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as of 14-Apr-2020

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Final Report for Period Beginning 22-Jun-2018 and Ending 31-Dec-2019
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Report Term: 0-Other

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: **STEM Participants:**

Major Goals: This workshop is designed to impart to the broader community the advances and current state of the art in the understanding and prediction of rotorcraft-related dynamic stall. Dynamic stall is an unsteady aerodynamic phenomenon resulting from the rapid angle of attack change of a lifting surface during which the flow separates and then later reattaches. Dynamic stall is characterized by complex flow field phenomena including shear layers and vortices that interact with one another and the airfoil, and it can be triggered by large angle of attack excursions, blade-vortex interaction, and shocks. The ability to predict dynamic stall and eliminate it from the flight envelope is necessary to improve upon current safety standards and to apply it to new designs.

This workshop is planned to disseminate new findings and methodologies to the research and engineering communities who are intimately involved in dynamic stall. It is important that these capabilities are more widely known; even with the plethora of peer-reviewed journals, there is still significant duplication on topics that have already been resolved. It is further necessary to determine the future path of research in this area; what gaps in knowledge or roadblocks in methods development still remain? In particular, active flow control (AFC) of dynamic stall has had significant funding in the past, but there are still no systems installed on current vehicles. Are there physics that can be exploited to make AFC viable? Are there results from dynamic stall research on rotorcraft be leveraged in other fields such as fixed wing, wind/wave energy, and engine systems? Panel sessions to discuss and disseminate these questions and others will be held.

Accomplishments: DYNAMIC STALL WORKSHOP was conducted.

Training Opportunities: Nothing to Report

Results Dissemination: A Microsoft Teams account for all participants and interested parties was created with the presentations. Conference papers at 2020 Vertical Flight Society Annual Forum and 2020 AIAA Aviation have been accepted and are being written. A special Journal section is being negotiated to write 4-5 State-of-the-Art papers on the topic.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: A Microsoft Teams account for all participants and interested parties (including US DoD) was created with the presentations. Conference papers at 2020 Vertical Flight Society Annual Forum and 2020 AIAA Aviation have been accepted and are being written. A special Journal section is being negotiated to write 4-5 State-of-the-Art papers on the topic.

PARTICIPANTS:

Participant Type: PD/PI
Participant: Marilyn Jones Smith
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

DYNAMIC STALL WORKSHOP PROCEEDINGS

September 10-11, 2019

Georgia Institute of Technology

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March 27, 2020

ARO Dynamic Stall Workshop

This workshop is designed to impart to the broader community the advances and current state of the art in the understanding and prediction of rotorcraft-related dynamic stall. Dynamic stall is an unsteady aerodynamic phenomenon resulting from the rapid angle of attack change of a lifting surface during which the flow separates and then later reattaches. Dynamic stall is characterized by complex flow field phenomena including shear layers and vortices that interact with one another and the airfoil, and it can be triggered by large angle of attack excursions, blade-vortex interaction, and shocks. The ability to predict dynamic stall and eliminate it from the flight envelope is necessary to improve upon current safety standards and to apply it to new designs.

This workshop is planned to disseminate new findings and methodologies to the research and engineering communities who are intimately involved in dynamic stall. It is important that these capabilities are more widely known; even with the plethora of peer-reviewed journals, there is still significant duplication on topics that have already been resolved. It is further necessary to determine the future path of research in this area; what gaps in knowledge or roadblocks in methods development still remain? In particular, active flow control (AFC) of dynamic stall has had significant funding in the past, but there are still no systems installed on current vehicles. Are there physics that can be exploited to make AFC viable? Are there results from dynamic stall research on rotorcraft be leveraged in other fields such as fixed wing, wind/wave energy, and engine systems? Panel sessions to discuss and disseminate these questions and others will be held.

Background and Motivation

This workshop is designed to impart to the broader community the advances and current state of the art in the understanding and prediction of rotorcraft-related dynamic stall. Dynamic stall is an unsteady aerodynamic phenomenon resulting from the rapid angle of attack change of a lifting surface during which the flow separates and then later reattaches. Dynamic stall is characterized by complex flow field phenomena including shear layers and vortices that interact with one another and the airfoil. Dynamic stall on a rotor can be triggered by large angle of attack excursions, blade-vortex interaction, and shocks.

Quantitative predictors of dynamic stall are not readily available for new rotor design needed for the U.S. Army's Joint Multi-Role (JMR) helicopter program or Future Vertical Lift (FVL) initiative. The ability to predict dynamic stall and eliminate it from the flight envelope is necessary to improve upon current safety standards. Dynamic stall behavior in rotorcraft applications is dependent on a large variation of conditions, and its complex and nonlinear behavior has been the focus of much research, including experimental and computational efforts. It is prohibitively expensive to run experiments, and current lower fidelity numerical analysis is not sufficient to capture the details of dynamic stall so computational fluid dynamics (CFD) or computational fluid dynamics-computational structural dynamics (CFD-CSD) analyses have also been investigated.

Extensive experimentation in the prior century has led to the development of this qualitative sequence of events that define the dynamic stall event. These were primarily on two-dimensional, non-rotating systems. More recent research has shown that the earlier two-dimensional efforts were the most difficult and least comparable to dynamic stall events that occur on current rotors. New lower fidelity methods for comprehensive codes developed since 2008 have improved the ability to predict dynamic stall, and recent correlations with advanced numerical CFD methods have demonstrated their ability to capture the physical phenomena that drive many dynamic stall events.

This workshop is planned to disseminate these new findings and methodologies to the research and engineering communities who are intimately involved in dynamic stall. It is important that these capabilities are more widely known; even with the plethora of peer-reviewed journals, there is still significant duplication on topics that have already been resolved. It is further necessary to determine the future path of research in this area; what gaps in knowledge or roadblocks in methods development still remain? In particular, active flow control (AFC) of dynamic stall has had significant funding in the past, but there are still no systems installed on current vehicles. Are there physics that can be exploited to make AFC viable? Are there results from dynamic stall research on rotorcraft be leveraged in other fields such as fixed wing, wind/wave energy, and engine systems? Panel sessions to discuss and disseminate these questions and others will be held.

Topics

The opening address included an introduction by the US Army on the historical and current importance of dynamic stall in design for traditional and future vehicle categories. The research areas that address dynamic stall were broken down into three major categories of development: Theoretical, Computational, and Experimental.

Each focus area was introduced by a one-hour joint keynote by one or more of the leaders in the field who will address the history of and current state of the art in dynamic stall. Attendees were invited to a 15-minute vignette on either a topic of ongoing research or a gap in the research based on the category.

Panels discussions populated by the keynote speakers and moderated by the PI or alternate were held for approximately 1.0 hour each, to address the following topics relevant to dynamic stall:

a) What is the next step in dynamic stall research? Are we done? What experiments are still needed – and what measurements are needed for CFD validation? What gaps are still found in computational and theoretical approaches.
b) Is there a realistic path for on-blade control? What interesting physics found without dynamic stall can be exploited.
c) Transitioning rotorcraft dynamic stall knowledge to other fields such as fixed wing, wind energy, and propulsion (engines/propellers).

Tuesday, September 10
MARC Auditorium, Georgia Institute of Technology

8:00 – 8:30 **Registration**
MARC Auditorium Lobby

8:30 – 8:45 **Welcome**
Marilyn Smith, Georgia Institute of Technology, GA, USA

8:45 – 9:15 **Army Keynote – Future Vertical Lift**
Matthew Munson, Army Research Office and Mahendra Bhagwat, U.S. Army, CCDC

Experiments in Dynamic Stall

9:15 – 10:15 ***State-of-the-Art in Dynamic Stall Experiments***
Anya Jones, Univ. of Maryland; Tony Gardner, DLR;
Karen Mulleners, EFH; Preston Martin, US Army

10:15 – 10:30 **Break**
MARC Auditorium Lobby

10:30 – 10:45 *Experiments in Dynamic Stall at University of Glasgow*
Richard Green, University of Glasgow, UK

10:45 – 11:00 *Interaction of the Leading Edge Vortex and Shear Layer Vortices for an Airfoil Undergoing Dynamic Stall*
Douglas Bohl, Clarkson Univ., NY, USA

11:00 – 11:15 *Modeling the Interplay Between the Shear Layer and Leading Edge Suction During Dynamic Stall*
Karen Mulleners, EPFL, Switzerland

11:15 – 11:30 *Compressible Dynamic Stall in an Unsteady Freestream*
James (Jim) Gregory, Ohio State University, OH, USA

11:30 – 11:45 *Stall Alleviation using Magnetohydrodynamic Plasma Actuators*
Jayant Sirohi, Univ. of Texas at Austin, TX, USA

11:45 – 12:00 *The Effects of Leading Edge Surface Roughness on Dynamic Stall at Low Reynolds Number*
John Hrynuk, U.S. Army Research Lab, MD, USA

12:00 – 1:15 **Attendee Group photo followed by Buffet Lunch**
MARC Auditorium Lobby

1:15 – 1:30 *Cycle-to-Cycle Variation in Dynamic Stall*
Jonathan Naughton, University of Wyoming, WY, USA

1:30 – 1:45 *Dynamic Stall Detection Using Infrared Thermography*
Christian Wolf, DLR, Germany

1:45 – 2:00 *A Photonic Skin Friction and Wall Pressure Sensor for Unsteady Separated Turbulent Boundary Layers*
Tindaro Ioppolo, NY Inst. of Technology, NY, USA

2:00 – 2:15 *Development of a Novel Rotating Volumetric Velocimetry Technique*
Vrishank Raghav, Auburn Univ., AL, USA

2:15 – 3:15 Panel Discussion

3:15 – 3:45 **Break**
MARC Auditorium Lobby

Low-Order Modeling and Theory for Dynamic Stall

3:40 – 4:30 ***State-of-the-Art in Modeling and Theory for Dynamic Stall***
David Peters, Washington Univ. (St Louis), USA; Marilyn Smith, GA Tech, USA

4:30 – 4:45 *Improved Understanding of Flows Past Round Edges for Modeling & Sensing of Vortex Shedding and Stall*
Ashok Gopalarathnam, NC State Univ, NC, USA

4:45 – 5:15 Panel Discussion

6:00 – 7:30 **Reception (Heavy Hors-D'Oeuvres)**
Rooftop Garden of the Clough Learning Center

Wednesday, September 11
MARC Auditorium, Georgia Institute of Technology

8:30 – 8:45 **Welcome**
Marilyn Smith, Georgia Institute of Technology, GA, USA

High-Fidelity Computation of Dynamic Stall

8:45 - 9:45 ***State of the Art in Dynamic Stall Computational Predictions***
Rohit Jain, U.S. Army; Francois Richez, ONERA;
Tony Gardner, DLR; Marilyn Smith, GA Tech

9:45 - 10:00 *On the Use of High Order FE Methods for 3D Dynamic Stall Simulation Over Rotating Blades*
John Ekaterinaris, Embry-Riddle Aeronautical Univ., FL, USA

10:00 - 10:15 *High-fidelity Simulation and Flow Control of an Airfoil Under Dynamic Stall Conditions*
Rinato Miotto, Ohio State University, OH, USA

10:15 - 10:45 **Break**
MARC Auditorium Lobby

10:45 - 11:00 *Contribution on Numerical Simulation of Dynamic Stall*
George Barakos, Univ of Glasgow (presented by Richard Green)

11:00 - 11:15 *CFD Simulations of Dynamic Stall on Helicopter Rotors*
Johannes Letzgus, Univ. of Stuttgart, Germany

11:15 - 11:30 *Collaborative Airfoil Design for Mitigating Dynamic Stall*
Vineet Ahuja, CRAFT Tech, PA, USA

11:30 - 12:15 **Panel Discussion**

12:15 - 1:15 **Lunch Buffet**
MARC Auditorium Lobby

Control of Dynamic Stall

1:15 - 2:00 ***State of the Art in Control and Mitigation of Dynamic Stall***
Ari Glezer, GA Tech

2:00 - 2:15 *Dynamic Stall Control by NS SDBD Actuators*
Andrey Starikovskiy, Princeton Univ, NJ, USA

2:15 - 2:30 *DLR activities in flow control to mitigate dynamic stall*
Tony Gardner, DLR

2:30 - 2:45 *Pitch Rate Induced Separation Delay Modeling of Dynamic Stall and Stall Flutter*
John Farnsworth, Univ of Colorado at Boulder, CO, USA

2:45 - 3:15 **Break**
MARC Auditorium Lobby

3:15 – 4:15 **Discussion:** *Future Research Directions and Needs*
Matthew Munson, U.S. Army Research Office

4:15 – 4:45 **Concluding Remarks**

4:45 **Adjournment**

Table of Contents

Experiments

State of the Art in Dynamic Stall Experiments

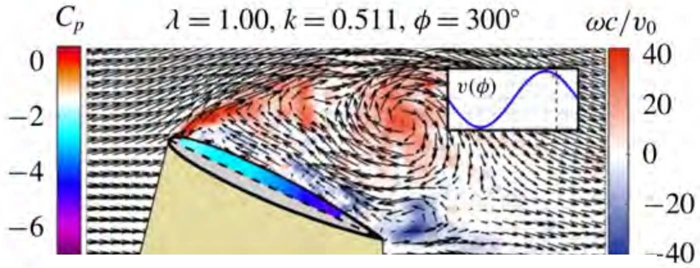
Anya Jones, UMD
Tony Gardner, DLR
Karen Mulleners, EFH
Preston Martin, US Army

Dynamic stall workshop — experimental team
What experiments exist?

Tony Gardner (DLR)

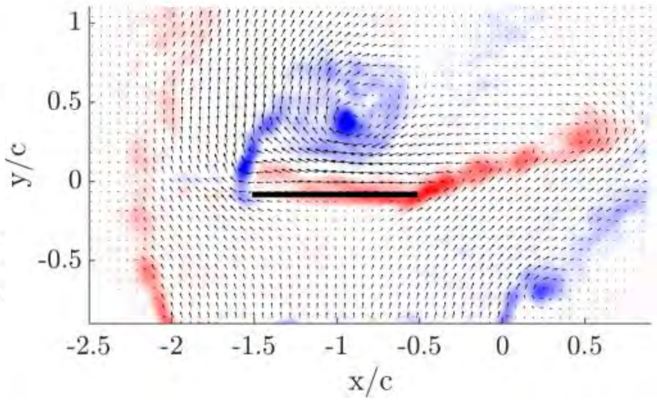
Simple experiments, low Reynolds number

Typical types of experiments:
- Geometries
    - airfoils/flat plates
    - fixed/rotary wing
- Maneuvering conditions
    - impulsive start and/or pitch
    - periodic motions including pitching, plunging, surging, flapping
- Unsteady inflow conditions (e.g., gust encounters, unsteady wind tunnels, BVI).
- Leading Edge Vortices: Mechanics and Modeling, *Annual Review of Fluid Mechanics,* 2019, Eldredge and Jones

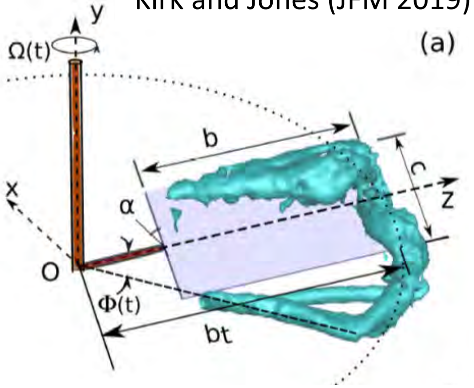


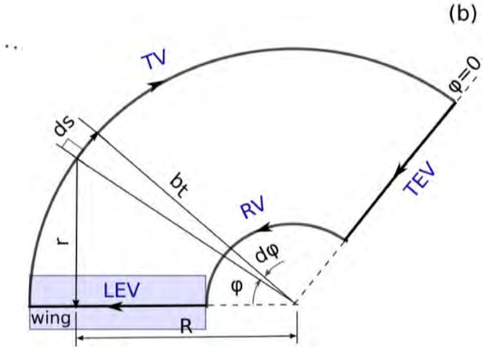
Surging wings oscillating into reverse flow, Kirk and Jones (JFM 2019)

Gust Encounter

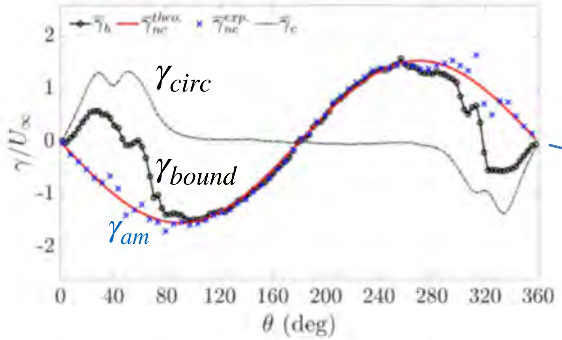


Gust encounters, Babinsky, et al. and Jones, et al. (not shown)

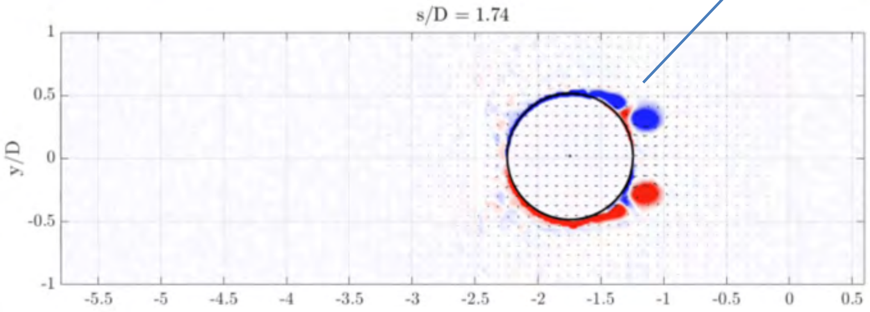




PIV visualization of 3D loop, AR=2
(Carr, DeVoria, Ringuette, *JFM* 2015)



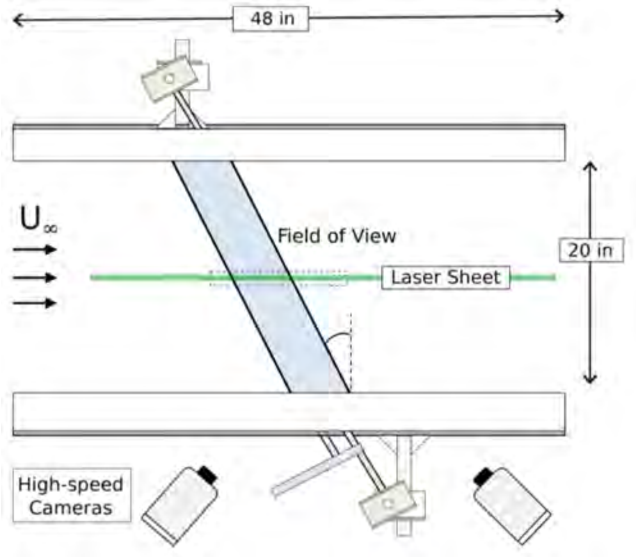
Boundary layer vortex sheets around cylinder



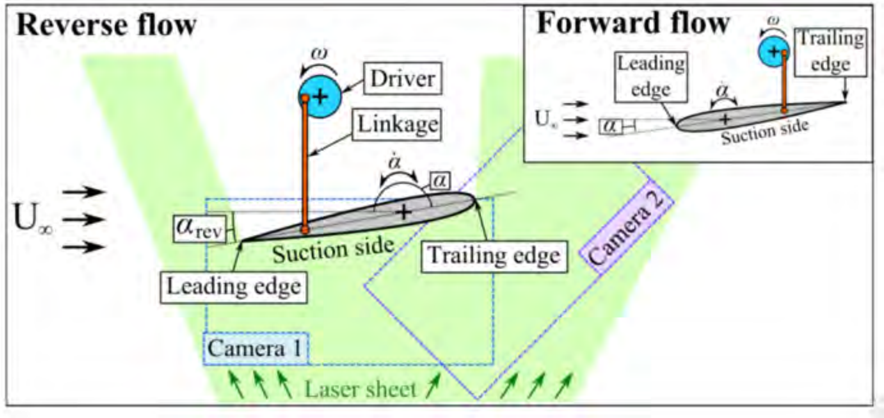
Comparisons with classical theory, Babinsky, et al.

Pitching airfoil experiments

- Very large number of test stands:
  - Glasgow, PolyMi
  - DLR, NASA, Onera, Army, Boeing, Sikorsky
  - Uni. Wyoming, Ohio state, Georgia tech, UMD, Notre Dame
  - And many, many more
- Variable quality on:
  - Sensor response
  - Pitching angle control
  - Facility effects: wind tunnel sidewall and ground/roof interference, tunnel flow quality
  - Contour precision
  - Roughness and transition control
  - Airfoil stiffness (bending and torsion)
  - DAQ: number of cycles, rate and length of acquisition
  - Tripped/untripped and trip thickness
- Many experiments use relatively low inflow speeds and pitching frequencies



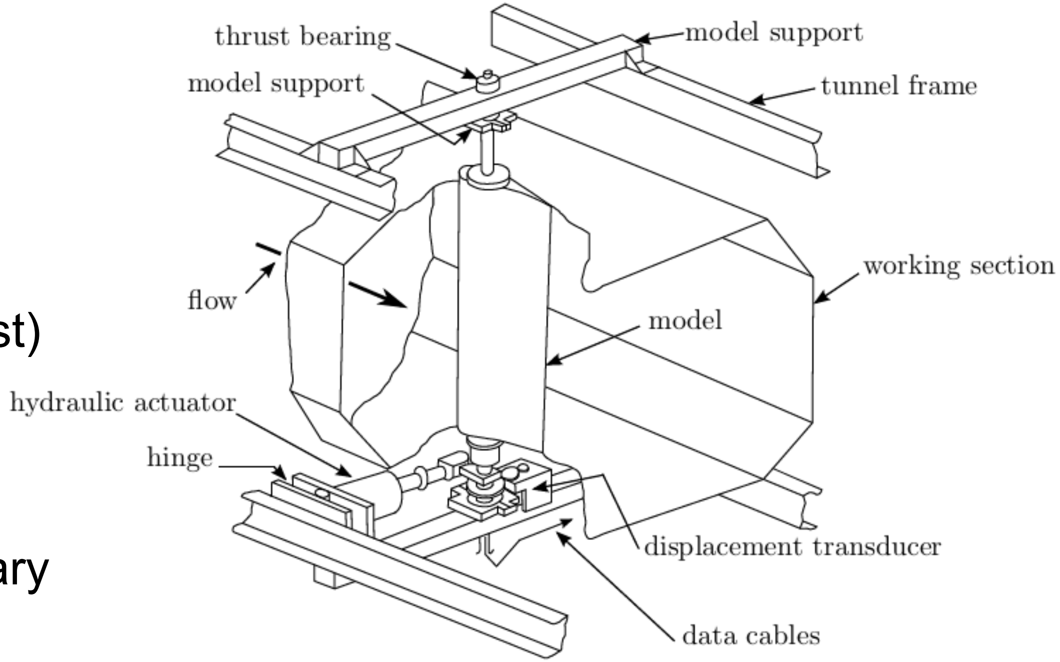
UMD: Smith and Jones, PRF, 2019



UMD: Lind and Jones, PoF, 2016

Pitching airfoil experiments (continued): Re>5e5

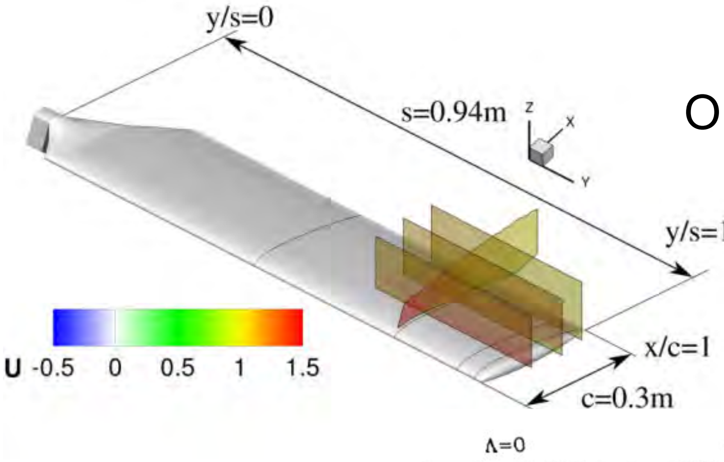
- Lately used for qualification of measurement techniques and dynamic stall control
- Existing datasets
  - DLR: OA209, DSA-9A
  - Army/Boeing: VR7, VR12 (Availability: VLRCOE members)
  - NASA: VR7, VR12, others?
    - Also older McCroskey, Piziali, McAlister data
  - Glasgow: 14 airfoils from 1980s and 1990s
  - UMD: NACA 0012 and NACA 0024 (Available on request)
  - Technion: NACA 0015 (Available at https://www.flowcontrollab.com/data-resource)
  - Onera: OA209 (Availability?)
- General assumption is that a structural model is not necessary and that the airfoil is known
- Many newer datasets for wind turbine airfoils
- Some flexible airfoils? AF Academy?
- **A-B comparisons are probably considerably more accurate than the absolute values**



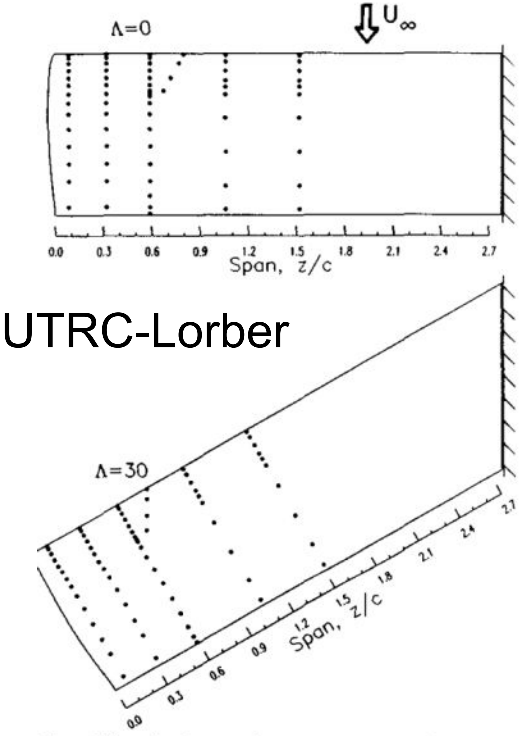
Glasgow University

Pitching finite wing

- 3D flow and wingtip effects
- Can be very sensitive to wall connection geometry
    - Sensitivity reduced by positive twist.
    - CFD situation of untwisted wing with nonslip wall is not experimentally realizable
- Increased bending and torsion
- The finite wing produces 2D flow at least as good as the 2D airfoil. (Gardner, A.D., et al., JAHS 2019)
- The effect of sweep (e.g., Lorber)



Onera-OA209



UTRC-Lorber

Fig. 1 Wing planforms and upper surface transducer locations.

