (k =0.21) , k_φ= 129.6 N·m/rad

Integrated Results

Rigid Case

1. Fully attached
2. Trailing edge stall begins setting up
3. Trailing edge separation initiates w/ secondary vortex
4. Minor TE stall, with weak secondary vortex
5.
6. Vortices shed
7.
8. Flow reattachment



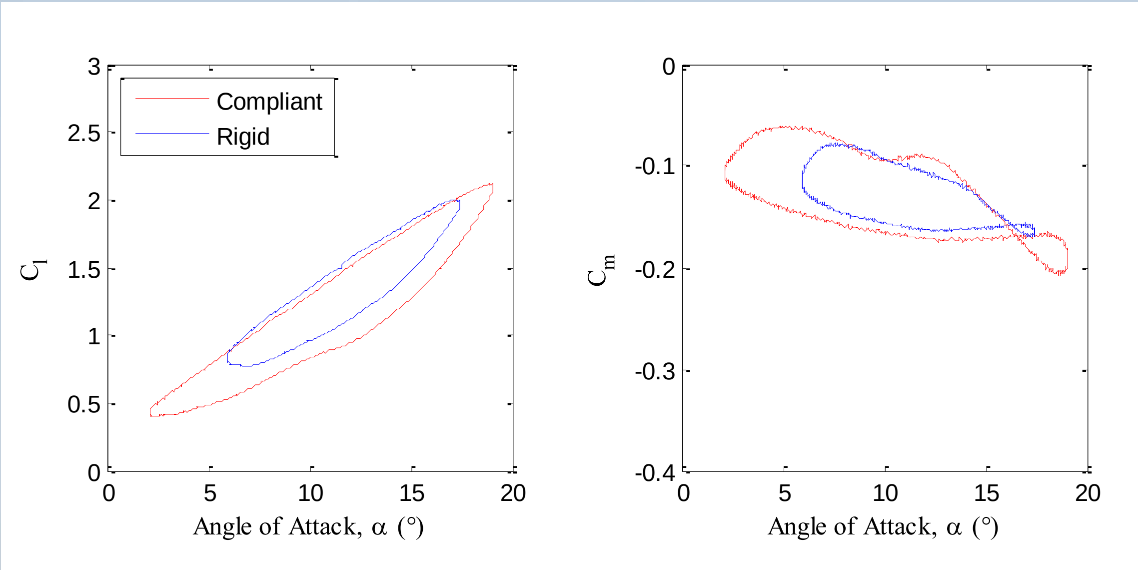
Integrated Results

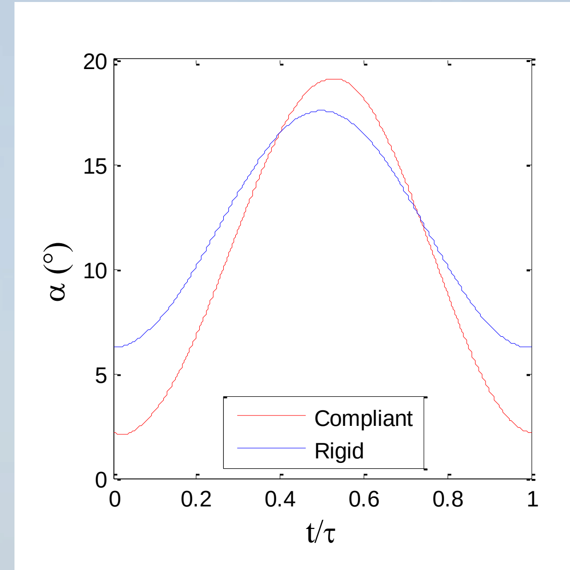
Compliant Case

1. Fully attached
2. Trailing edge stall begins setting up
3. Trailing edge separation initiates w/ secondary vortex evident
4. TE stall. Additional structure in front of TE vortex
5. Suction side vortices merge
6. Secondary vortex sheds first, primary follows
7. Remnants of merged vortex
8. Flow reattachment

Results

Analysis of Integrated Results



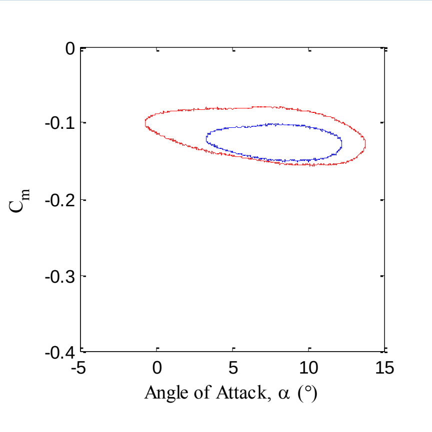


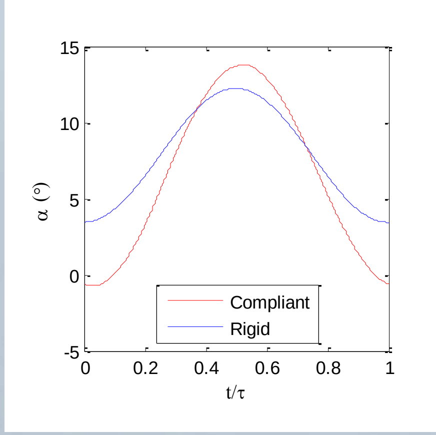
- **Evidence of increase in hysteresis**
- **Increased dynamic loading**
  - More extreme AoAs
  - Change in aerodynamic structures
- **Exotic stall observed in compliant case may result from non-sinusoidal pitch frequency**
- **Moment increase is more involved**
  - Result of asymmetric AoA schedule
  - See paper for in-depth explanation