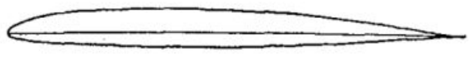
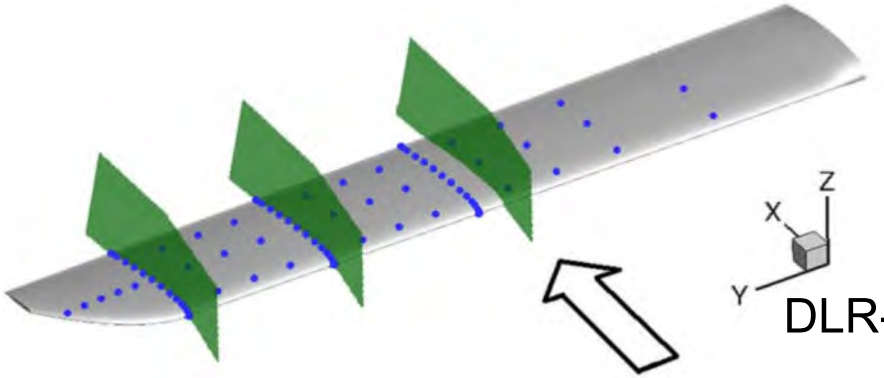
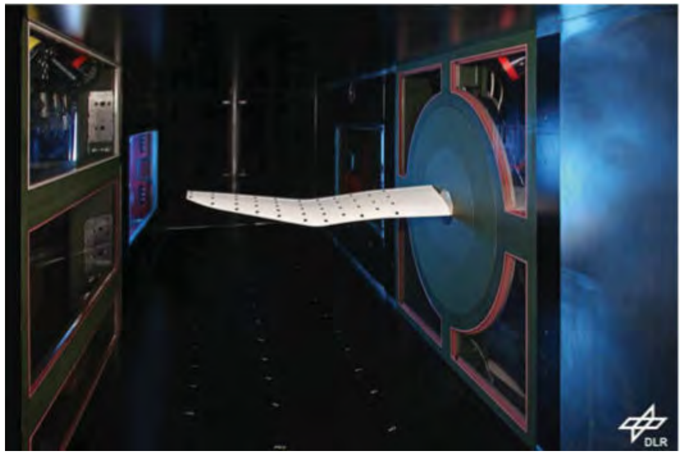


Fig. 2 SSC-A09 airfoil section.



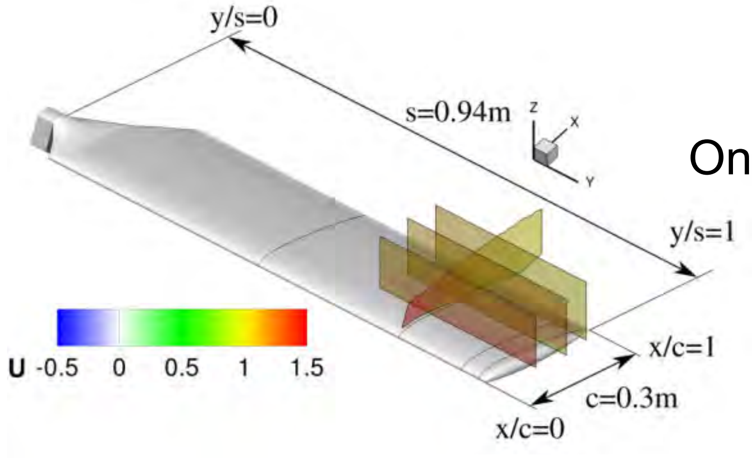
DLR-Merz



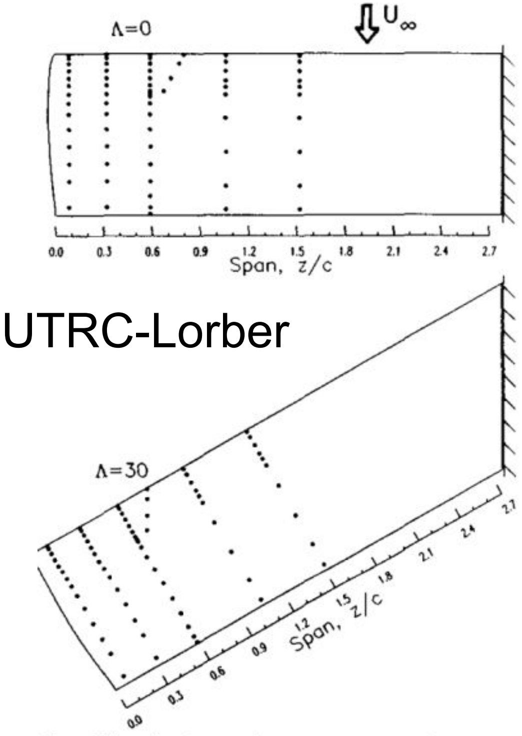
DLR-Möwe

Pitching finite wing (continued)

- Lately used for code validation without rotation
- Datasets:
  - DLR: DSA-9A + Parabolic Wingtip;
    - EDI-M109/EDI-M112 with ERATO planform (Airfoil not freely available)
  - Onera: OA209 + simple wingtip
  - UTRC: Sikorsky SSC-A09 + simple wingtip
  - NASA: NACA0015
  - US air force academy: NACA0015



Onera-OA209



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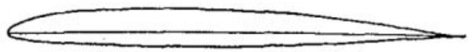

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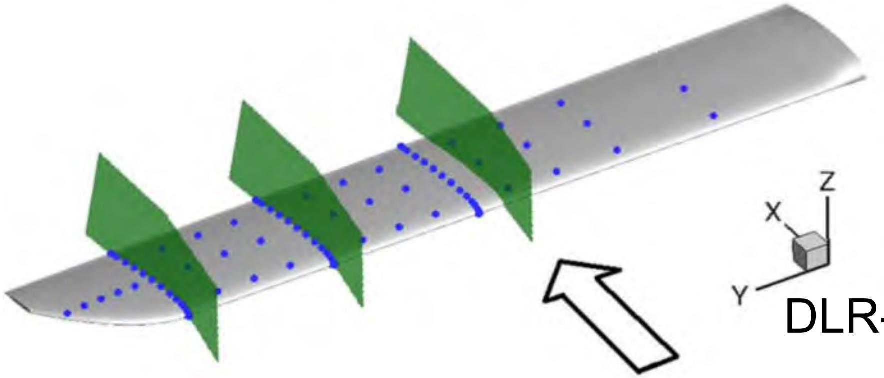
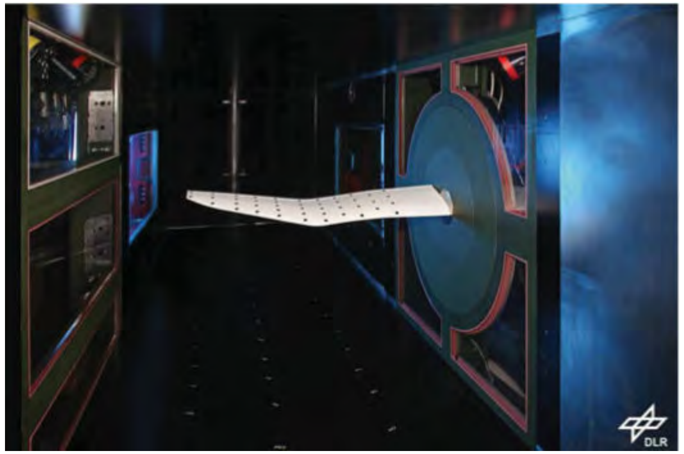


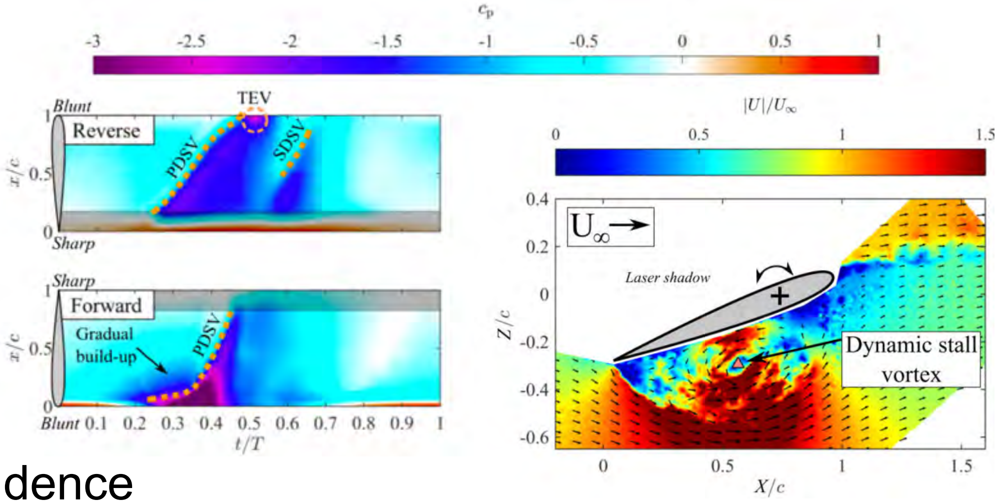
DLR-Merz



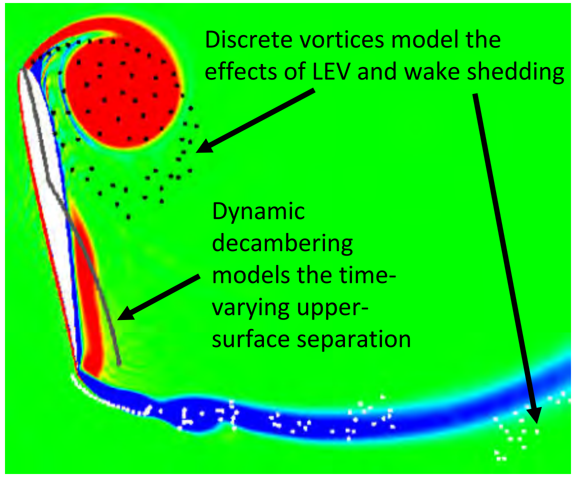
DLR-Möwe

Other variants

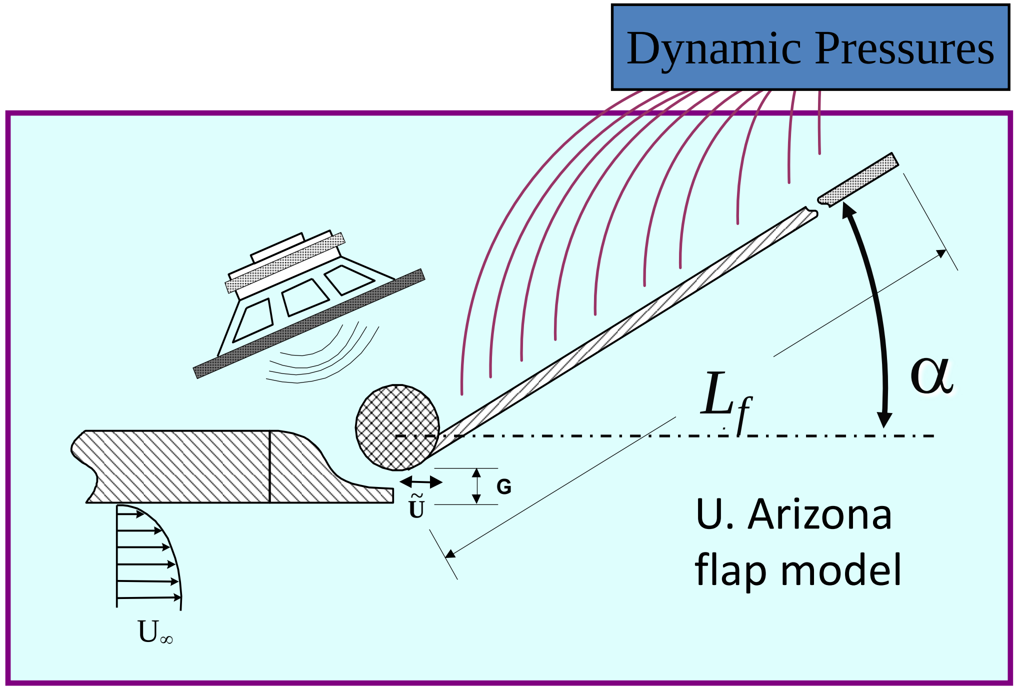
- Pitching vs plunging
    - Very difficult to achieve directly comparable flows
    - Differences to gusts/vortex encounter/maneuvers?
- Reverse dynamic stall (sharp edge dynamic stall)
    - Early flow separation, slower pressure wave, little Re dependence
    - Large variations in behavior with advance ratio reduced frequency
- Ramping motion vs pitching motion
    - Vortex progression after stall can be atypical of rotorcraft
    - Few experiments with good periodicity and many samples
    - Practical for CFD validation?



UMD reverse flow
Lind and Jones, PoF, 2016



NC State pitching airfoil



U. Arizona flap model

Parameters characterizing DS experiments

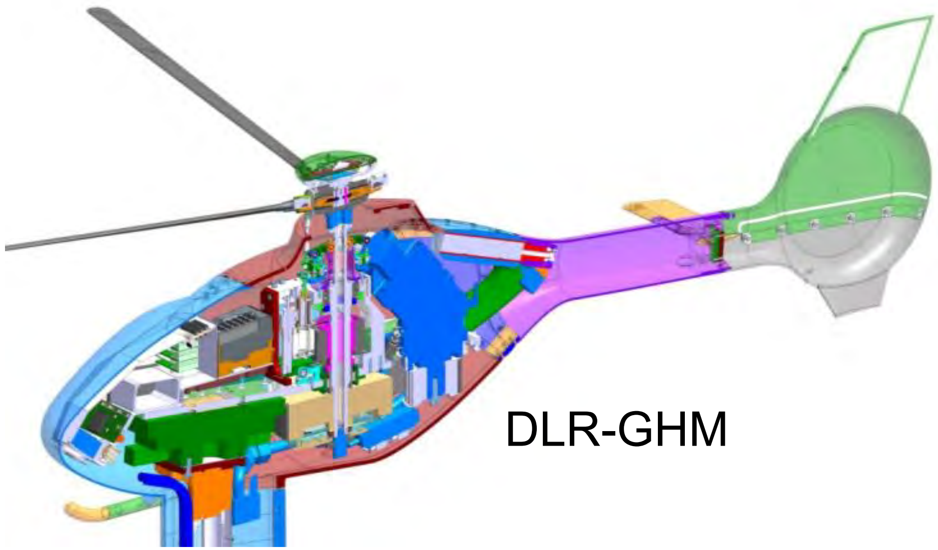
- Airfoil/blade geometry
  - 3D vs. 2D
  - Blunt vs. sharp LE/TE
  - Thick vs. thin
- (Unsteady) flow conditions
  - Advance ratio
  - Reduced frequency
- (Unsteady) airfoil/wing kinematics
  - Pitch amplitude
  - Mean blade incidence
  - Reduced frequency
- Re number
- Mach number

Things to think about:

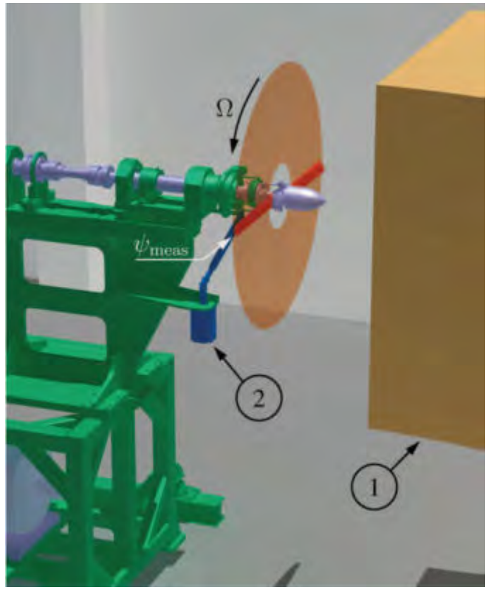
- What else?
- When are each of these important? (What parameter space?)
- Why? (What are the underlying physics?)

Stiff rotor

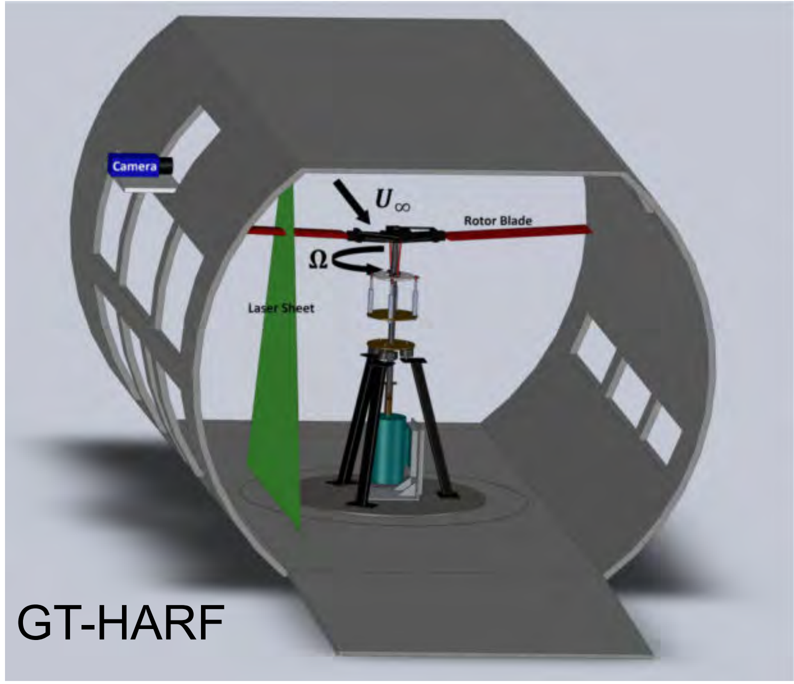
- Small-scale rotors with very stiff blades
- Reynolds-number problems?
- Better equipment and optical measurements due to lower cost of operation
- Operation into deep dynamic stall!
- 3D flow is difficult to properly visualize
- Many small-scale experiments have blades of too low AR and/or very bulky hubs/mounting.



DLR-GHM



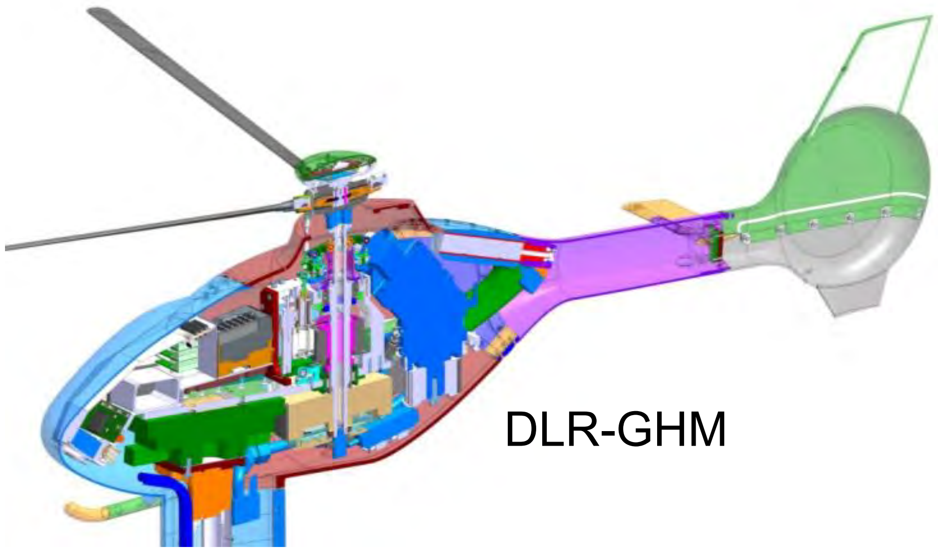
DLR-RTG



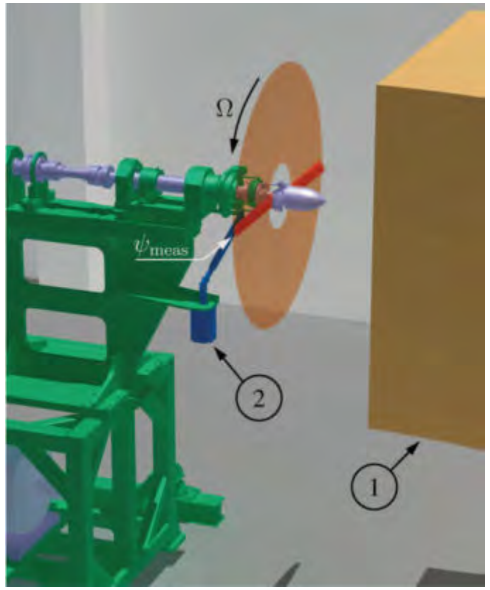
GT-HARF

Stiff rotor

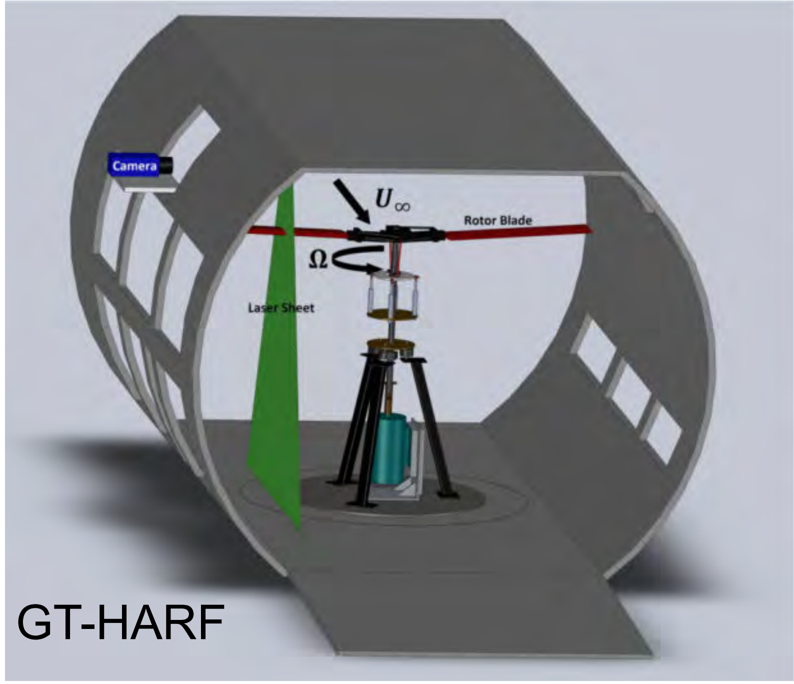
- Lately used for code validation with rotation
- Datasets:
    - DLR: RTG axial inflow
    - Georgia Tech high advance ratio facility
    - TUM Rotor under development
    - DLR wind tunnel rotor under development (planned for 2018, coming 2020)
    - Wind energy datasets?



DLR-GHM



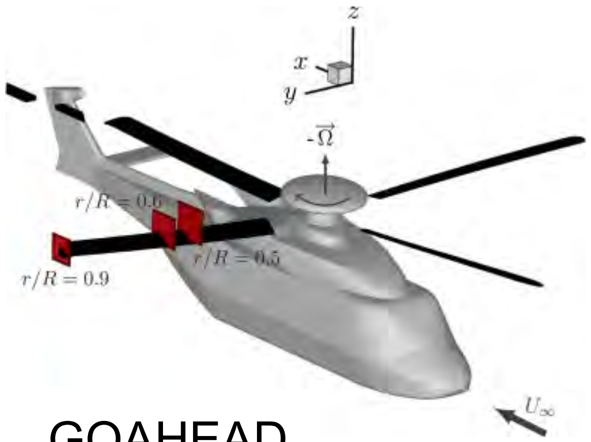
DLR-RTG



GT-HARF

Flexible rotor in the wind tunnel

- GOAHEAD – Data only freely available to the GOAHEAD group. Structural and aero models exist. Data taken for a relatively small number (40) of cycles.
    - Trim and reproducibility problems near stall
    - Large cycle-cycle variations
- 7A/7AD – Freely available, well used, structural and articulation model, requires computing wind tunnel walls and mount
- UH60A – Large test matrix including slowed rotor
    - Points 9125/9145/9175 computed using RCAS/Helios. Availability: Tom Norman (NASA ARC)
    - Thrust sweep and speed sweep
- UMD GLMWT (PIV, some pressures)
- PSP Rotor?



GOAHEAD

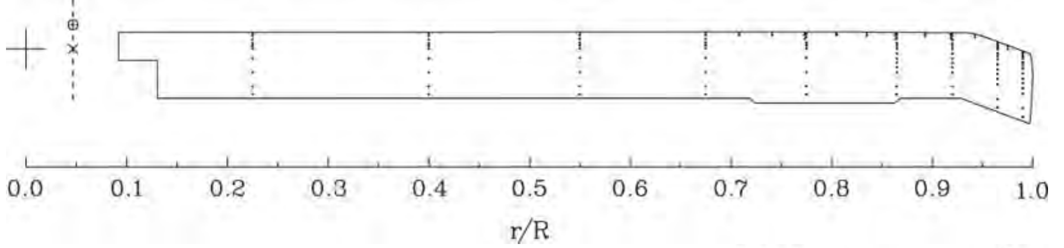
Fig. 1. Picture of 7A rotor in the S1MA wind-tunnel.

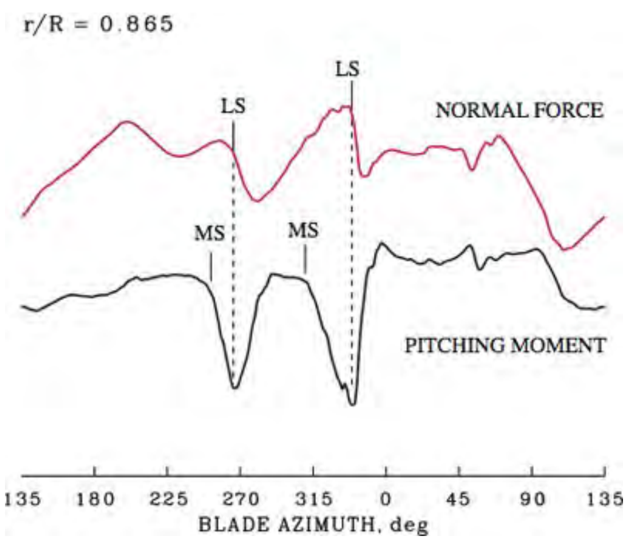
UMD GLMWT

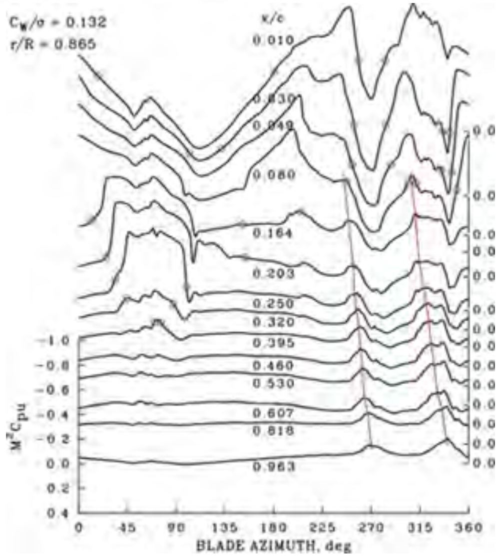
Flight tests

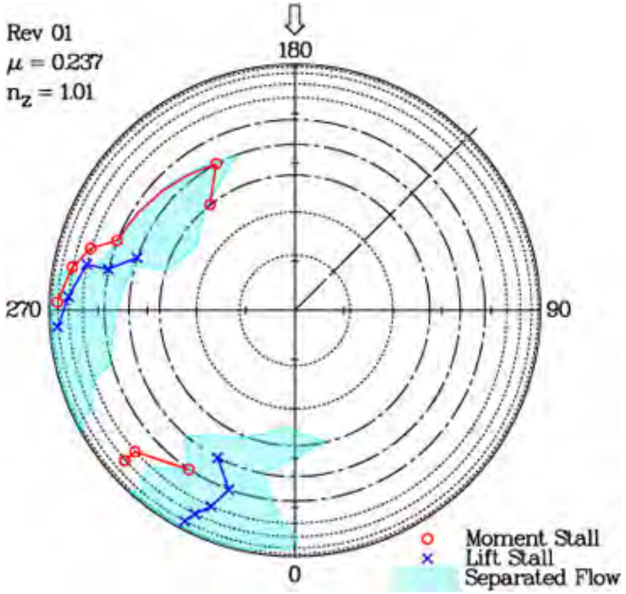
- UH60A (Images from UH60 airloads program tutorial)
- Data availability
- Detection via 242 pressure sensors, individual analysis and integrated
- DS in level flight: counter 9017 – Airloads workshop case (μ=0.3, Ct/σ=0.12)
    - Availability: Bob Kufeld (NASA ARC)
- DS in pull-up: counter 11029

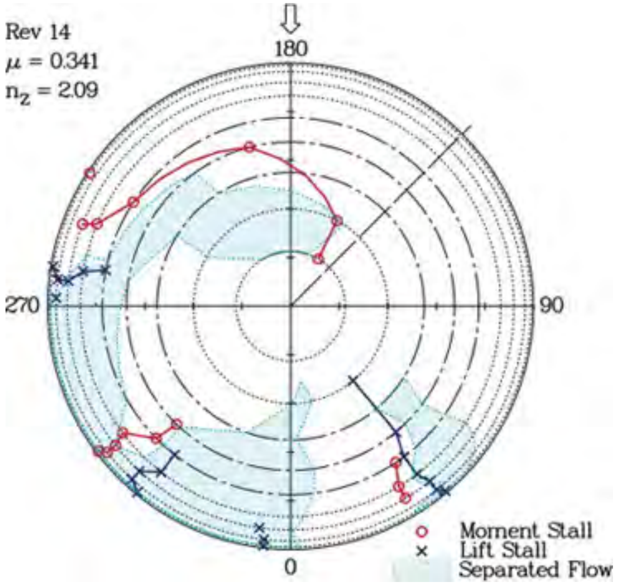
NASA UH-60











Measurement techniques

✘	Not yet used in this situation
✓	Used for Dynamic stall
(✓)	Used but not for dynamic stall

Method	Pitching airfoil	Finite wing	Rotor in Lab.	Rotor in WT	In Flight
Pressure measurements by sensor	✓	✓	✓	✓	✓
Hot-film analysis	✓	✓	?	(✓)	✘
PIV (2C)	✓	✓	✓	✓	(✓)
Micro-PIV	✓	?	?	✘	✘
Tomo-PIV and STB	✘	✘	✓	✘	✘
PSP/TSP	✓	✘	(✓)	(✓)	✘
BOS	(✓)	(✓)	(✓)	(✓)	(✓)
DIT for BL Transition	✓	✓	✓	(✓)	(✓)
DIT for stall detection	✓	✘	✓	✘	✘

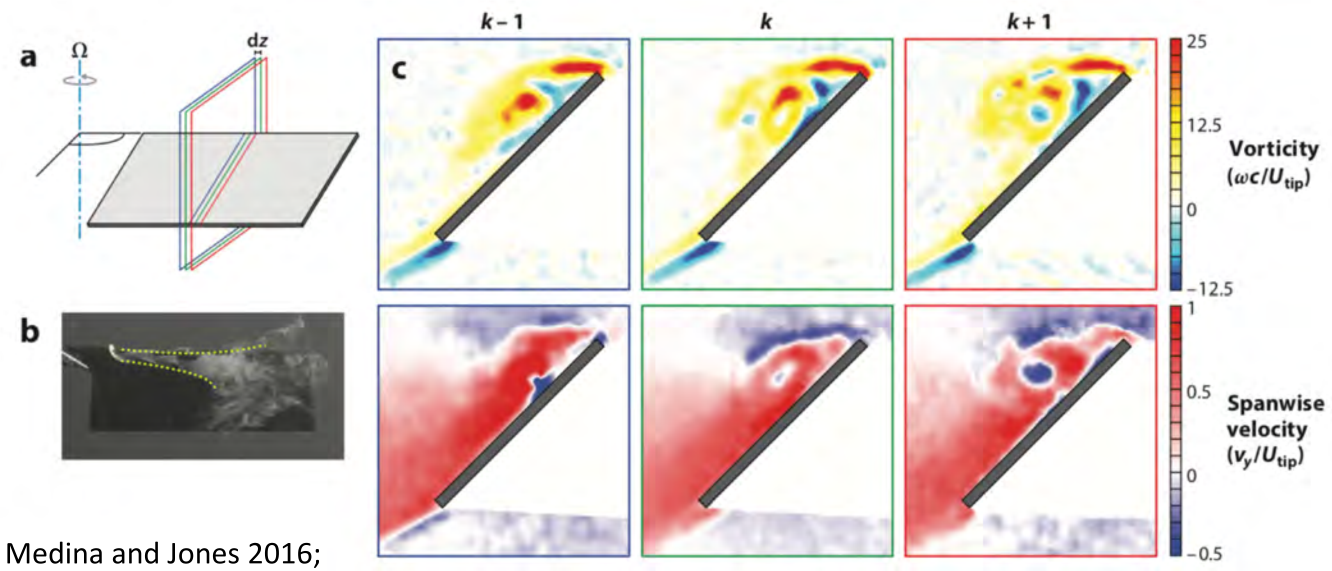
Dynamic stall workshop — experimental team
What have we learned from these experiments?

Anya Jones (UMD), Karen Mulleners (EPFL)

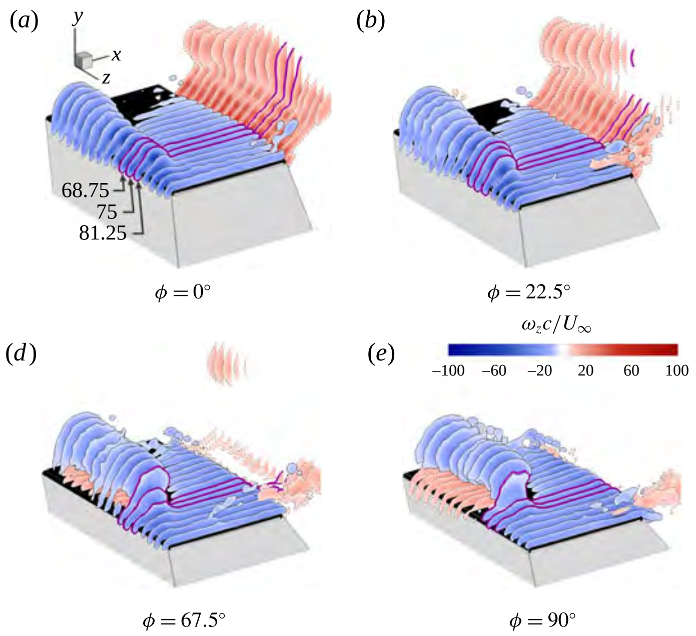
Simple experiments, low Reynolds number

- **Dynamic stall vortex** = (single) coherent leading edge vortex
- Force decomposition into circulatory and non circulatory contributions including added mass
- Rotating wings
  - Attached LEV for duration of wing rotation
  - Vortex burst
- 2D kinematics (pitching, surging, plunging)
  - LEV grows and sheds quickly (like “classical” dynamic stall)

- Significant discussion regarding
  - How to define the extent of the LEV
  - How to define LEV shedding
  - How to predict LEV strength and trajectory



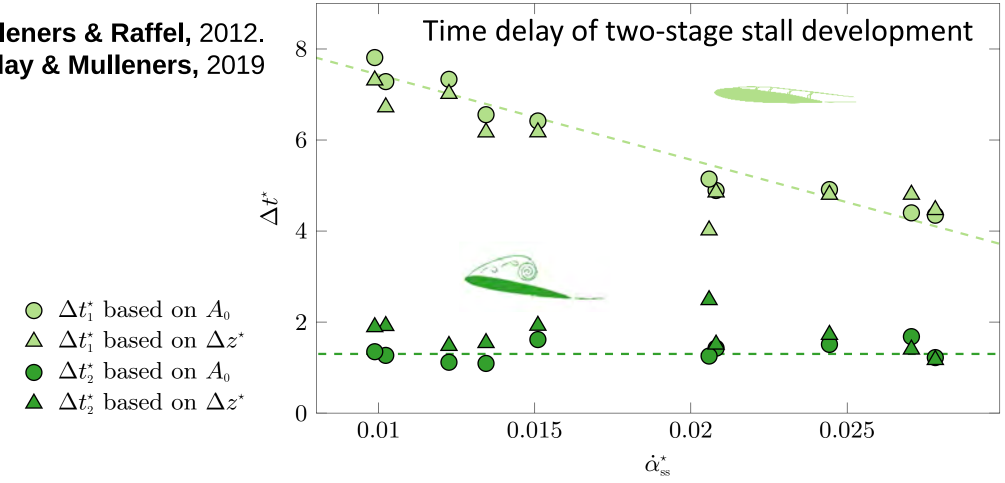
Medina and Jones 2016;
Eldredge and Jones 2019 (ARFM)



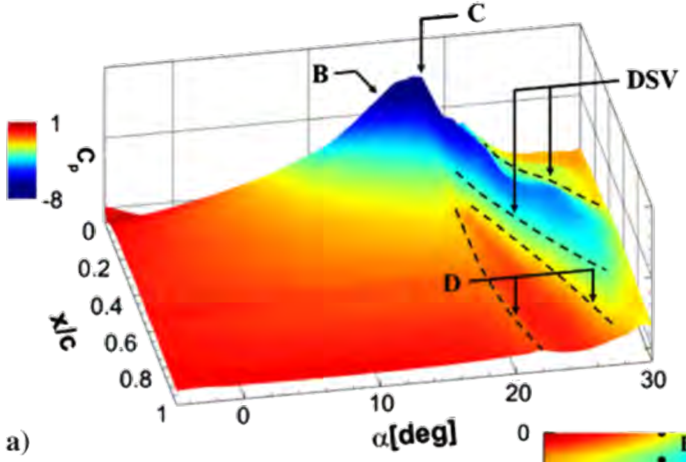
Akkala, J.M. & Buchholz, J.H.J., 2017. Vorticity transport mechanisms governing the development of leading-edge vortices. *Journal of Fluid Mechanics*, 829, pp.512–537.

Pitching airfoil experiments at higher Re

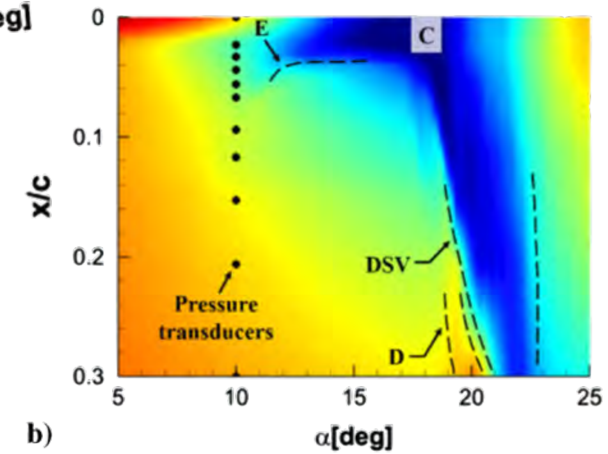
Mulleners & Raffel, 2012.
Deparday & Mulleners, 2019



- **Dynamic stall vortex** consists of various small scale coherent structures
- **Dynamic stall onset**:
  - Origin at LE for low Re
  - Change from “trailing-edge stall” at low frequencies to “leading edge stall” at higher frequencies → different force curves (sharp vs slow roll-off on lift)
  - Separation point does not have to be at the leading edge
    - e.g.OA309 stalls initially at about x/c=0.2
    - shock-induced dynamic stall separates at the shock position
  - High flow speeds: shock-buffet type stall, with circulation shedding through a small-vortex shear stream rather than a single dynamic stall vortex
  - High Ma: increasing pitching moment with increasing angle of attack instead of low Ma pitching moment peak

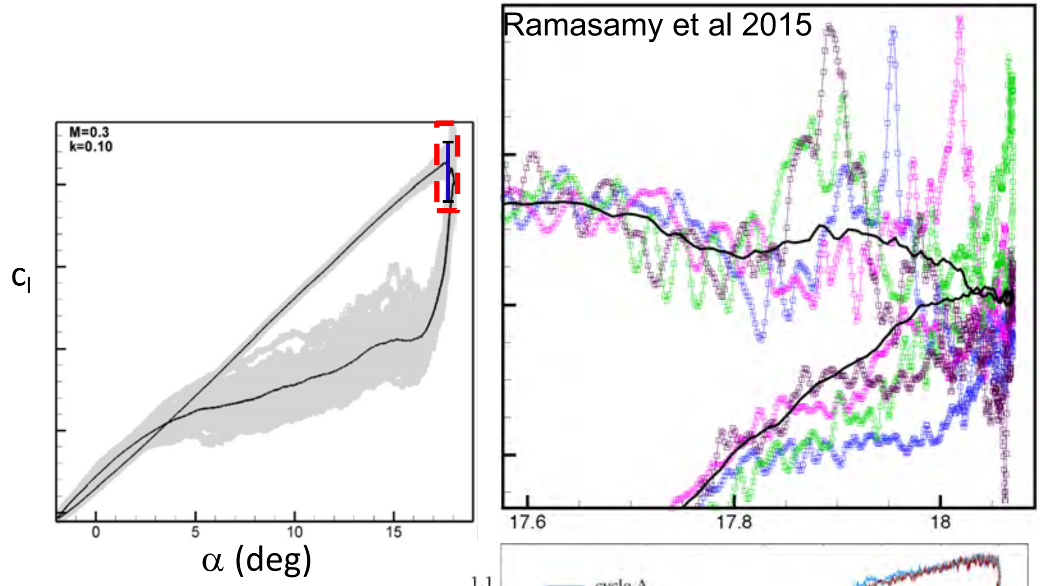


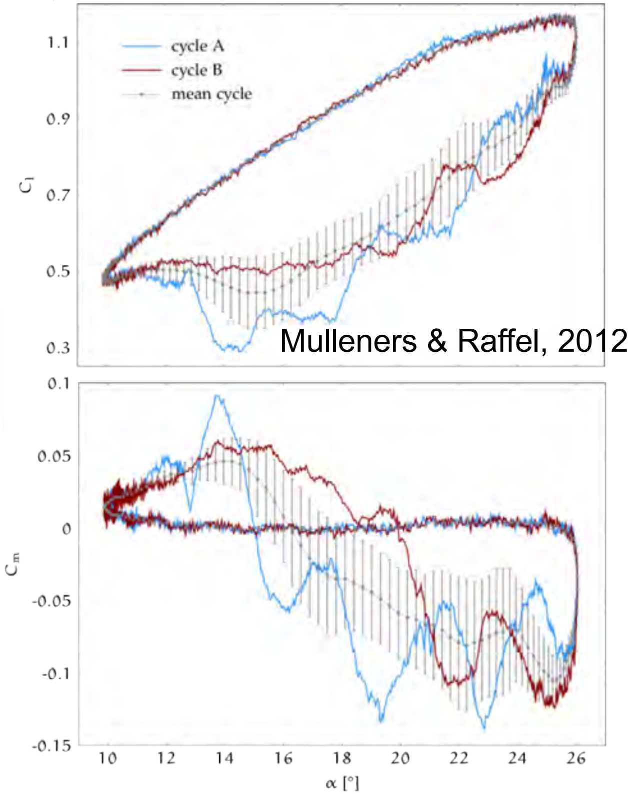
Gupta, R. & Ansell, P.J., 2019. Unsteady Flow Physics of Airfoil Dynamic Stall. *AIAA Journal*, 57(1), pp.165–175.

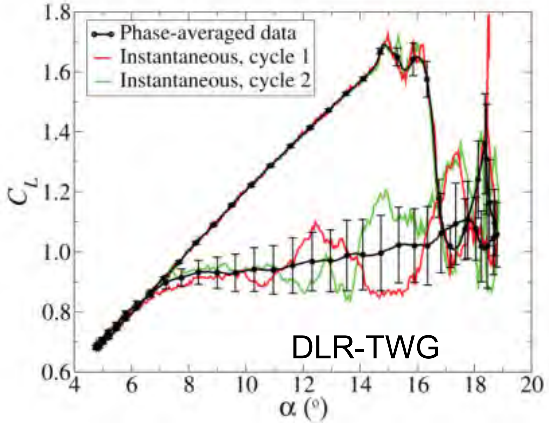


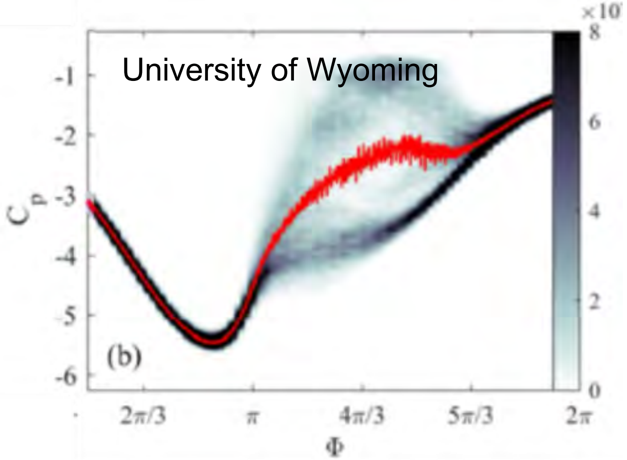
Pitching airfoil experiments at higher Re

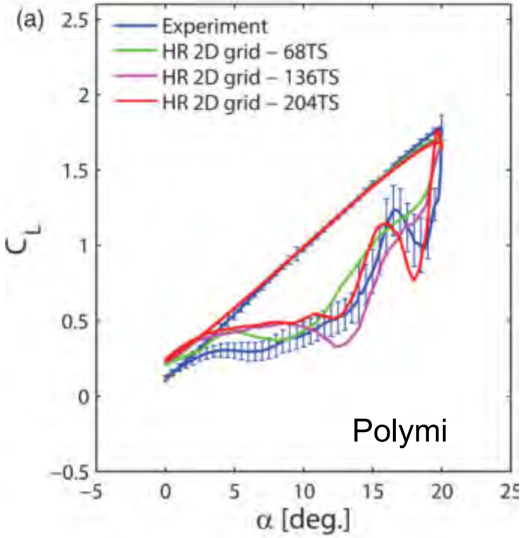
- **Cycle-to-cycle variations** of the flow and forces occur after stall onset.
  - They are often <u>not</u> experimental uncertainties.
  - They are relevant and should <u>not</u> be averaged out.
    - Preferably analyze instantaneous data directly
    - For statistical relevance ensemble average the derived quantities
    - Origin:
      - Light vs deep stall
      - Vortex shedding during full stall





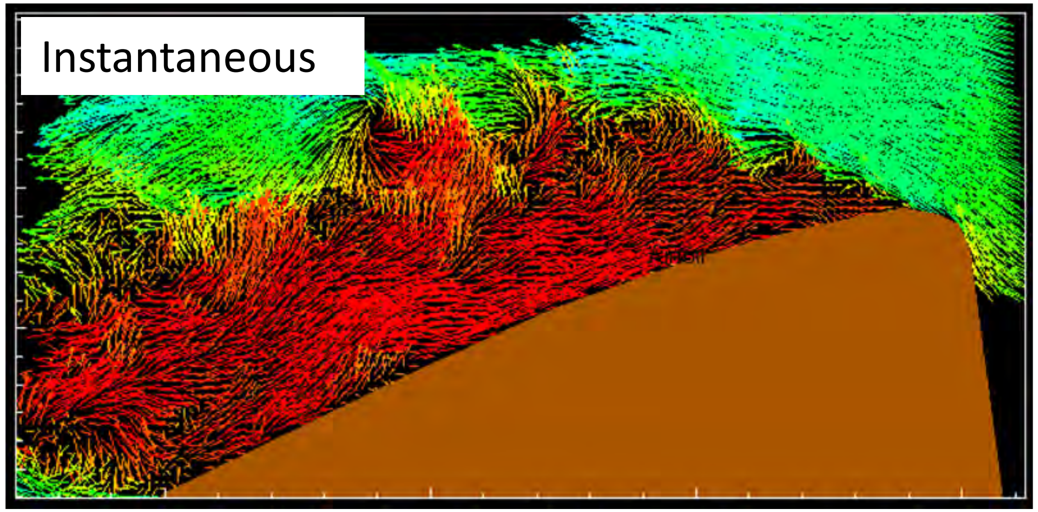


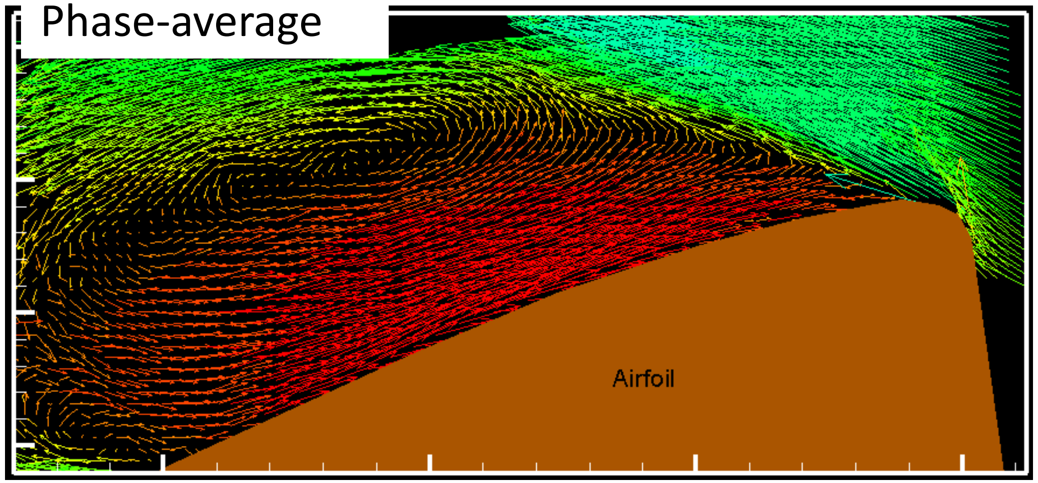


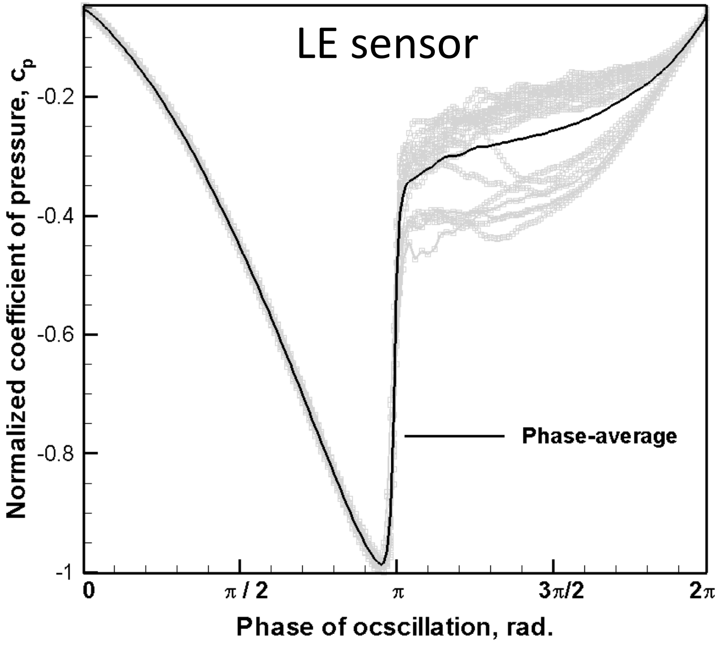


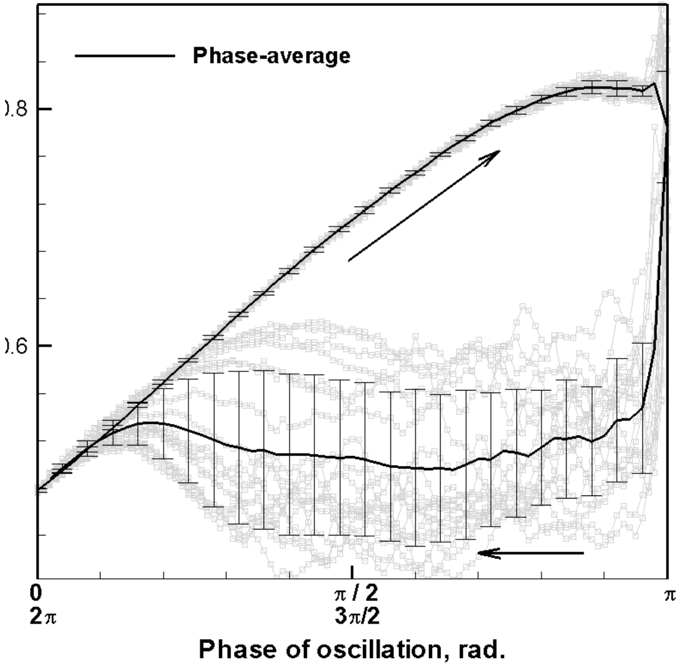
Cycle to Cycle Variation

- Phase-average and variance do not represent observed flow variations. Variations are not turbulent fluctuations.
- Furcation seen in individual pressure sensors – appear as scatter in integrated loads.
- Need to cluster the data