- **Asymmetric AoA schedule**
  - Changes in "Instantaneous reduced frequency"
  - Airfoil sees higher *k* momentarily and stalls accordingly

Summary

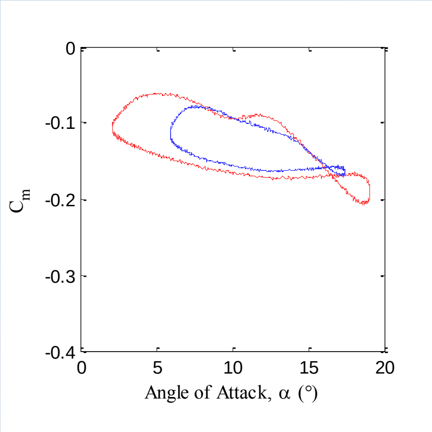
Fully Attached

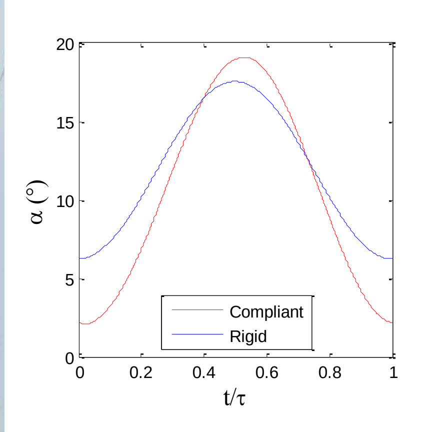




- **Asymmetric AoA**
- **No stall**

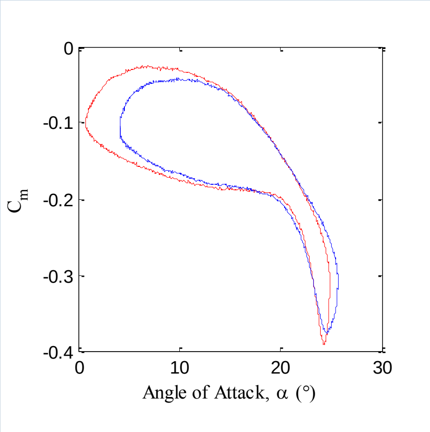
Intermediate Stall

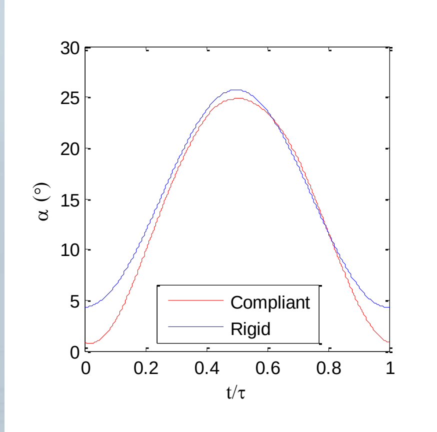




- **Asymmetric AoA**
- **Strengthened stall**
- **Additional structure**

Deep Stall





- **High c_m lowers AoA_{max}**
- **Stalls prior to AoA_{max}**
- **Deep stall insensitive to small AoA change**

Conclusions

- **Coupling of surface and flow-field measurements critical to understanding complex flow**
- **Presence of compliance affects:**
  - AoA schedule
  - Flow structures
  - Dynamic loading
    - **Hysteresis increased**
    - **Lift & Moment increased**
- **High sensitivity to operating conditions**
  - $\alpha = 10^o \pm 5^o \rightarrow \alpha = 12^o \pm 5^o$
  - Varying inflow may push blade into this region
- **Adverse consequences**
  - Fatigue of components
  - Possibility of more complex phenomenon with plunge
    - **Flutter, LCOs**
- **Demonstrate potential for aerodynamic control**
  - Minimize negative aspects, possibly improve performance
  - Large gains from little changes
    - **Little (intelligent) effort required**

Acknowledgements

- **Funding for this work**
  - Grant number DESC0001261 from the Department of Energy monitored by Timothy J. Fitzsimmons
  - A gift from BP Alternative Energy North America, Inc.

- **Background Photo Credit**
  - Barrow Offshore Wind Farm, Irish Sea
  - http://upload.wikimedia.org/wikipedia/commons/e/e4/Barrow_Offshore_wind_turbines.jpg

- **Full Work – AIAA Paper**

  - Magstadt, A. S., Strike, J. A., Hind, M. D., Nikoueeyan, P., and Naughton, J. W., “Compliance Effects in Dynamically Pitching Wind Turbine Airfoils,” AIAA Paper 2013-234, Jun 24-27 2013-2994, 43rd Fluid Dynamics Conference, San Diego, CA. Chapter DOI: 10.2514/6.2013-2994

Thank you.

Questions?