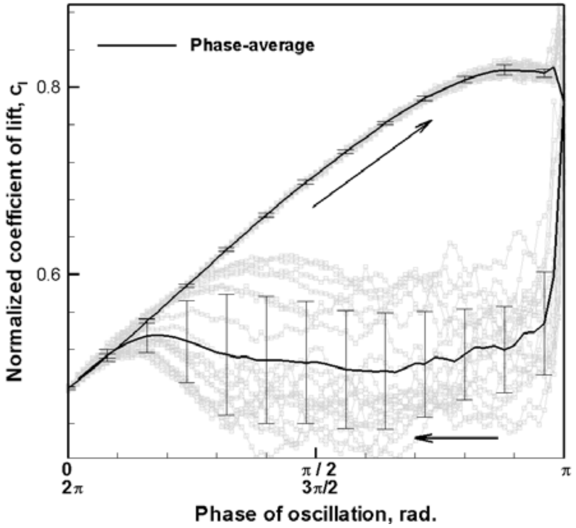


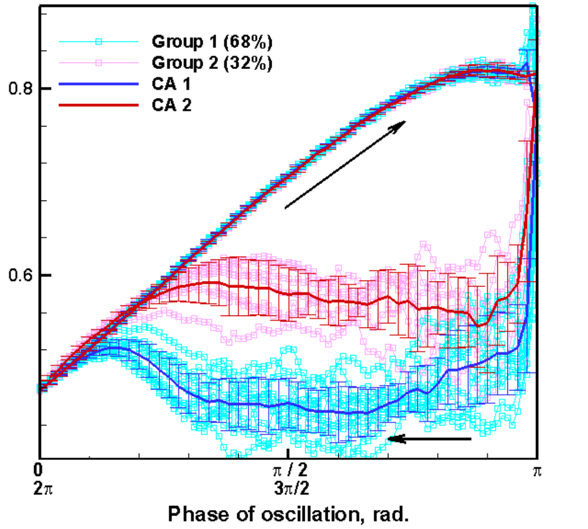


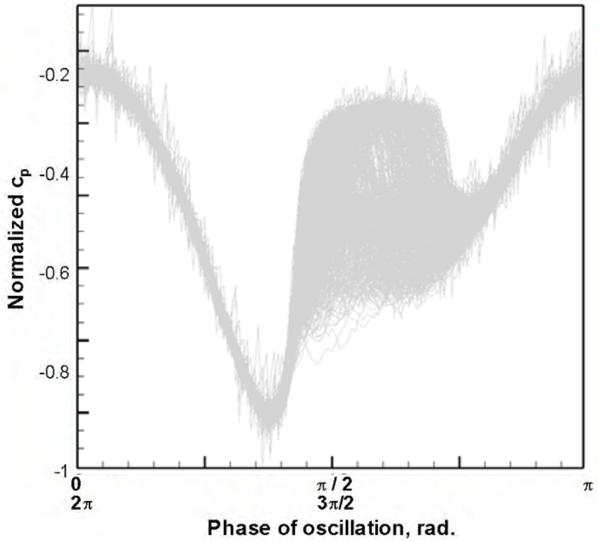
Data Driven Clustering – Advanced data analysis

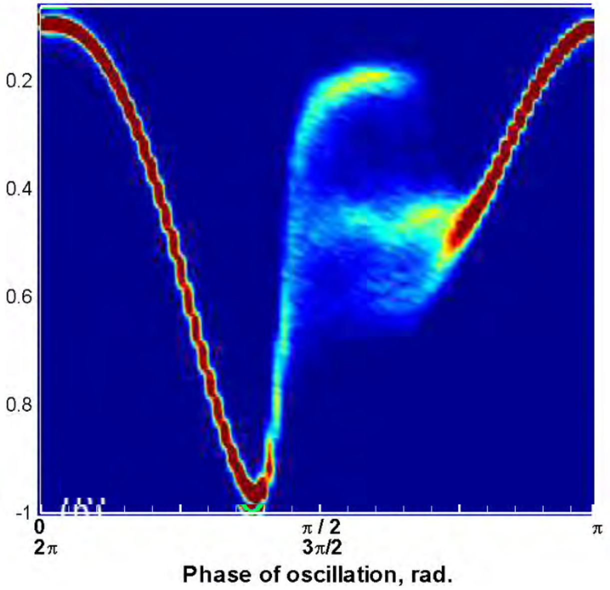
- Replace phase-average and variance with
  - Cluster-average, variance, proportion, and probability of occurrence
- Existing clustering techniques do not provide explainable groups and are not repeatable

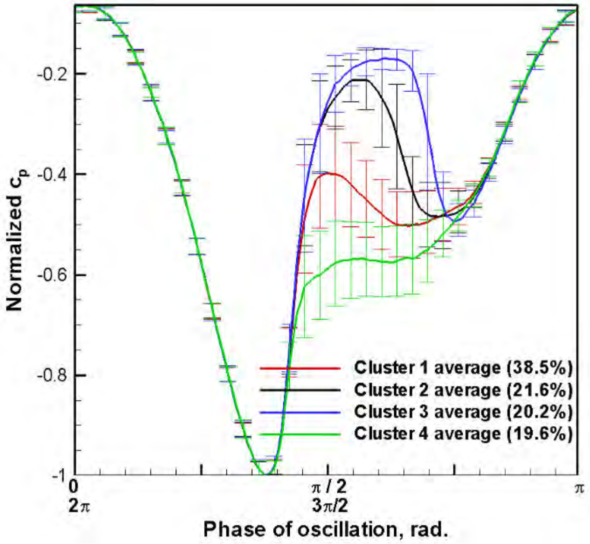
- POD based data driven clustering produce reliable/repeatable/explainable results.

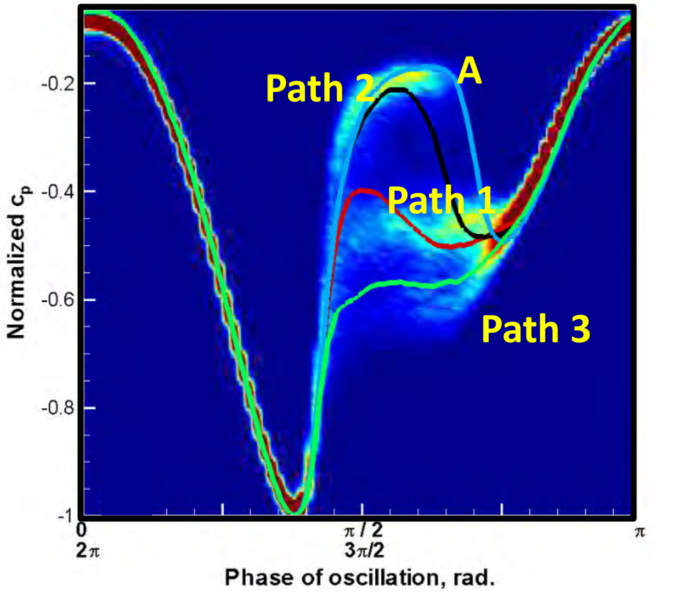




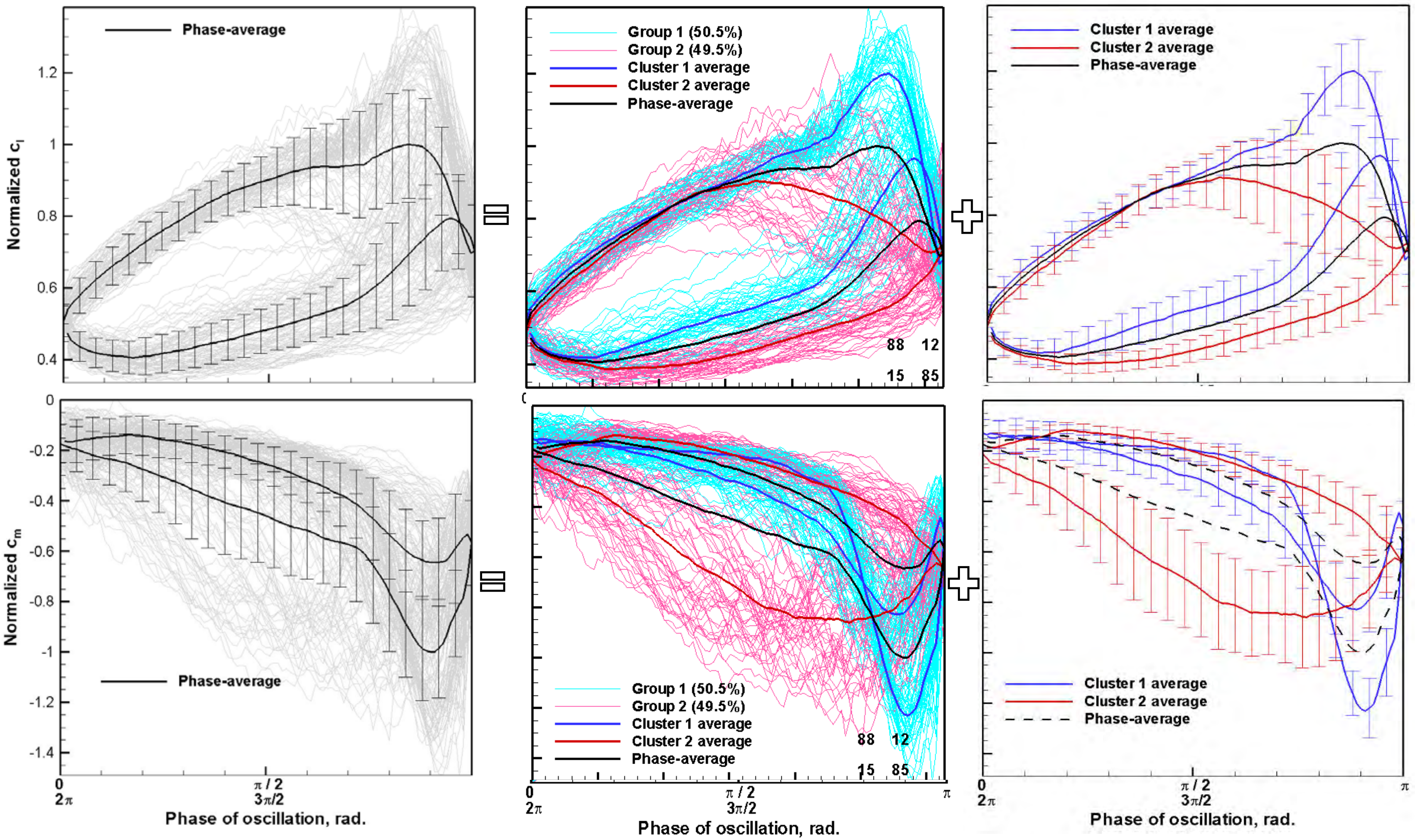








Phase-average combines various physical mechanisms

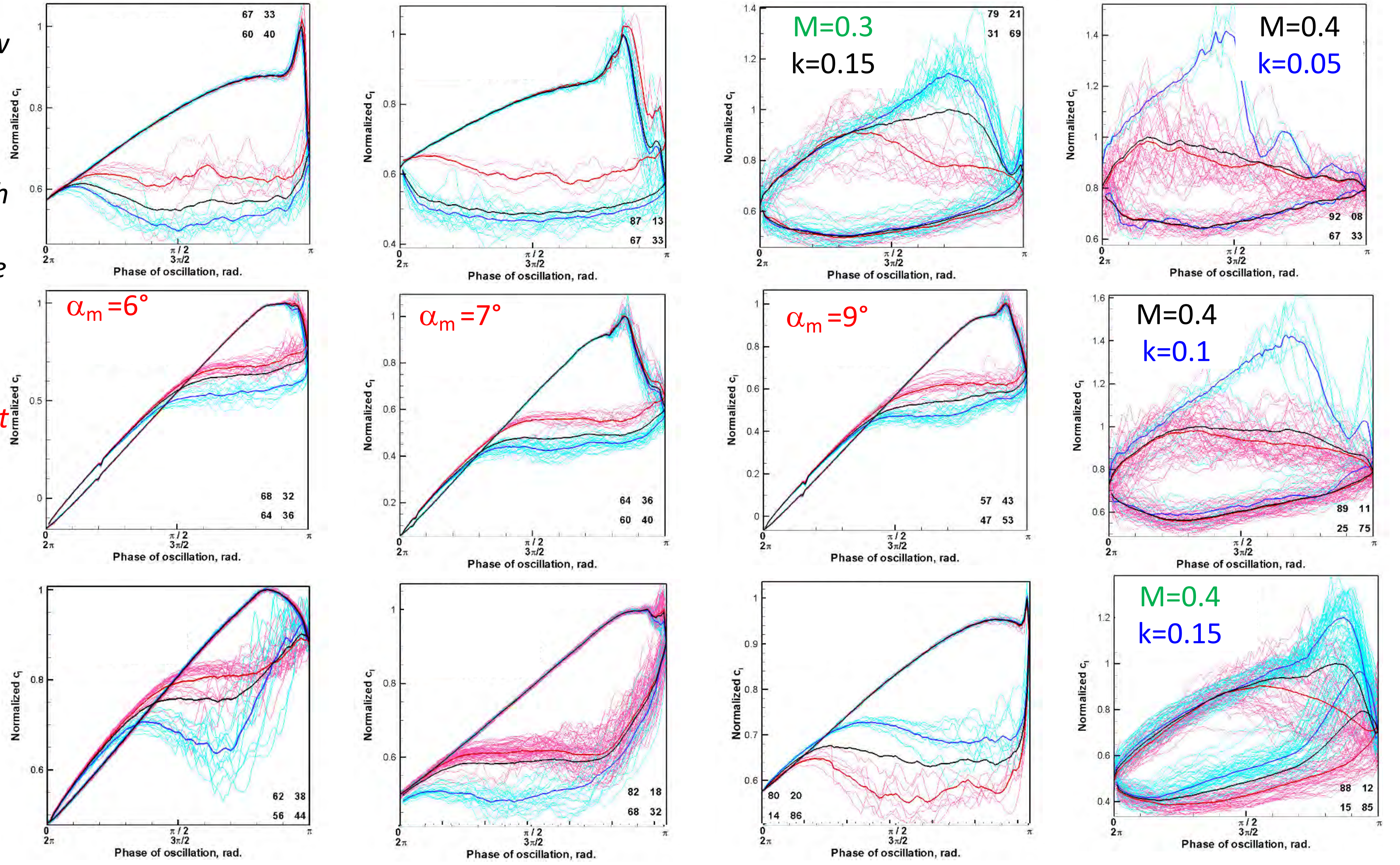


- Phase-average is not within 1σ variation at peak loads
- Counter clockwise loop in cm is missing in phase-average
- Clustering represents the variations better – reduced uncertainty

Prevalence of Clusters Across k, α_m and M

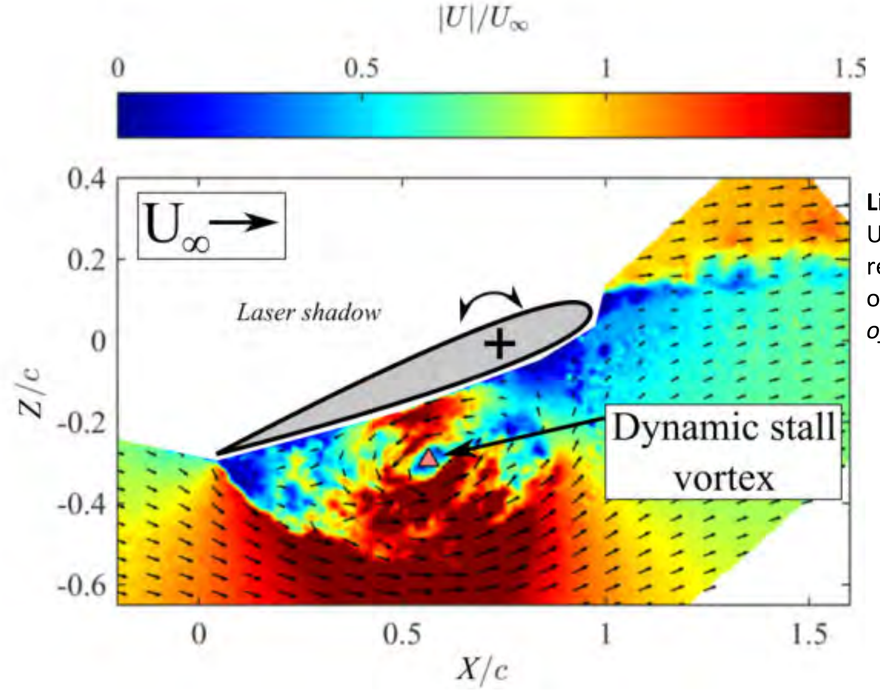
"The fundamental nature of the flow about a stalling wing is one of chaos. There is a general overall flow state with pseudo-random variations about it varying the depth of the stall. This, when using the data to validate CFD predictions, the chaotic aspect of the phenomenon should be considered. The results presented in the basic data set are cycle-averaged. This may or may not be representative of the individual cycles. In many cases, the C2C variation can be significant. It may be useful to look at the individual cycles or delete a few cycles from the average when in the minority - nonrepresentative."

- Piziali, R. A., 1994
NASA TM 4632

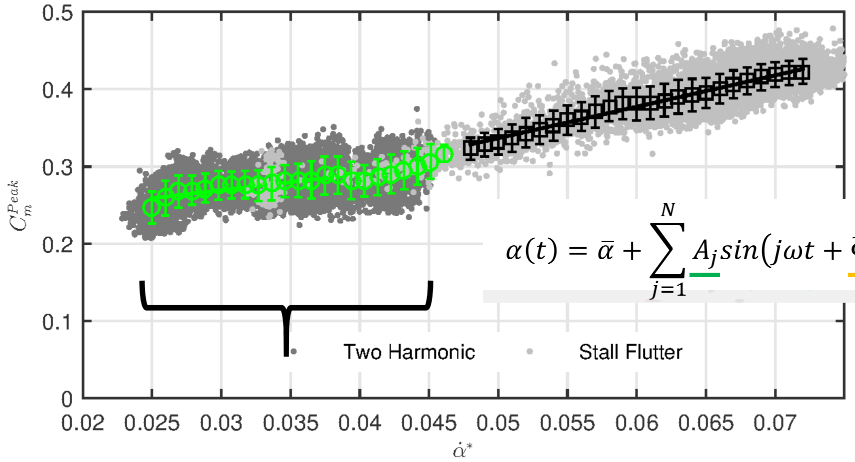


Other variants

- Reverse dynamic stall (Sharp edge dynamic stall):
  - Early flow separation, slower pressure wave, little Re dependence
  - Large variations in behavior with advance ratio reduced frequency
- Ramping motion vs pitching motion
  - Vortex progression after stall can be atypical of rotorcraft
- Pitching vs plunging
  - Very difficult to achieve directly comparable flows
- Moving airfoil vs varying inflow
  - Effect of buoyancy force (and added mass)
  - Still some controversy (Rival vs OI)
- Higher harmonic pitching motions



Lind, A. H. & Jones, A. R. Unsteady aerodynamics of reverse flow dynamic stall on an oscillating blade section. *Physics of Fluids* **28,** 077102–23 (2016).



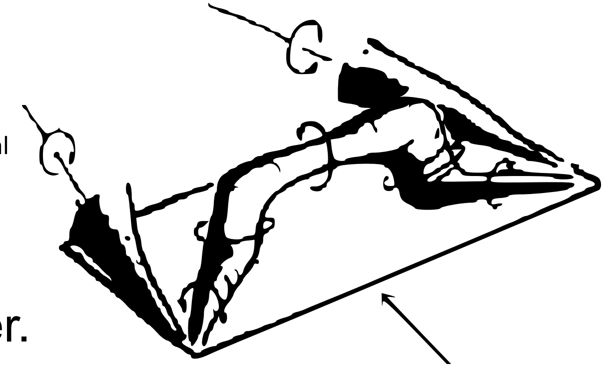
$$\alpha(t) = \bar{\alpha} + \sum_{j=1}^{N} A_j sin(j\omega t + \widehat{\Phi}_j)$$

Culler, E. C. E. & Farnsworth, J. A. N. Higher frequencies in stall flutter moment development. *Journal of Fluids and Structures* **85,** 181–198 (2019).

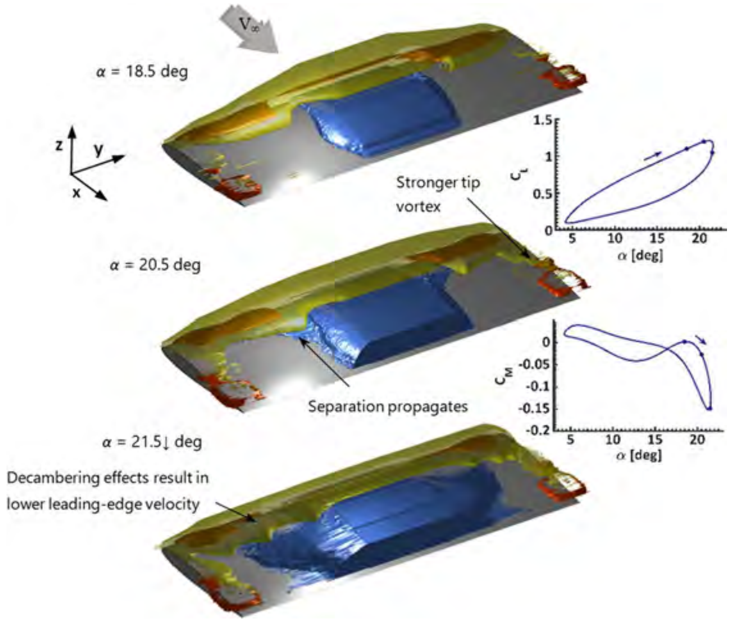
Pitching finite wing

- Flow is 3D, dynamic stall vortex is predominantly 2D
- The finite wing produces 2D flow at least as good as the 2D airfoil in the center.
- Existence of dynamic stall cells?

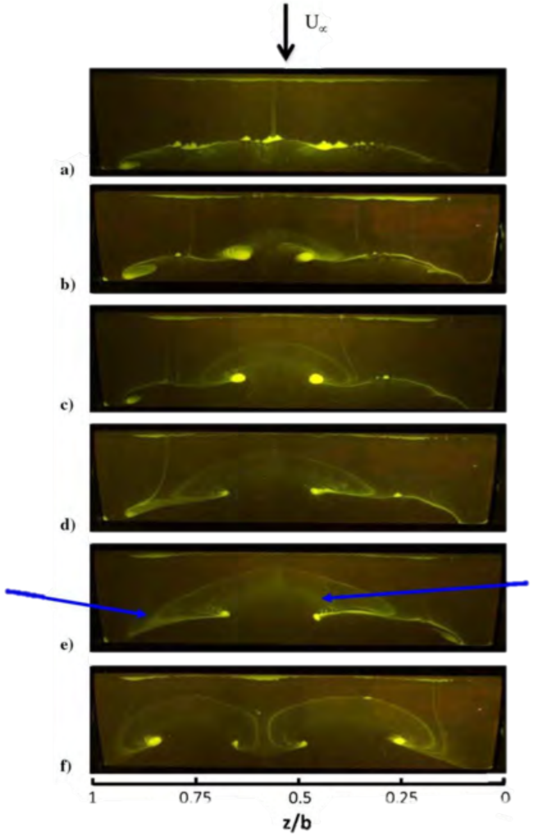
Coton F. & **Galbraith R.** an experimental investigation on three- dimensional dynamic stall on a finite wing. The Aeronautical Journal, 103(1023):229–236, 1999.



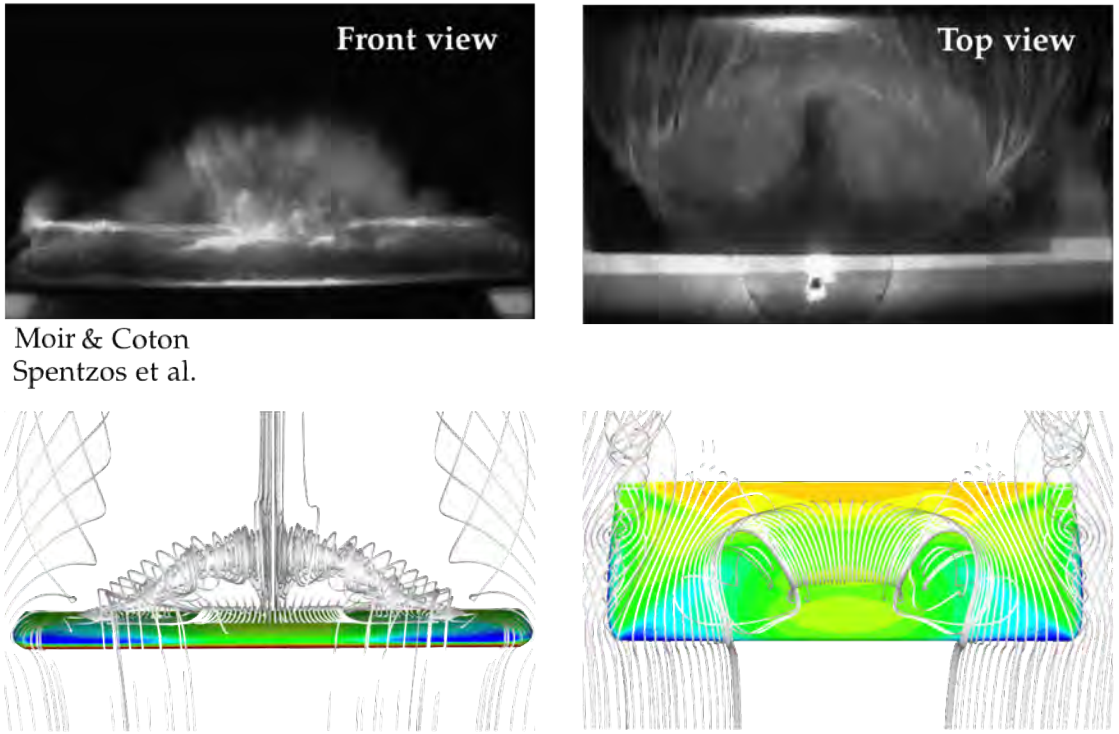
Moir S. & **Coton F. A**n examination of the dynamic stalling of two wing planforms. Aero. Rept. 9526, Glasgow University, 1995.



Angulo, I.A. & Ansell, P.J., 2019. Influence of Aspect Ratio on Dynamic Stall of a Finite Wing. *AIAA Journal*, 57(7), pp.2722–2733.



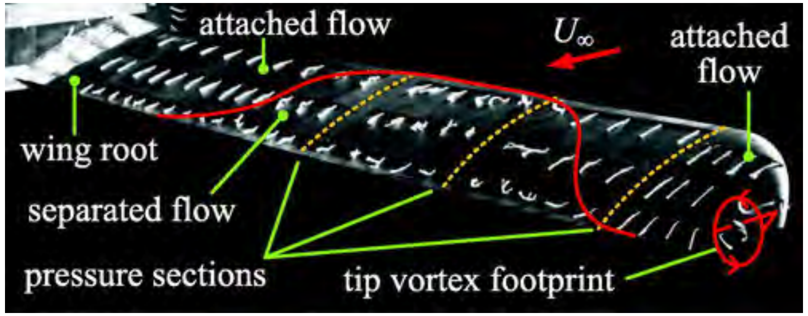
Dell'Orso, H. & Amitay, M. Parametric investigation of stall cell formation on a NACA 0015 Airfoil. *AIAA Journal* **56,** 3216–3228 (2018).



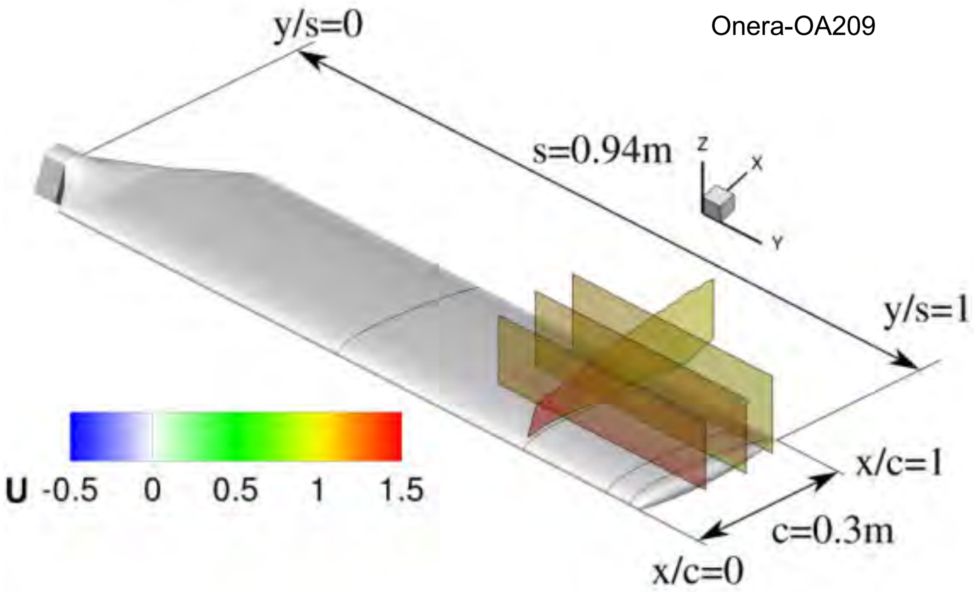
Spentzos A. , **Barakos G.** , **Badcock K.** , & **Richard B. CFD** study of three- dimensional dynamic stall of various planform shapes. In Proceedings of the 30*th* European Rotorcraft Forum, Marseille, France, September 14–16 2004.

Pitching swept (finite) wing

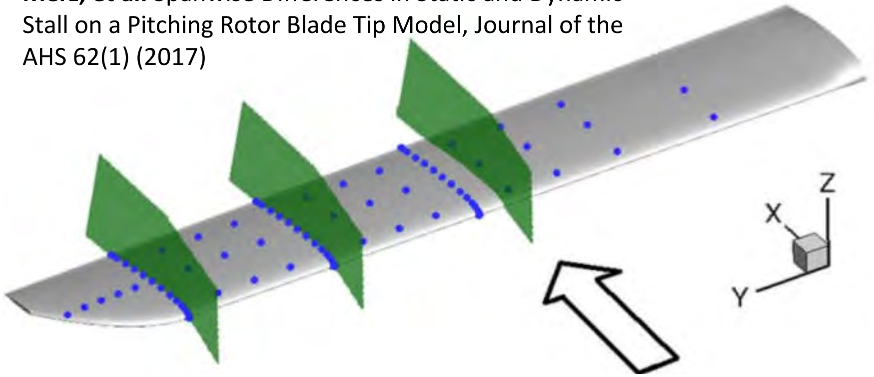
- Asymmetry of dynamic stall vortex for asymmetric blade attachment
- DS on the inboard portion of a swept wing is qualitatively similar to that observed in 2D and occurs nearly simultaneously over the entire span (Lorber et al. 1991)
- The effect of sweep is to delay stall and increase maximum lift for both static polars and dynamic stall.
- Negative aerodynamic damping is worse for the swept wing than for the unswept wing, except where the delay of stall leads to the flow remaining attached.



Wolf, C. C., Merz, C. B., Richter, K. & Raffel, M. Tip-Vortex Dynamics of a Pitching Rotor Blade-Tip Model. *AIAA Journal* **54,** 2947–2960 (2016).



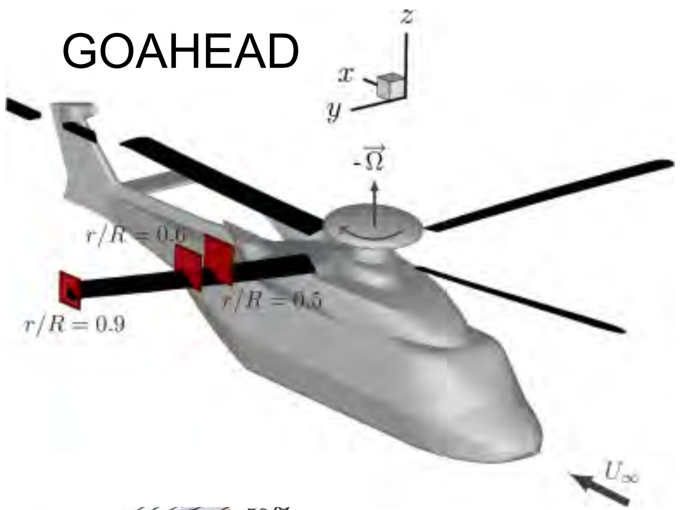
Merz, et al. Spanwise Differences in Static and Dynamic Stall on a Pitching Rotor Blade Tip Model, Journal of the AHS 62(1) (2017)

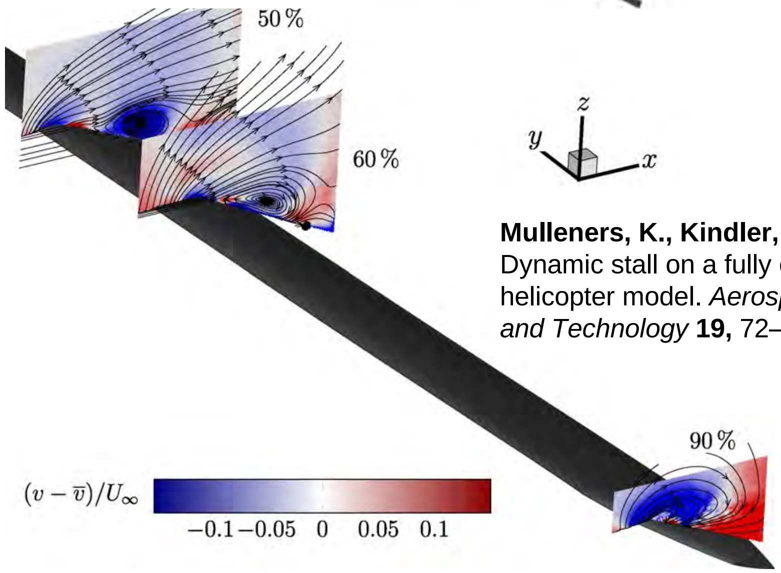


Model rotor in the wind tunnel

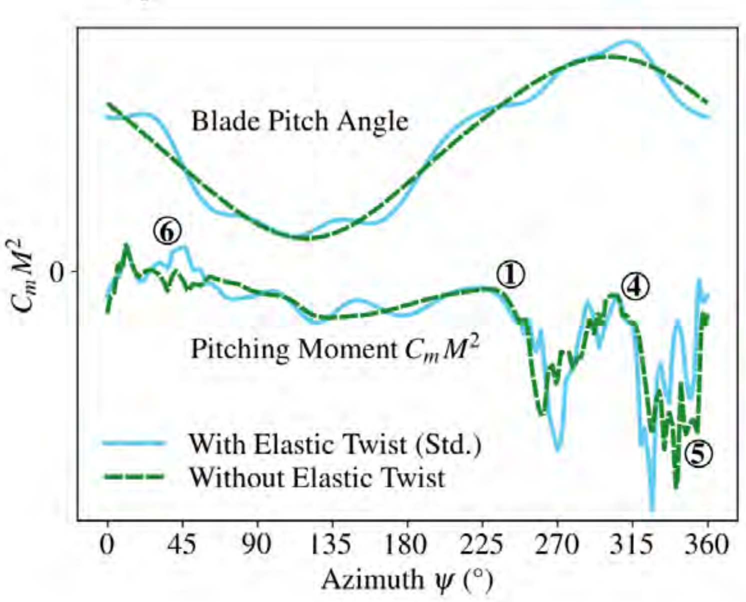
- Dynamic stall vortex = more compact than for pitching airfoil
- Rotational motion of the rotor has a stabilizing effect on the formation and convection of the dynamic stall vortex.
- Dynamic stall can lead to strong aerodynamic flutter and the typical double-hump local aerodynamic angle of attack progressions
- Multiple vortices shed when reverse flow is present, some of which may result in BVI

GOAHEAD

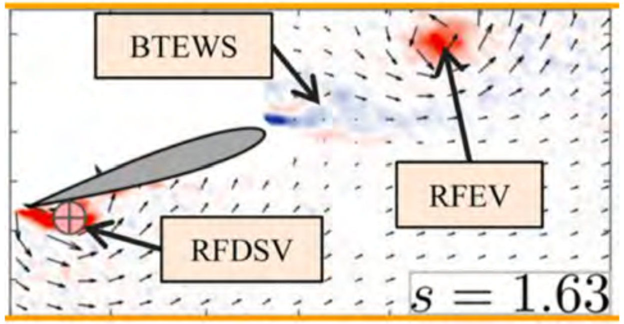




Mulleners, K., Kindler, K. & Raffel, M. Dynamic stall on a fully equipped helicopter model. *Aerospace Science and Technology* **19,** 72–76 (2012).



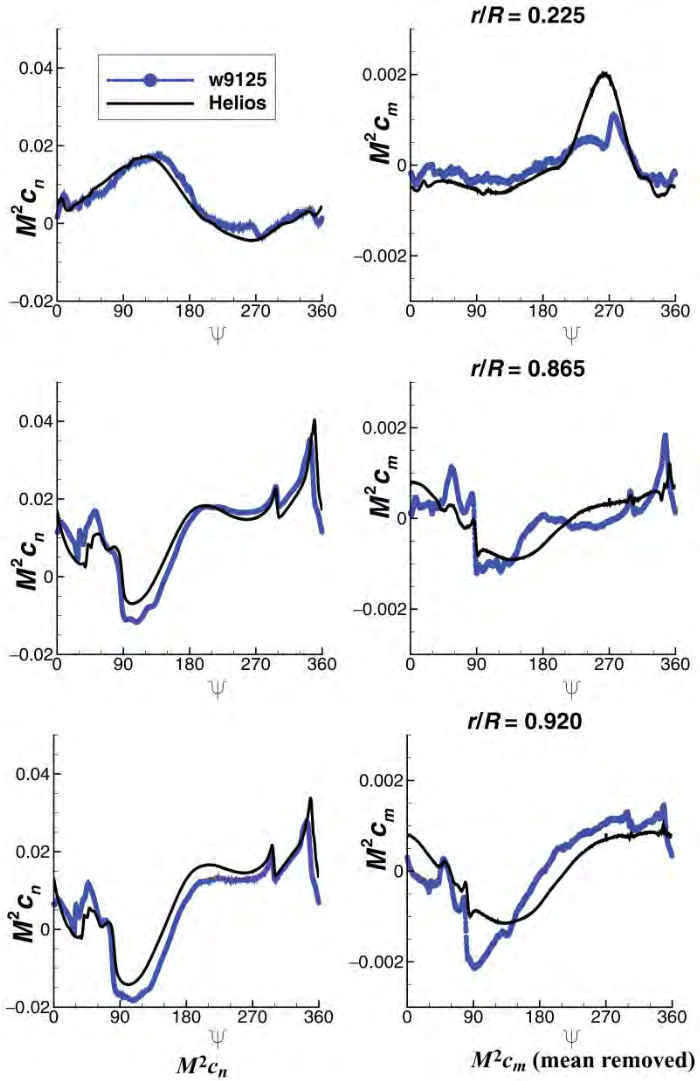
Uni. Stuttgart.



Lind, et al., EXIF 2018

Full-scale UH60A

- Relatively (for a DS case) good capture of forces
- Large bending and torsional moments seen for high advance ratio, low RPM conditions, even under minimal thrust levels.
- Over 5° of peak-to-peak elastic twist



Potsdam AHSJ. 2016

Dynamic stall workshop — experimental team
Where should we go from here?

Everyone!

Discussion led by
Anya Jones (UMD)

Disclaimer: In the following slides I have attempted to summarize and combine notes from everyone. Apologies if I misinterpreted what you wrote and/or forgot to credit you. Let me know and we'll update the slides. (AJ)

What progress has been made? Summary

Types of experiments

- Simple experiments
- Pitching airfoil experiments
- Pitching finite wing experiments
- Variations on kinematics (plunging, surging, flapping, etc.)
- Reverse flow
- Small scale rotors
- Large scale rotors
- Flight tests
- Collaboration with CFD

Challenges

- Matching relevant parameters
- Effects of mounting/end conditions
- Too many different airfoils/geometries
- Expense
- Difficult conditions to perform measurements in
- Impossible to acquire data everywhere

Measurement techniques

- Pressure sensors
- Hot film
- PIV
- PSP
- DIT

Challenges

- Time resolution
- Spatial resolution (e.g., optical access, sensor placement)
- Harsh conditions (e.g., large forces, high dynamic range)

What progress has been made?

What do we know?

- Good basic understanding of the dynamic stall process under many conditions (JN, AJ, MRa, MRi)
  - Types of features
  - Necessary conditions
- Simple and low Re experiments are pretty well understood (AJ, MRi)
- Cycle-to-cycle variations are important (MRa, KM)
- Leading edge modifications can weaken or strengthen DSV (JH)
- LESP is the current standard for predicting separation (AG, AJ)
- Non-standard pitching/plunging motions exhibit interesting but poorly understood dynamics (JH)

Need to put a much finer point on this! (AJ)

- Measurement techniques continue to improve (JN)
  - Improved spatial and temporal resolution
  - Surface and flow-field measurements available
- New analysis techniques (JN, MRa)
  - Statistical analysis including modal approaches
  - Beginning to use machine learning / data driven approached

So we have some reason to be optimistic …

What next?

What do we still need/want to know? (1 of 2)

Defining and mapping the dynamic stall parameter space

- Timing and impact of **dynamic stall flow features** under different conditions and combinations of conditions (JN, KM, HB, AJ)
    - DS in more **complex conditions** (e.g., inflow, unsteady freestream, wakes) (AJ, KM)
        - Effects of unsteady freestream, inflow, and radial flow (AJ, JS, PF)
        - Wake interactions (MRa, AJ)
        - Aeroelastic effects (MRa)
    - Geometric complexities
        - What are the differences between 2D, 3D, and rotating wing? (MRa, AJ, KM, Mri, PF, VR)
        - Sensitivity of all of the above to airfoil shape (including reverse flow) (AJ, MRa)
    - Effect of boundary layer transition? (TG)

Modeling and prediction

- Prediction of subtle features (e.g., DSV growth, separation, trajectory) (AJ, JN, HB, JS, KM)
    - Criterion that determines the onset of stall (AJ, MRa, KM, JS, TI)
    - Better understanding of LESP (AJ, HB, KM)
    - Reduce empiricism of dynamic stall models (KM, AJ)

What next?

What do we still need/want to know? (2 of 2)

Getting more from the data we have

- Further analysis
  - Better understanding of **cycle to cycle variations** (MRa, JN)
  - Eliminate/correct empirical corrections to PIV data (HB)
  - Where to place what kind of sensors? (TI)
  - New types of **data analysis** (e.g., machine learning, or anything beyond modal analysis) (AJ)

Looking at the bigger picture

- Bringing in other fields
  - How to mitigate noise? (AJ)
  - How to integrate with flow control community?
- Meta questions
  - How do DS concerns affect future vehicles and how to avoid, eliminate, or mitigate these? (MRa)
  - What to do with the enormous amounts of data we are collecting? (AJ, JN)
    - Is there a role for data science / machine learning in processing experimental data?
  - How to interface with other communities? (e.g., sensing and control, data science, flight test, flow control, optimal sensing, wind/water energy, low Re, atmospheric science) (AJ)
  - How can we more efficiently/effectively share data? (e.g., NSF FDSI) (AJ)

What next?

How are we going to do it? (1 of 2)

Collaboration!

- Among experimentalists
  - Larger scale collaborations **bridging the gaps** from simple experiments in 2D to 3D, large scale, flight tests, and CFD (AJ, Mra, PF)
  - Using the **same airfoil**, simultaneous time-resolved surface pressure and velocity field measurements for large number of cycles on airfoil, finite fixed-wing and rotating-wing (MRa, AJ)
- With **CFD**, theory, and modeling
  - Further and closer collaboration with CFD (AJ, JN, JH)
    - Validate physics in simulations
    - Exploit strengths of each (e.g., parameter sweeps, data acquisition, Re/M)
- With **other communities**
  - Work with other communities with similar interests (e.g., wind energy, low Re) (AJ, JN)

Organization!

- Need a **standard reference data set** for comparisons (MRa)
- Need a **standard for all measurement and computational effort**, e.g., including number of oscillation cycles, spatial and temporal resolution, details of the experimental conditions, etc. (AJ, MRa)
- Can/should we compile a **reference list of existing data** (or at least that which is publicly available)?

What next?

How are we going to do it? (2 of 2)

New technology

- Better measurement resolution in the boundary layer (JH, TI)
- Newer, more, better sensors for detection of DS (AJ)
- Smarter sensor placement (AJ)
- Integration of flow control (AJ)

Why have we not done this?

Resources

- Cost of conducting experiments at relevant Re, M numbers
  - Access to large wind tunnels, complex rigs, flight tests, etc.
  - Access to high resolution measurement systems
  - Risk of failure
  - Funds to “repeat” experiments / the race for bigger and better

Technology

- Manufacturability
- Existence of relevant measurement techniques
- Existence of relevant data analysis techniques

Knowledge

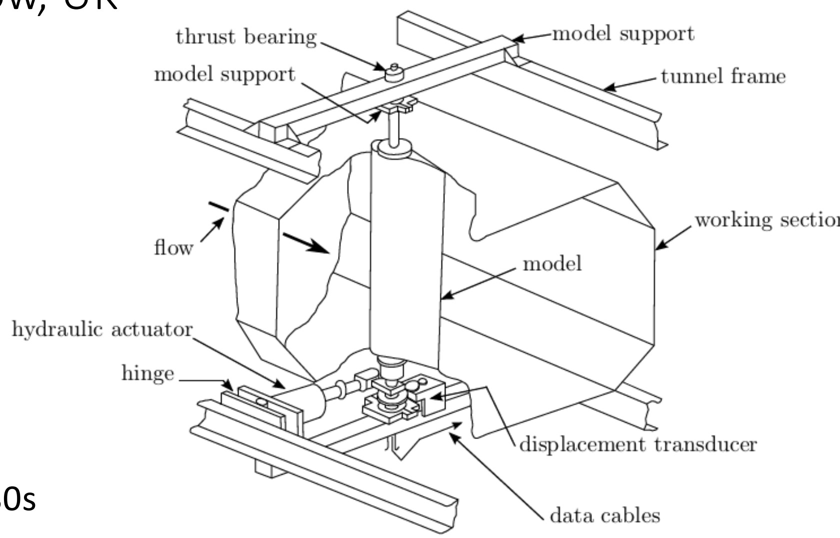
- Poor understanding of the overall phenomenon resulting from too many variables
  - “Dynamic stall” is too broad of a term
  - Need more precise definitions and clarity
- What is the current state of the art?
- Where are the current knowledge gaps?

Are there specific experiments that should be done?

Experiment	Challenge
Build up from simple experiments to complex ones using the same airfoil and similar conditions	Specialized facilities in each lab, coordination amongst many groups over long times
Repeat experiments in multiple labs to assess sensitivity to conditions	Funding for repeat experiments
Well-defined BVI	Vortex paths are sensitive to wind tunnel conditions
Flight tests	Cost, measurement techniques

Dynamic stall research at Glasgow University

Richard Green, University of Glasgow, UK



- Low-speed dynamic stall research since early 1980s
- 2D data have been published widely
- Many aerofoil shapes tested: NACA 23012 and similar, NACA0012-NACA0030 plus others
- Surface mounted pressure transducer arrays
- See http://dx.doi.org/10.5525/gla.researchdata.464 for selection of data
- Most recent tests (2017) have been for thick aerofoil sections for tidal turbines (fouling)

Motivation and funding bodies

- Initial thrust and long term effort by Roddy Galbraith
- Need by UK helicopter industry for data to assist with rotor design process….support for development of Beddoes/ Leishman model

- Many funding bodies over the years….
- EPSRC/ SERC (UK research)
- RAE/ DRA/ DERA/ Qinetiq (government laboratories)
- Westland Helicopters/ AW (UK helicopter industry)
- Garrad Hassan/ Senvion/ Andritz-HydroHammerfest among others (wind turbine, tidal turbine industry)
- AFOSR, US ARO
- Link with NREL

- Data at http://dx.doi.org/10.5525/gla.researchdata.464

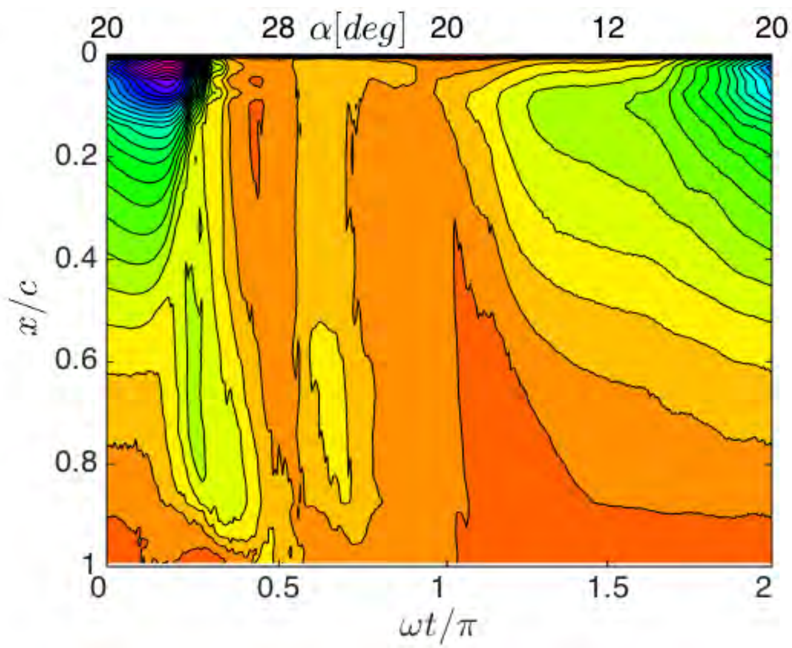
Summary of work done

- 2D dynamic stall
- Oscillatory motion, constant pitch rate
- Dynamic stall, dynamic reattachment
  - See database
- Flow control concepts for dynamic stall
- Data at http://dx.doi.org/10.5525/gla.researchdata.464

- 3D dynamic stall (Coton, Galbraith): rectangular, swept tip and delta wing

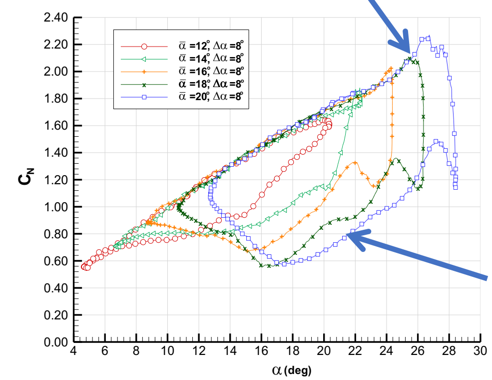
- Relevant to mention blade-vortex interaction also (parallel, orthogonal)

Typical result….

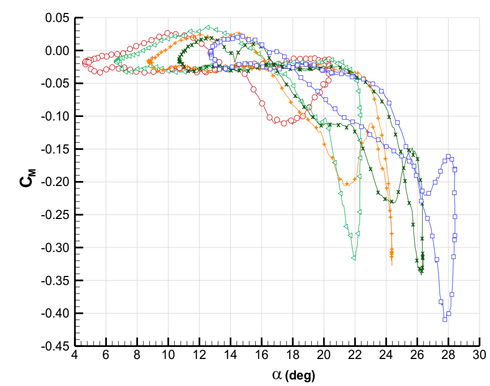


- RAE 9645
- Sinusoidal oscillation, Re=1 million, k=0.103
- Deep stall, post-stall shedding, dynamic reattachment

Dynamic stall



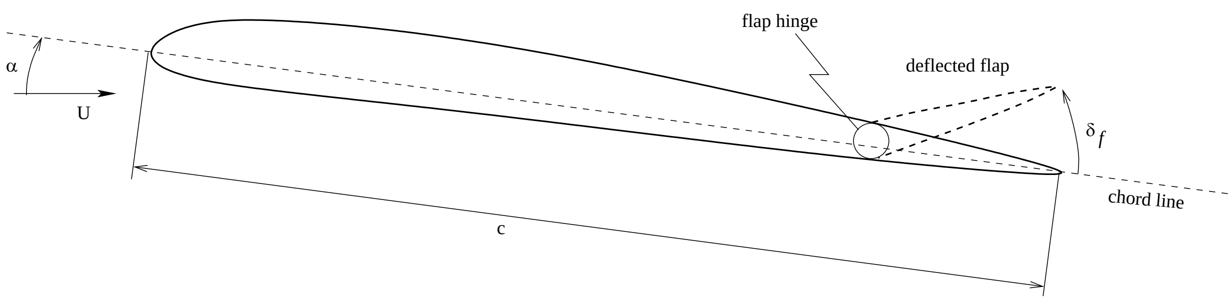
Downstroke,
dynamic reattachment

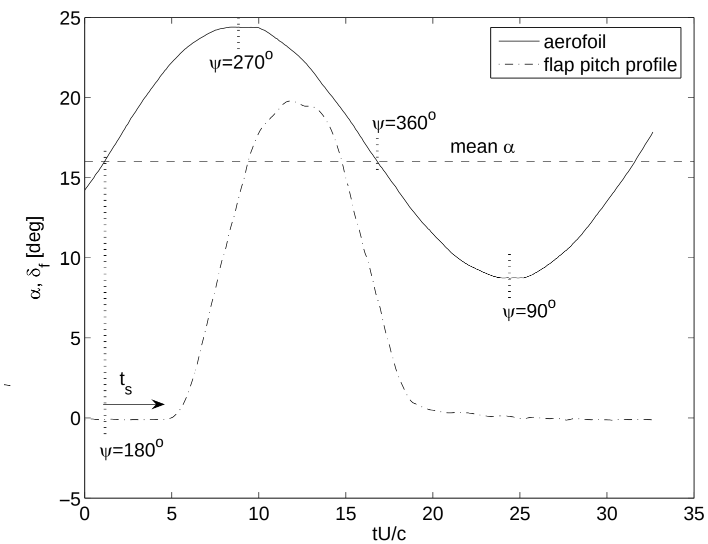


Negative damping
in moment cycle

Dynamic stall: flow control with trailing edge flap

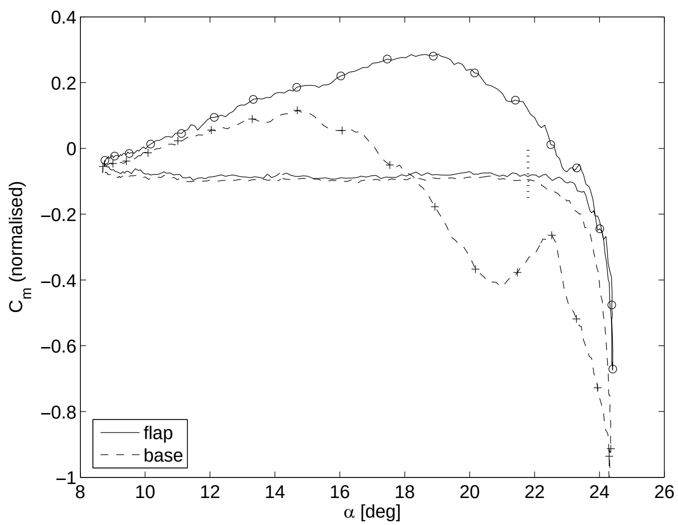
- Part of DARP project for flow control concepts
- Scheduled trailing edge flap
- Does not prevent or delay stall, but mitigates against adverse effect
- Pitch cycle damping analysis
- See Aeronautical Journal, vol. 115, pp493- 503 (2011)



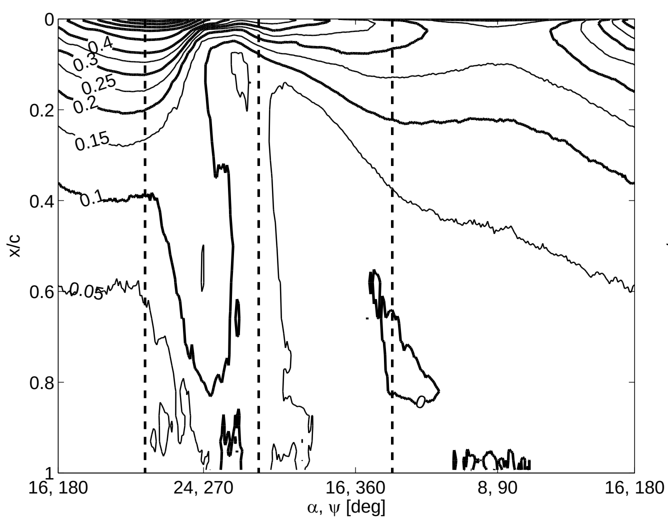


Trailing edge flap effect

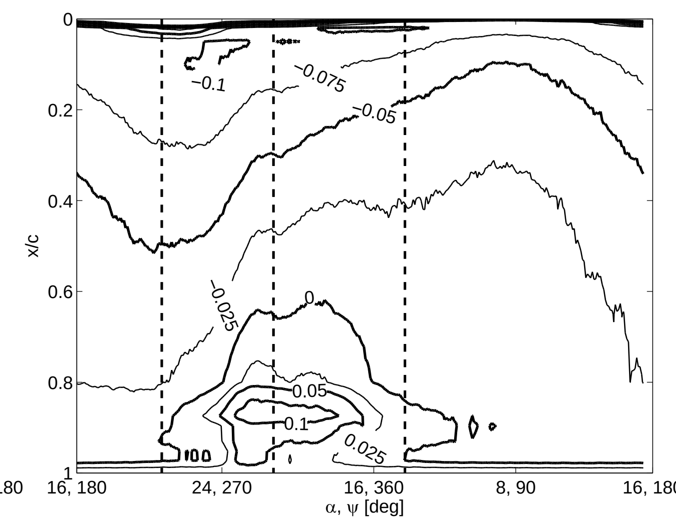
- Scheduled trailing edge flap can change damping from negative to positive
- Dynamic stall still occurs, effect is due to modification of pressure on lower surface of flap



Pitching moment



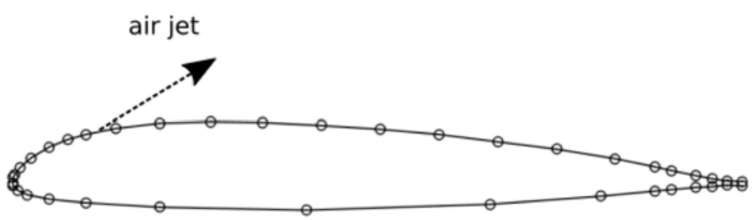
Upper surface pressure



Lower surface pressure

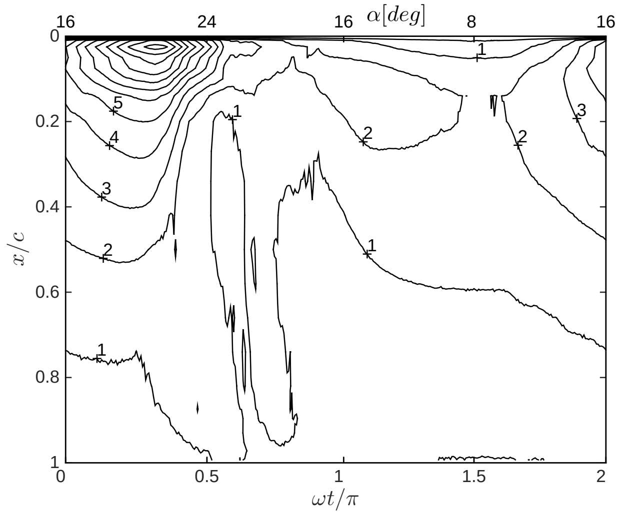
Dynamic stall: flow control with air jet vortex generators

- Air jet vortex generators
- Array of spanwise jets at 12% chord
- Steady blowing, pulsed blowing to delay dynamic stall
- See AIAA Journal, Vol. 56, No. 5 (2018), pp. 2070-2074 and Journal of the American Helicopter Society, Vol. 64, 032004, (2019)

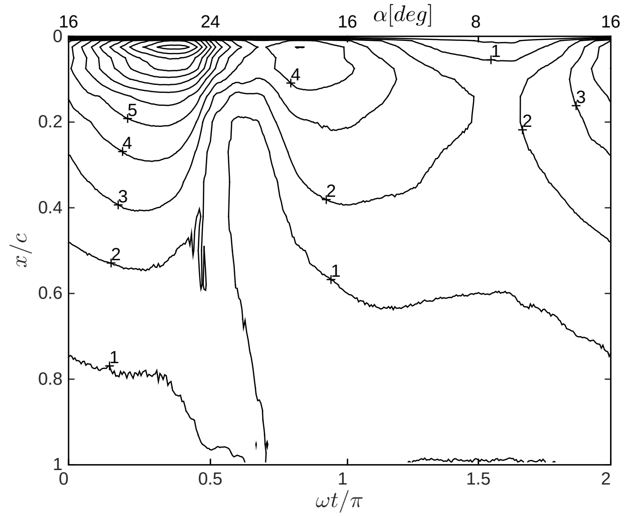


Effect of air jet vortex generators to suppress and delay dynamic stall

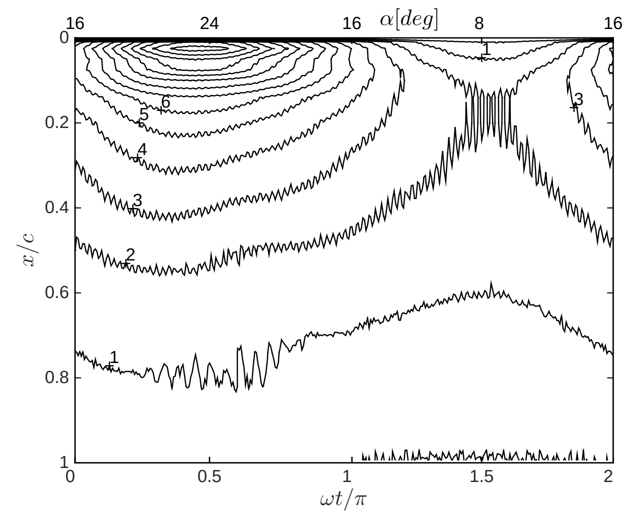
Re=1 million, sinusoidal motion profile, k=0.103



No blowing



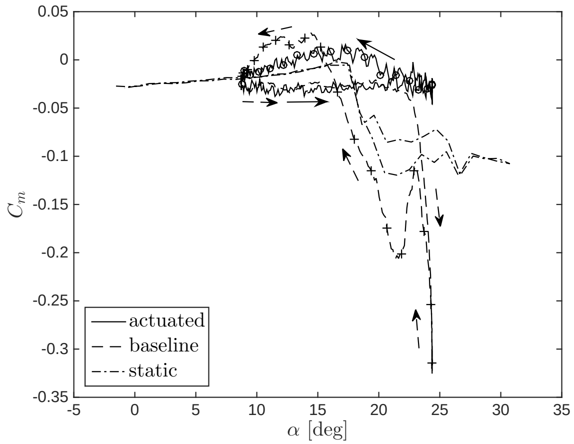
Steady blowing, Cμ=0.0028
Attenuation of dynamic stall



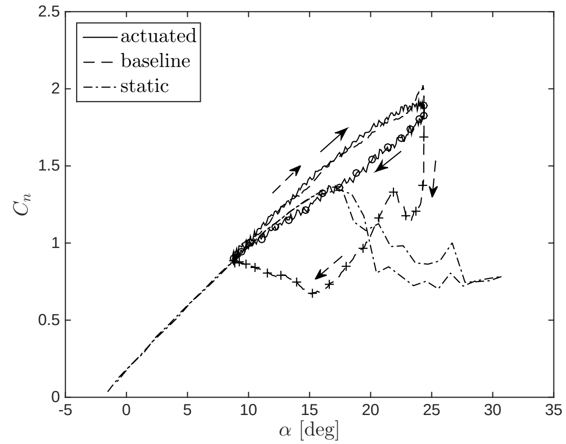
Pulsed blowing, F+=1.04, Cμ=0.0021
Absence of dynamic stall

Air jet vortex generator effect (continued)

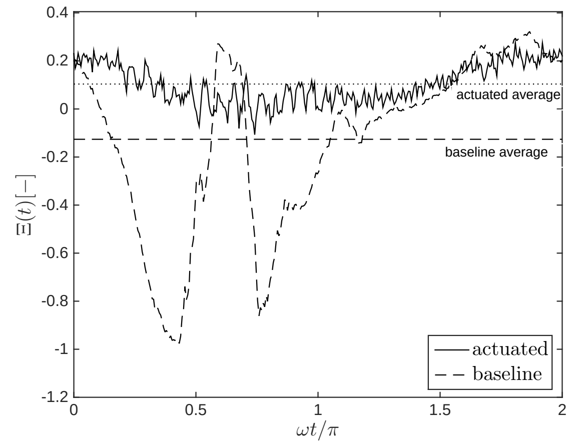
- AJVGs can lead to improvement in damping
- Same actuation parameters as previous slide



Pulsed jet, Cm



Pulsed jet, Cn



Pulsed jet, damping cycle (Hilbert Transform)

Potential for future work

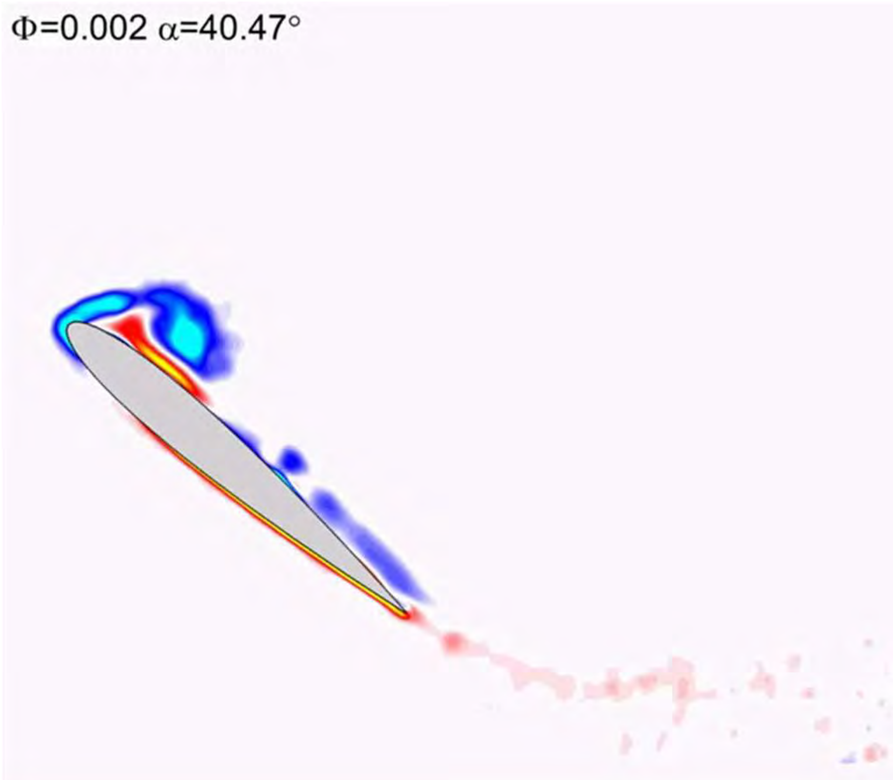
- Interest in fouling effect for wind turbines and tidal turbines
  - Tests done as recently as 2017
  - Data for estimation of effect on turbine performance

- Very little 3D dynamic stall data available

- For rotorcraft, CFD at high advanced ratio indicates dynamic stall on retreating blade occurs simultaneously with BVI; vortex induced dynamic stall
- Fundamental research
- Potential for using GU dynamic stall system to do this, subject to some modification

- Model construction can now be done at far lower cost than previously
- Low cost pressure transducers work perfectly well

Thank you for your attention.



Interaction of the Leading Edge Vortex and Shear Layer Vortices for an Airfoil Undergoing Dynamic Stall

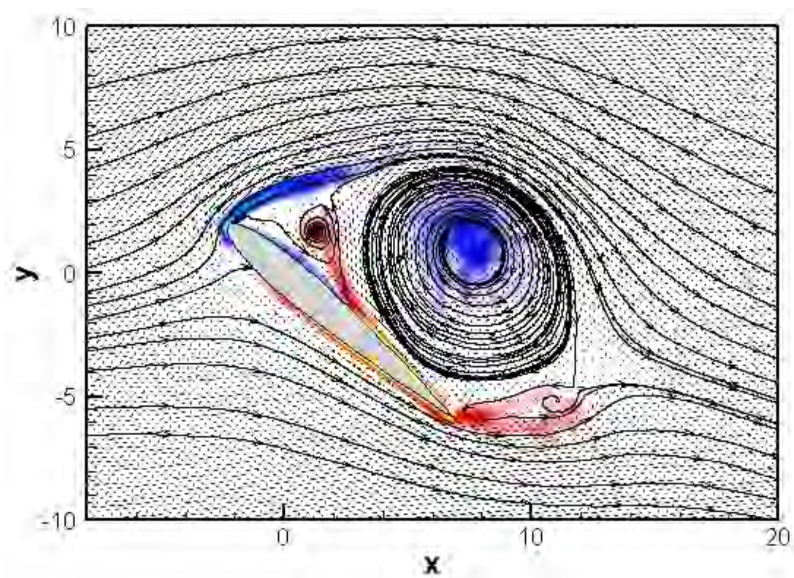
ONR Award: N00014-14-1-0418

Doug Bohl
Clarkson University

Melissa Green
Syracuse University

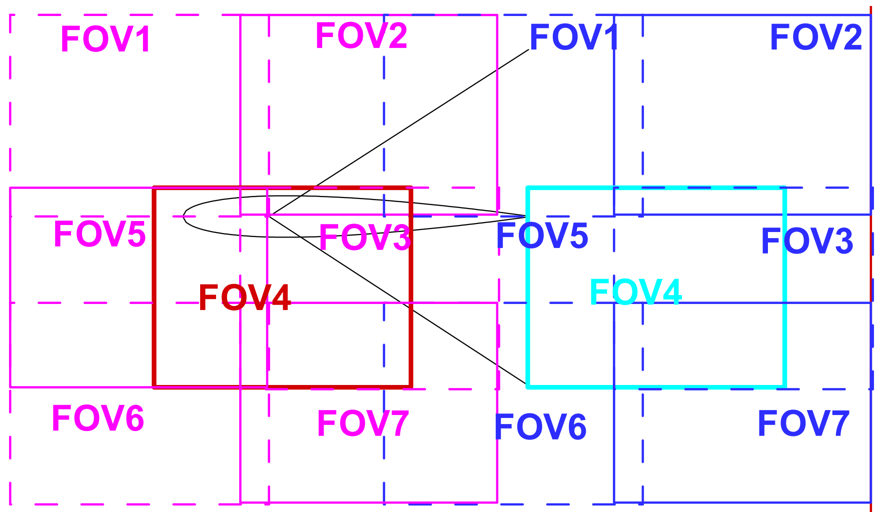
Study Goals

- Investigate a range of DS conditions from light to deep
- Examine vortex formation, unsteady separation along suction surface, and vortex interaction

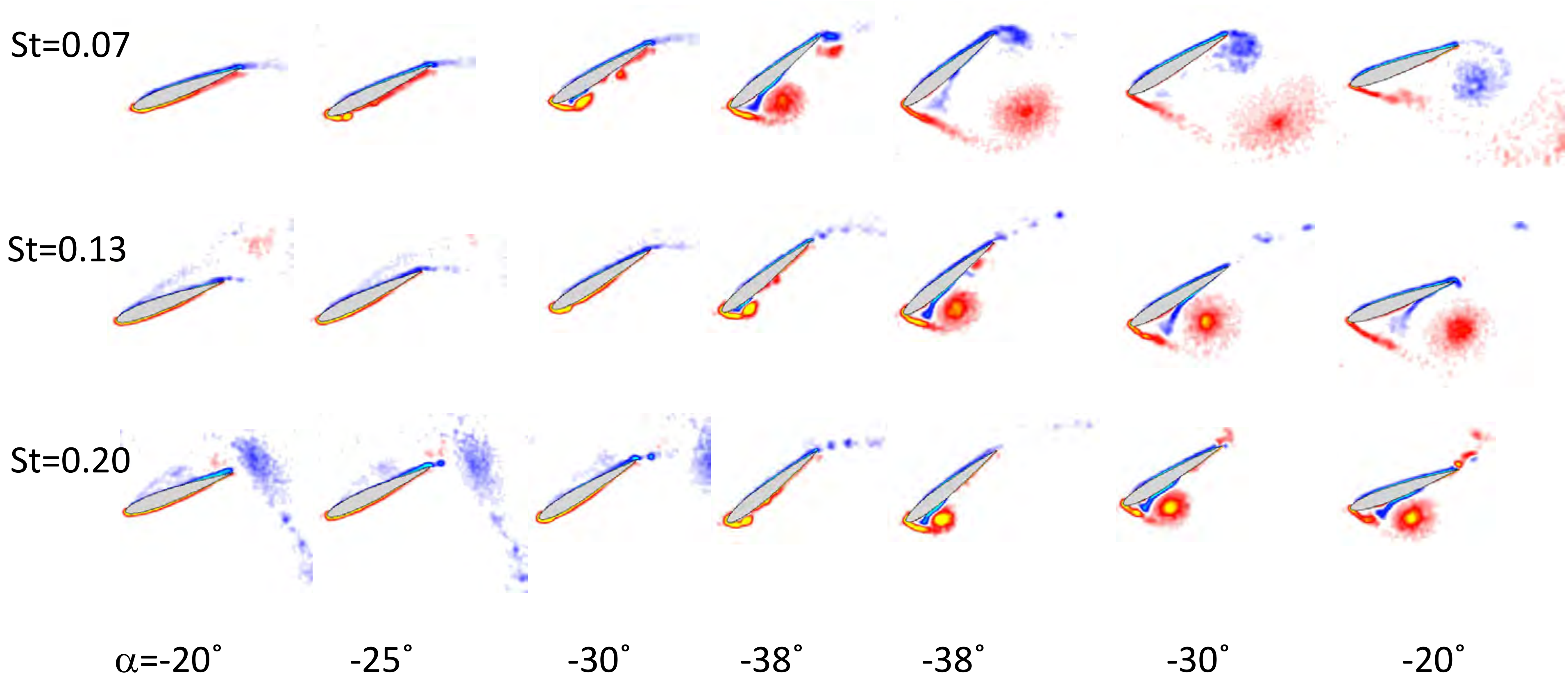


Experimental Details

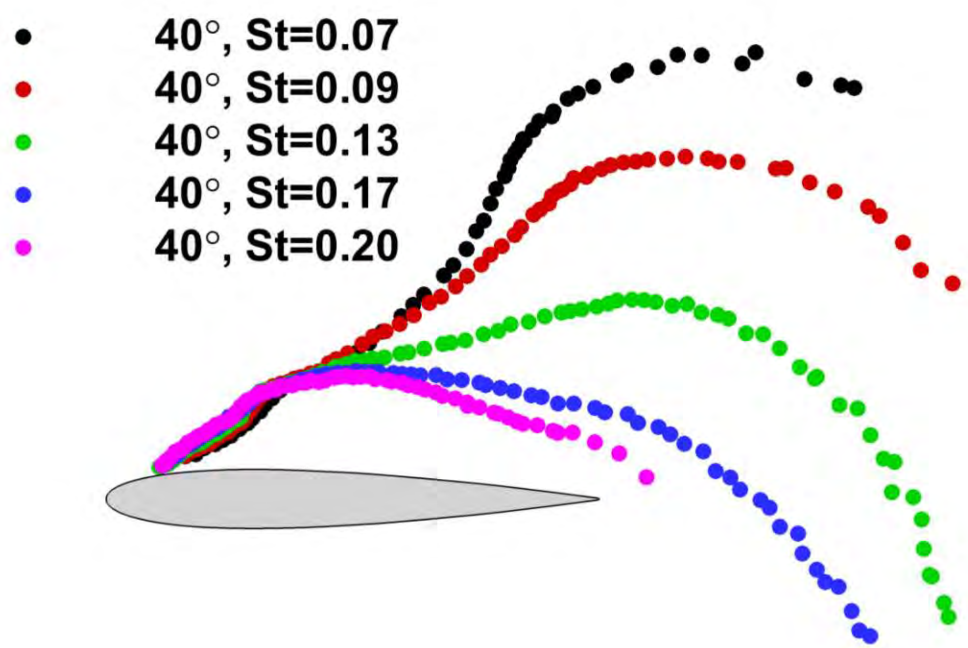
- NACA 0012 Airfoil, Re=12000
- Sinusoidal Motion about ¼ chord location
  - α_{max}=±20°, ±30°, ±40°
  - St=0.07-0.20 (k=0.23-0.64; Ω*=0.05-0.28)
- 14 FOV's (Origin at pitch location)
- Data mirrored (y=0 and phase) to provide full flow field above and below
- After assembly ~1.3 million raw vectors for each phase
- Data interpolated onto a regular grid with 2d, 2nd order polynomial
  - Regular grid spacing: 0.5 mm (0.004c)
  - No-slip applied at the airfoil surface
- Experiments performed at Syracuse University
  - ELD 2000L recirculating water tunnel

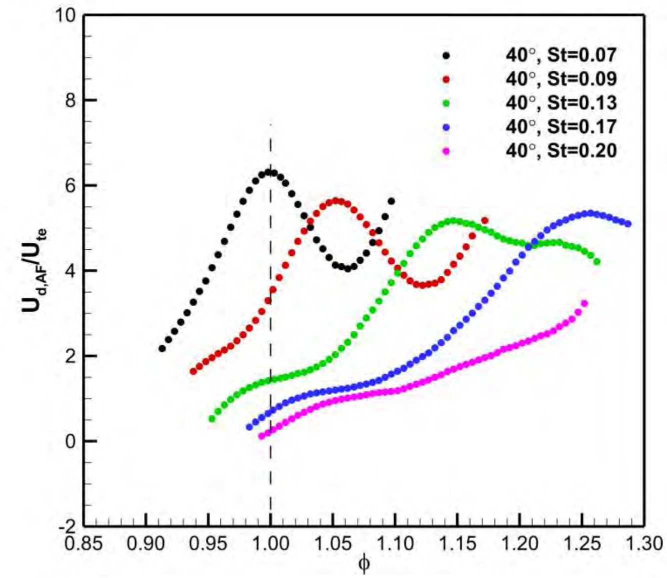


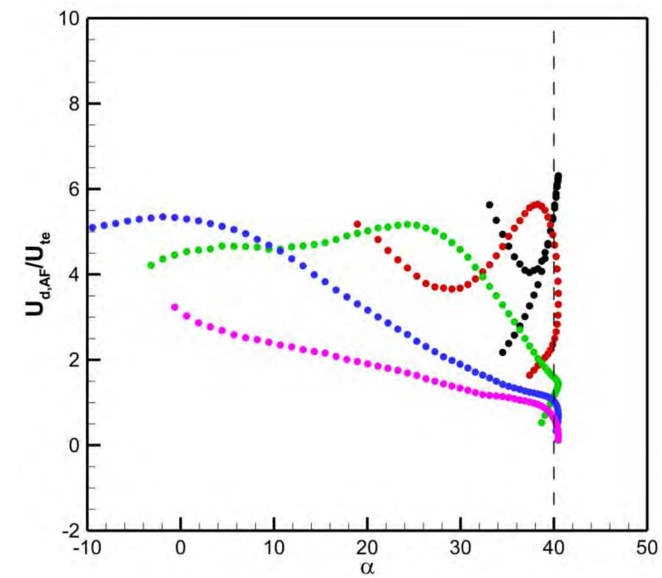
Vorticity Snapshots



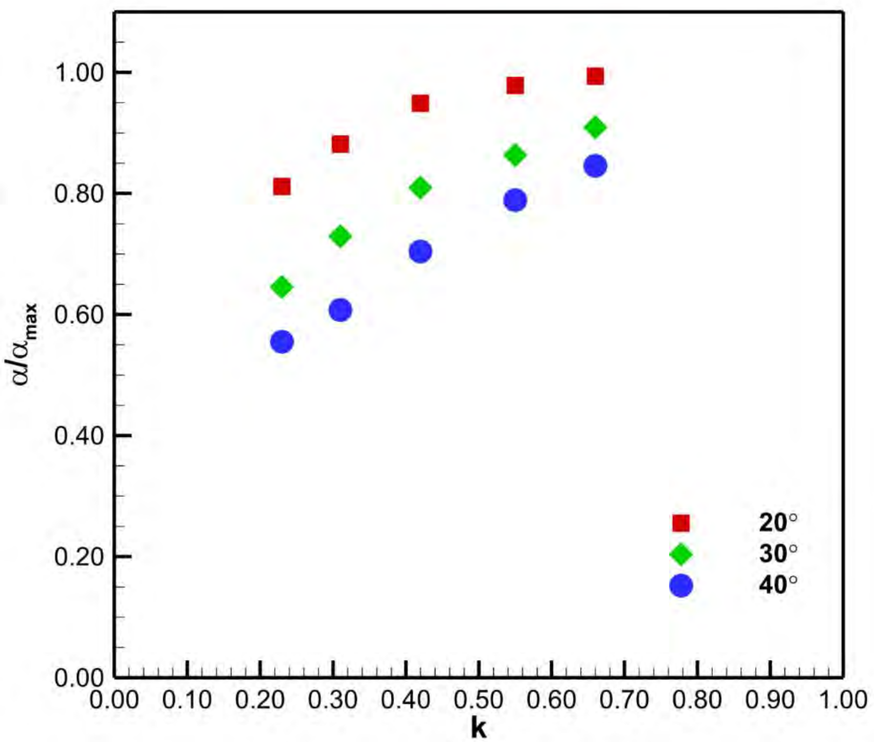
DSV Tracking: y vs x

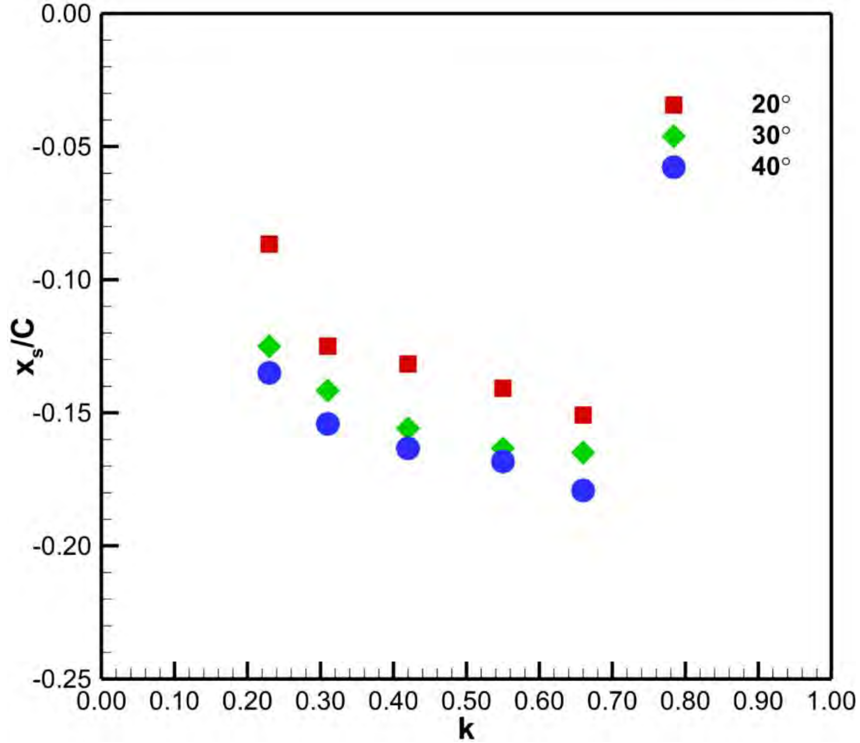




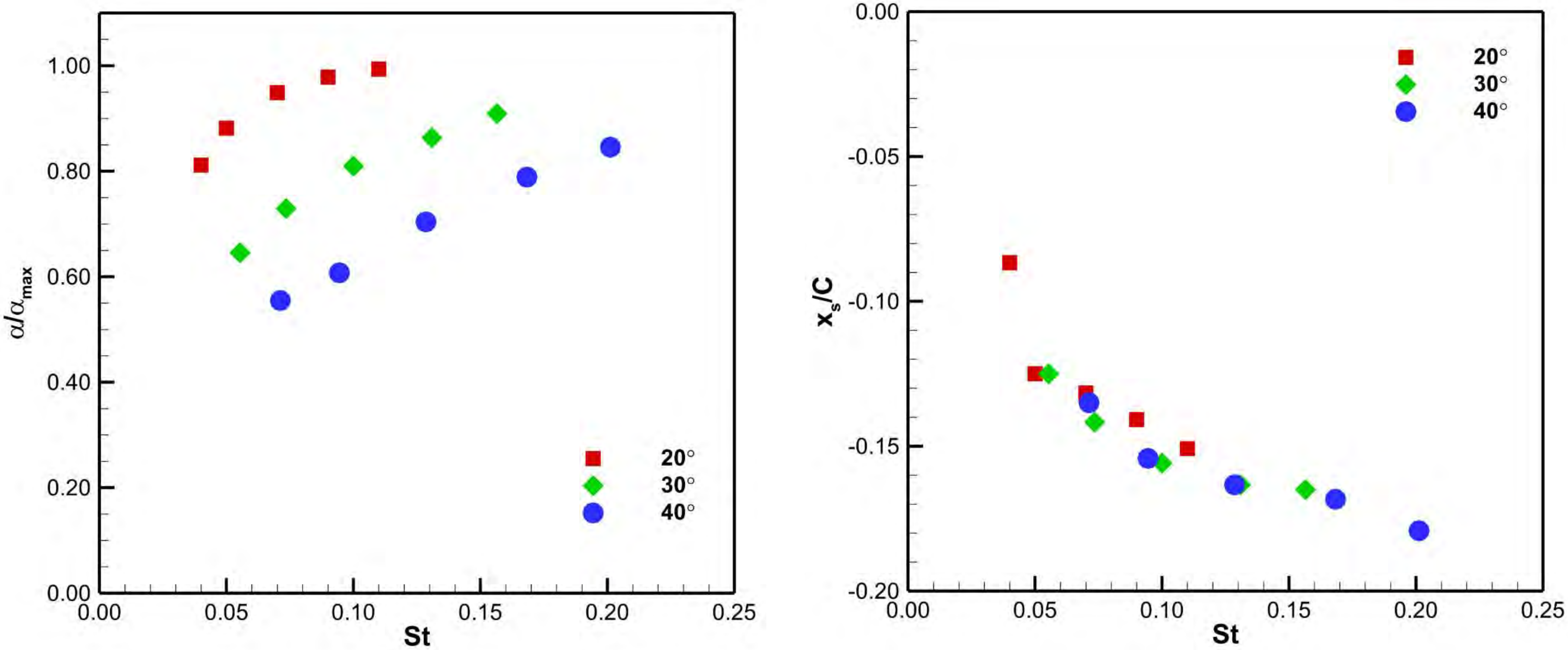


Scaling of DSV Initiation Characteristics

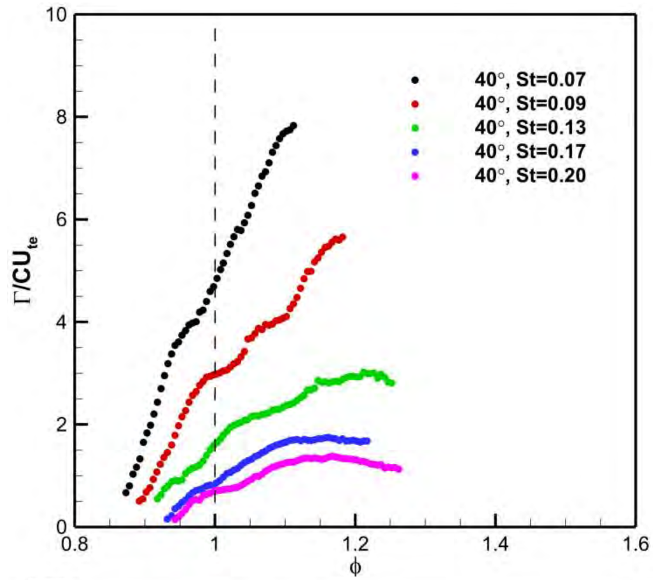


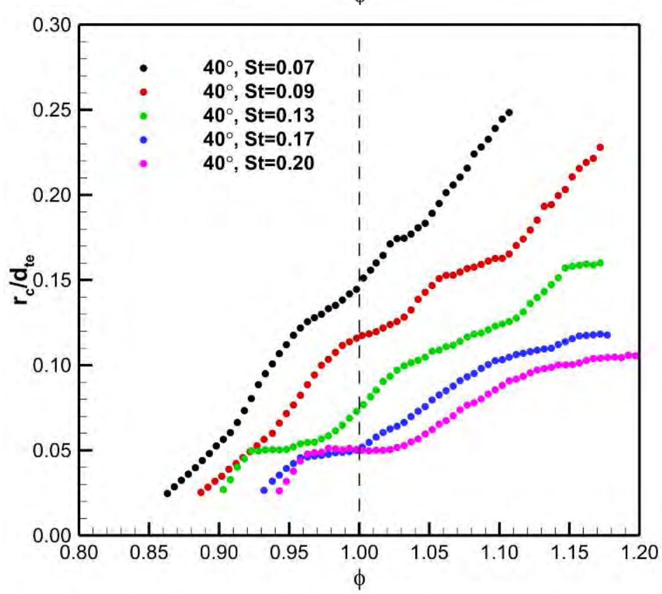


Scaling of DSV Initiation Characteristics



Circulation/radius



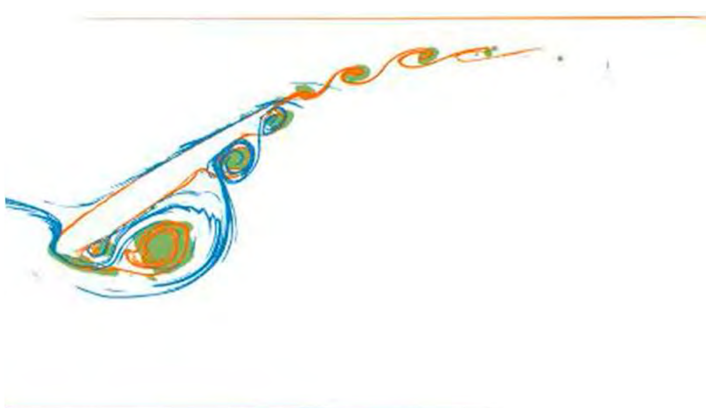


- Differences in circulation level based on St
  - Decrease in circulation with increased St
- DSV is fed by the leading edge for increasing time at lower St
- Higher St cases remain in proximity to airfoil surface past change in direction
  - Restricts the growth in the DSV size
  - “Plateau” ends at/near the time the motion reverses

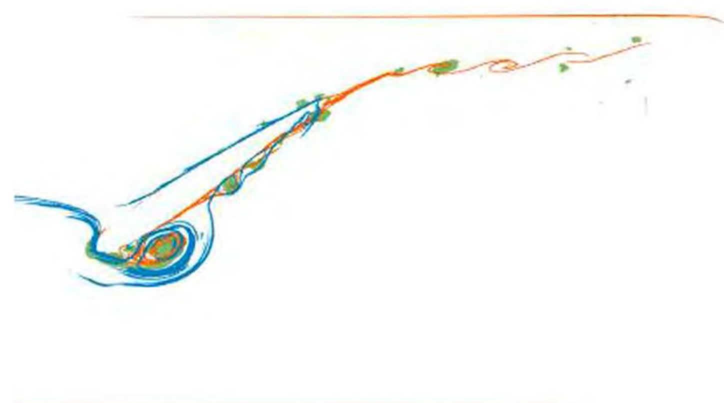
FTLE Fields 40° Cases

St=0.07

St=0.13

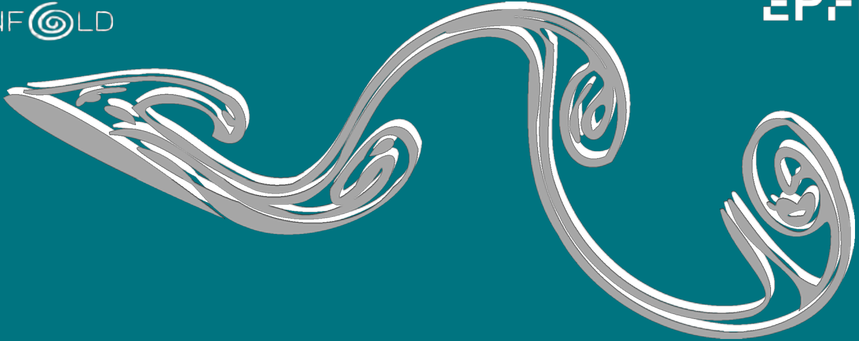


St=0.20



Conclusions

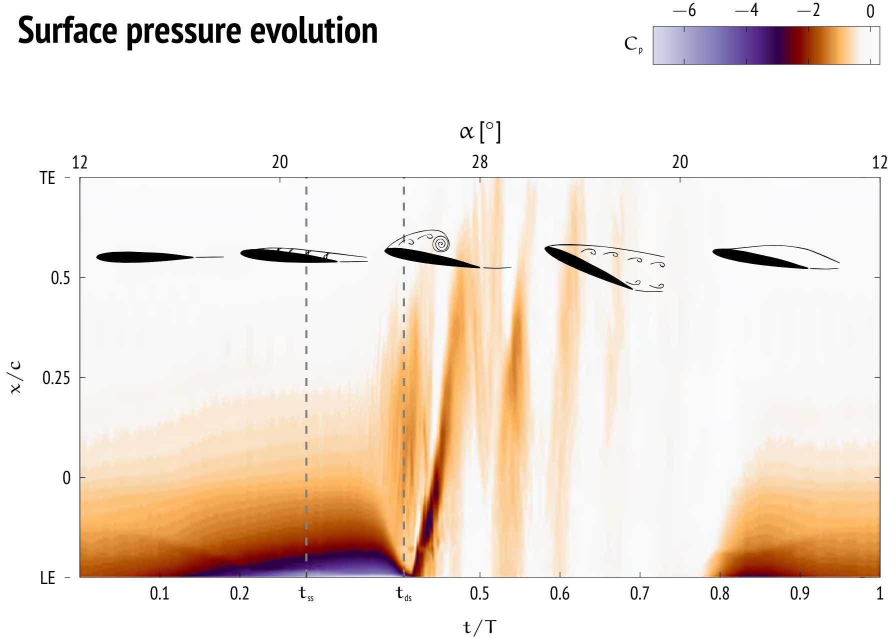
- DSV formation angle/phase does not appear to scale with "obvious" parameters
- DSV formation location appears to scale based on St
  - Characteristic pitching lengths and pitching speeds are important
  - Able to predict where DSV will form
- Dynamic separation complex
  - Secondary regions of vorticity may/may not form, interact etc.
  - Occurs within a region in parameter space
- DSV fed from the leading edge shear layer- continues for longer times
  - Interaction of DSV with the SLV's can be observed in circulation, core size and FTLE computations
- Future/in progress
  - Detailed high resolution boundary/shear layer measurements in unsteady separation cases
  - Passive control using bioinspired shapes
  - Flexibility (e.g. flexible trailing edges)
  - Non-uniform freestream



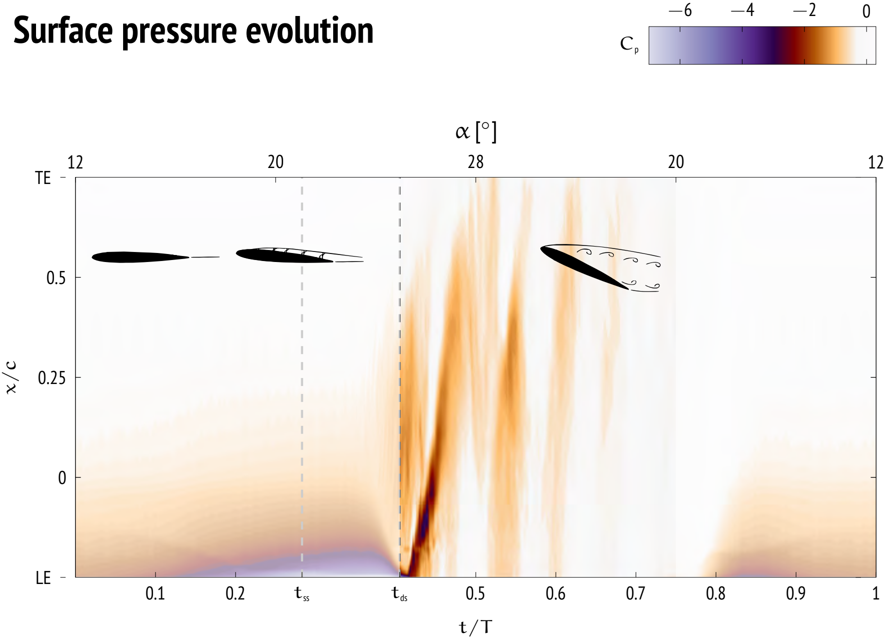
Modelling the interplay between the shear layer and leading edge suction during dynamic stall

Julien DEPARDAY, Karen MULLENERS

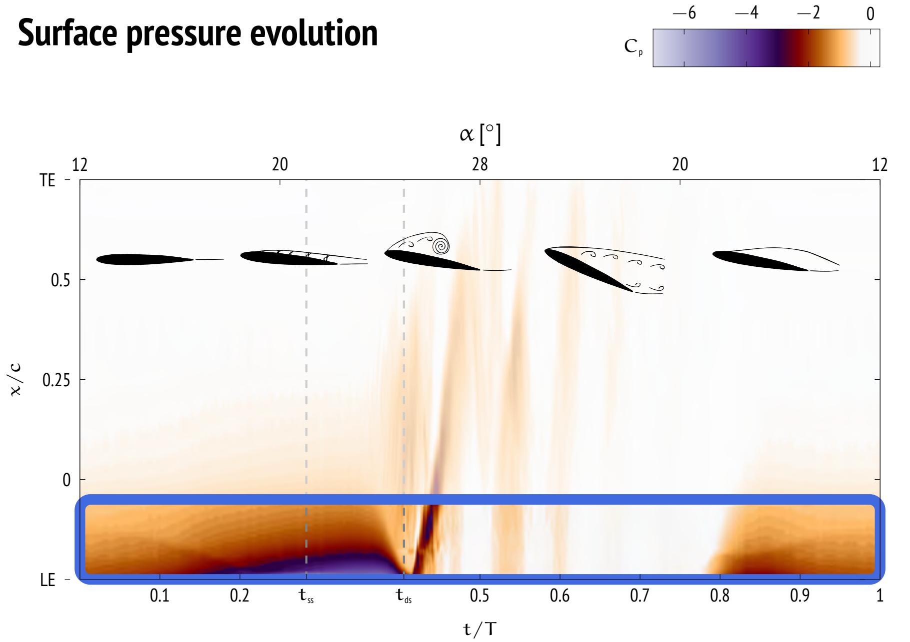
Surface pressure evolution



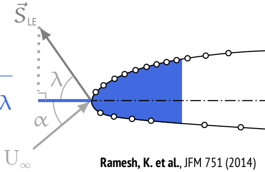
Surface pressure evolution



Surface pressure evolution

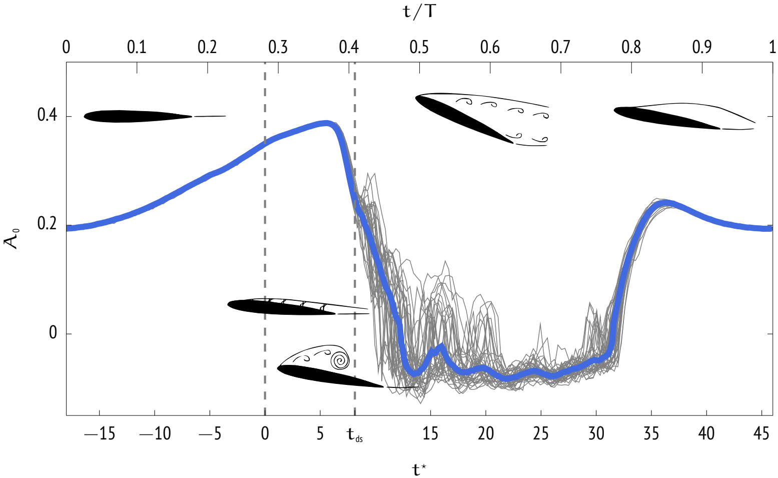


Leading edge suction parameter

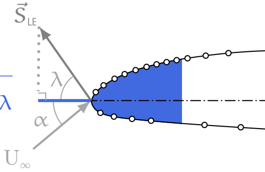


$$\mathcal{A}_{0,exp} = \sqrt{\frac{2}{\pi}|S_{LE}|\cos\lambda}$$

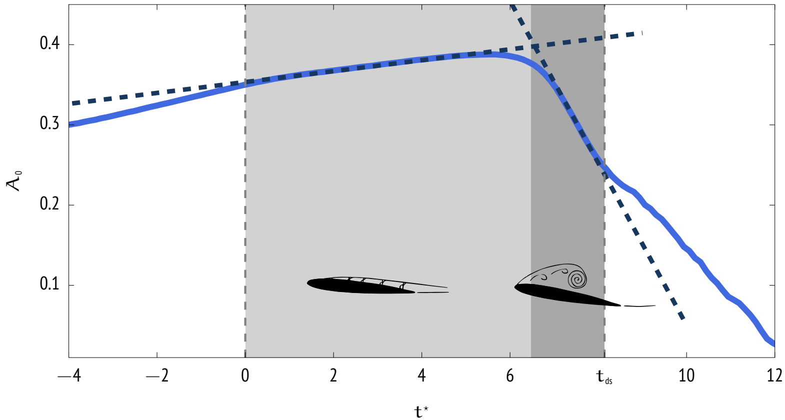
Ramesh, K. et al., JFM 751 (2014)



Leading edge suction parameter

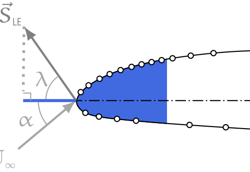


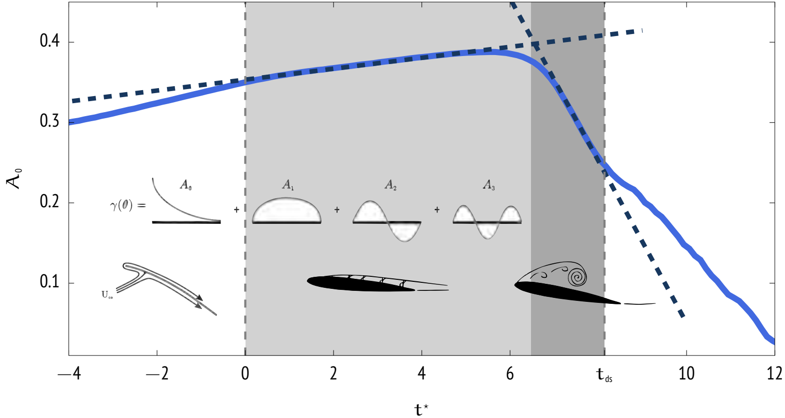
$$\mathcal{A}_{0,\mathrm{exp}} = \sqrt{\frac{2}{\pi}|S_{LE}|\cos\lambda}$$



Leading edge suction parameter

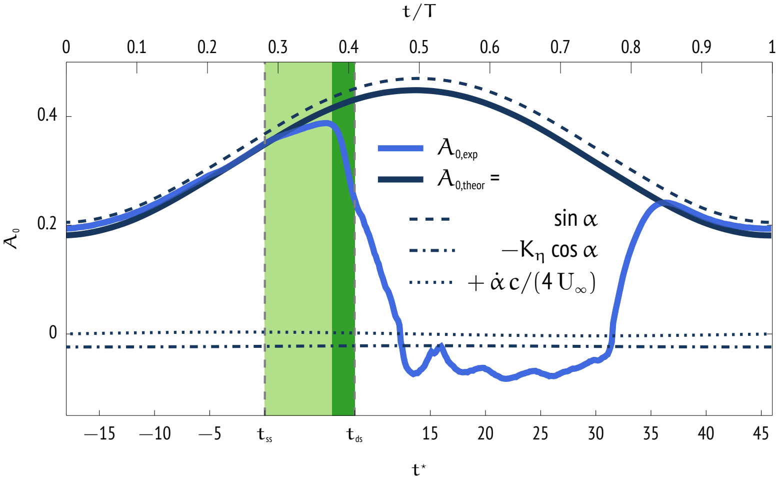
$$A_{0,\mathrm{exp}} = \sqrt{\frac{2}{\pi}|S_{\mathrm{LE}}|\cos\lambda}$$



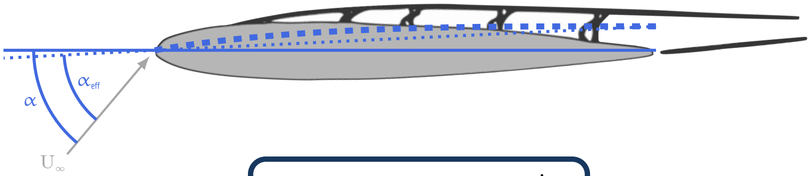


Leading edge suction parameter - theoretical model

$$\mathcal{A}_{0,\text{theor}} = \sin\alpha - K_\eta \cos\alpha + \dot{\alpha}\frac{c}{4U_\infty}$$



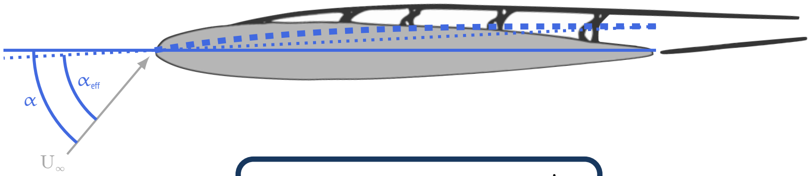
Effect of the shear layer development



$$\boxed{A_{0,\text{theor'}} = \sin\alpha - K_\eta \cos\alpha + \frac{\dot{\alpha} c}{4U_\infty}}$$

Effect of the shear layer development

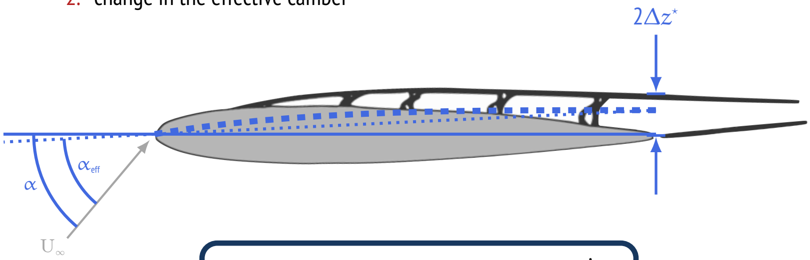
1. change of the effective angle of attack



$$A_{0,\text{theor}'} = \sin \alpha_{\text{eff}} - K_\eta \cos \alpha_{\text{eff}} + \frac{\dot{\alpha} c}{4 U_\infty}$$

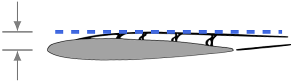
Effect of the shear layer development

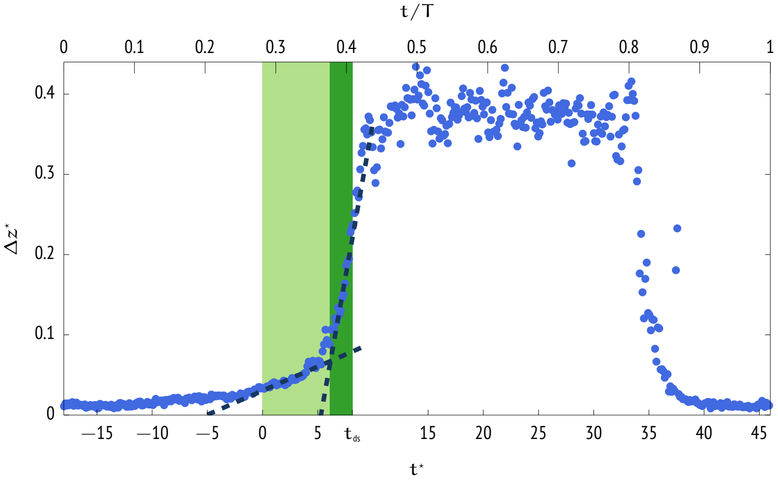
1. change of the effective angle of attack
2. change in the effective camber



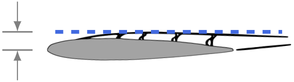
$$A_{0,\text{theor'}} = \sin\alpha_{\text{eff}} - (K_\eta + \Delta z^\star)\cos\alpha_{\text{eff}} + \frac{\dot{\alpha}c}{4U_\infty}$$

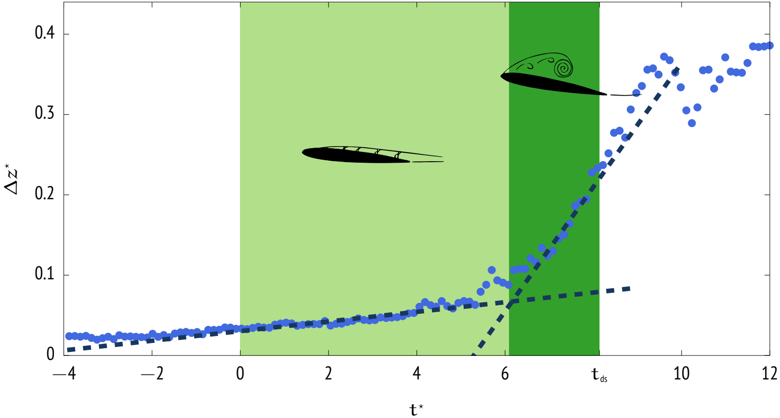
Effect of the shear layer development





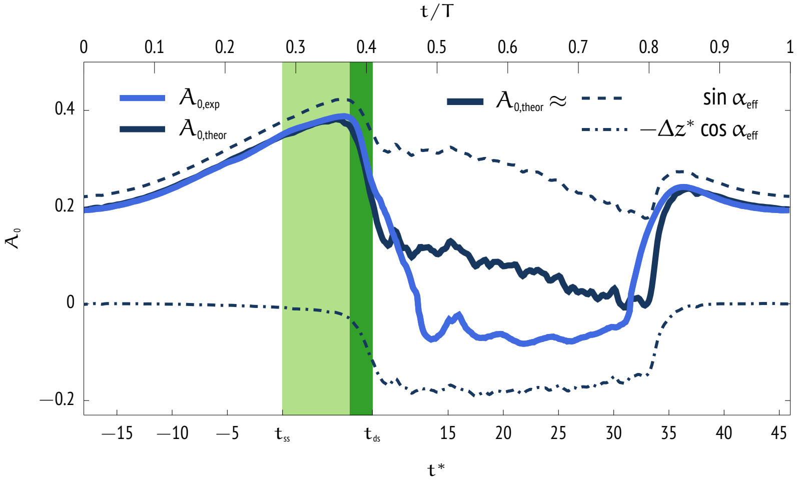
Effect of the shear layer development



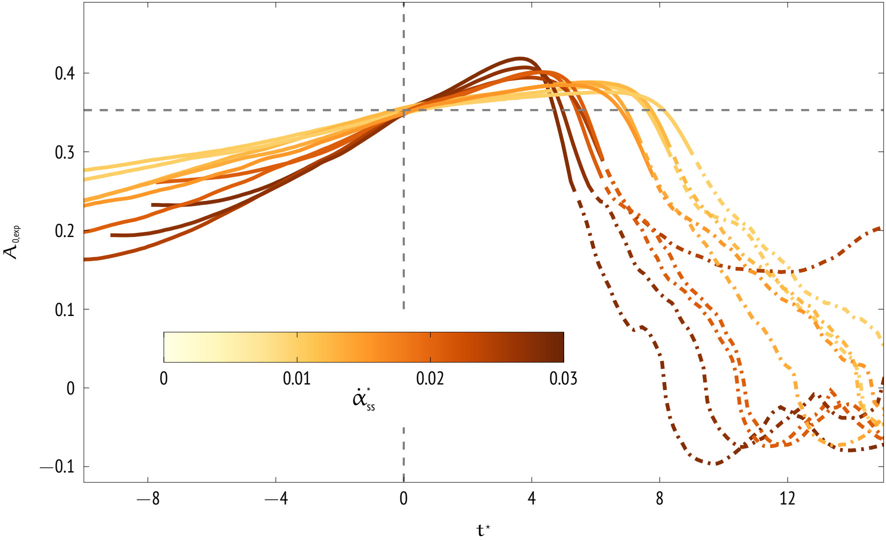


Leading edge suction parameter - improved theoretical model

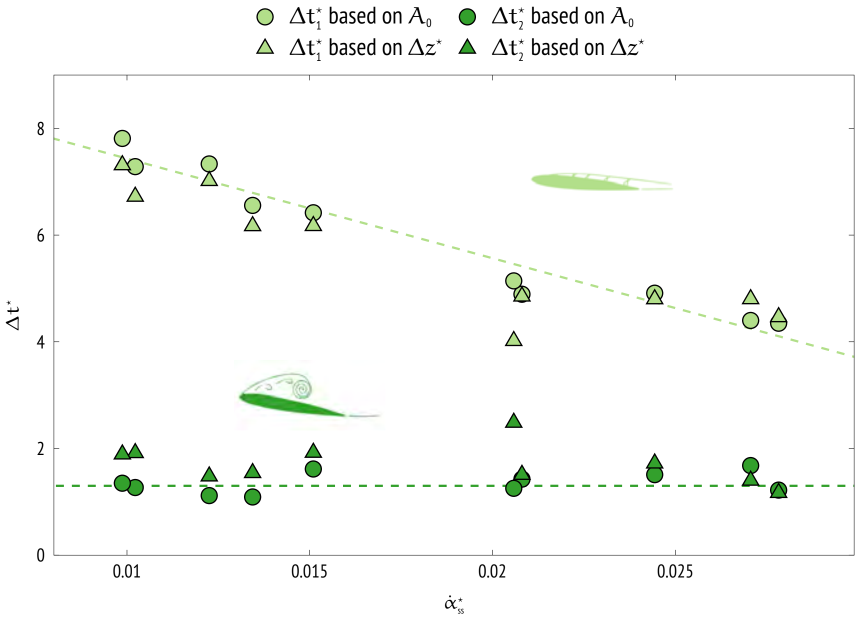
$$A_{0,\text{theor'}} = \sin\alpha_{\text{eff}} + \dot{\alpha}\frac{c}{4U_\infty} - K_\eta \cos\alpha_{\text{eff}} - \Delta z^\star \cos\alpha_{\text{eff}}$$



Influence of motion unsteadiness

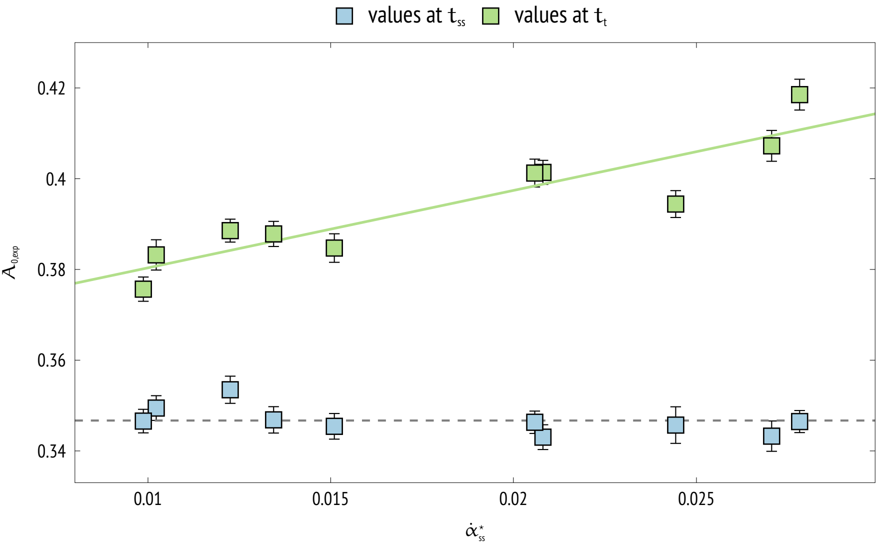


Timing

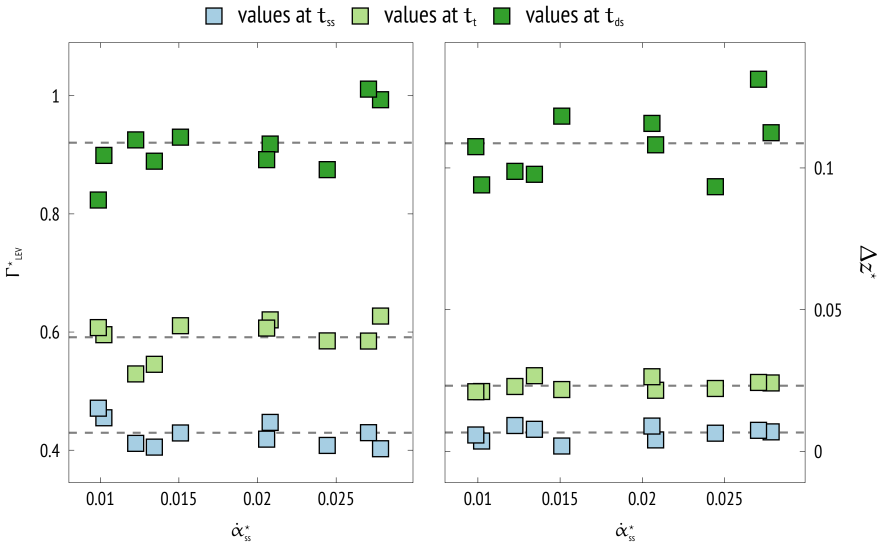


$\Delta t_1^\star$ based on A_0
$\Delta t_2^\star$ based on A_0
$\Delta t_1^\star$ based on $\Delta z^\star$
$\Delta t_2^\star$ based on $\Delta z^\star$
$\Delta t^\star$
0
2
4
6
8
0.01
0.015
0.02
0.025
$\dot{\alpha}_{ss}^\star$

Critical value of the leading edge suction parameter?



Other critical stall parameters?



Conclusions

- Two-stage stall development independently confirmed by surface pressure and velocity field measurements
- Improved model predicts magnitude and timing of leading edge suction parameter peak by including a two-fold influence of the growth of the shear layer
- Stall delay Δt_1 decreases with increasing unsteadiness
- Vortex formation time Δt_2 independent of the unsteadiness
- Critical value of leading edge suction parameter increases with increasing unsteadiness
- Circulation and shear layer height reach motion independent critical values

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Compressible Dynamic Stall in an Unsteady Freestream

Jim Gregory
Professor, Department of Mechanical and Aerospace Engineering
Director, Aerospace Research Center
The Ohio State University

Presented at
ARO Dynamic Stall Workshop
Georgia Institute of Technology
September 10, 2019

THE OHIO STATE UNIVERSITY

Acknowledgements

Naigle, Frankhouser, Williams, Gregory, and Bons, "Experimental Modeling of Compressible Dynamic Stall in Unsteady Flow through Interpolation of Phase-Matched Conditions in Steady Flow," AHS Technical Meeting on Aeromechanics Design for Vertical Lift, San Francisco, CA, January 20-22, 2016.

This research was supported by the Army Research Office, grant numbers: W911NF-15-1-0207, W911NF-17-1-0110

Background:
Studies on Dynamic Stall

- Bulk of Wind Tunnel research conducted at:
  - Steady Freestream
  - Incompressible
  - Low Reynolds Number
  - Pitching Airfoil
  - 2-D Flow
  - No Plunge

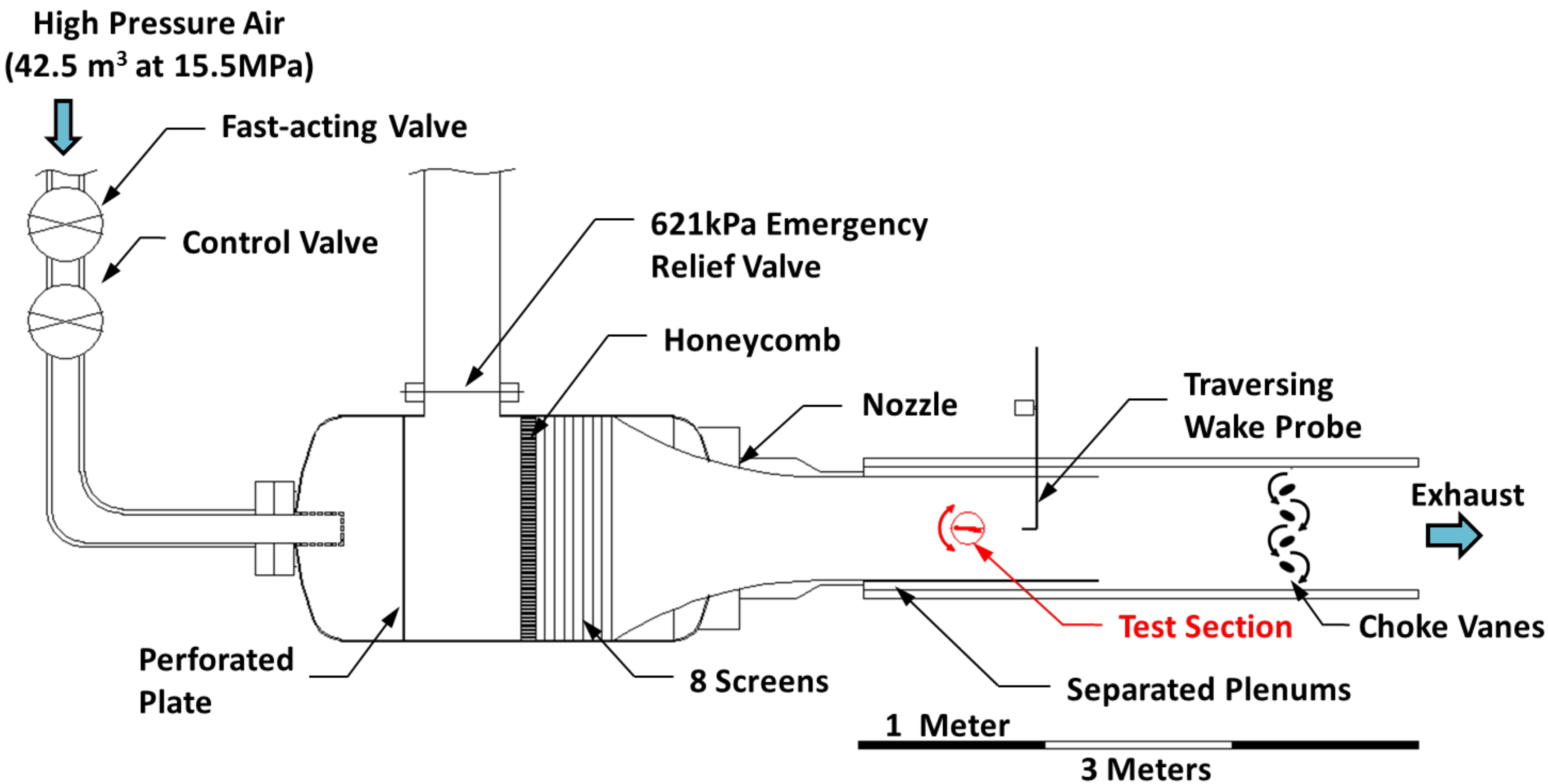
- Here, we consider:
  Unsteady Freestream
  Re, M, and k matched to flight

- **To what extent can *steady* freestream wind tunnel data accurately represent full *unsteady* dynamic stall data?**

Comparison Cases:

1. Pitching Airfoil in Time-varying Freestream (Baseline Condition)
2. Pitching Airfoil in Steady Freestream (Mean Mach and Reduced Freq.)
3. Quasi-Unsteady: Interpolation of Steady Freestream Data
4. Pitching Airfoil in Steady Freestream (Mach and Reduced Freq. matched with instantaneous values at Stall)

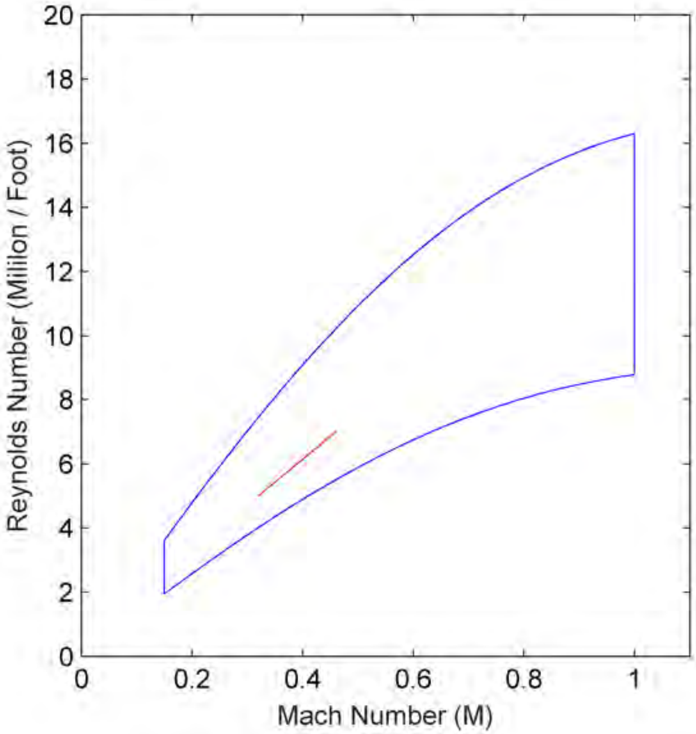
Experimental Setup:
6"×22" Unsteady Transonic Wind Tunnel

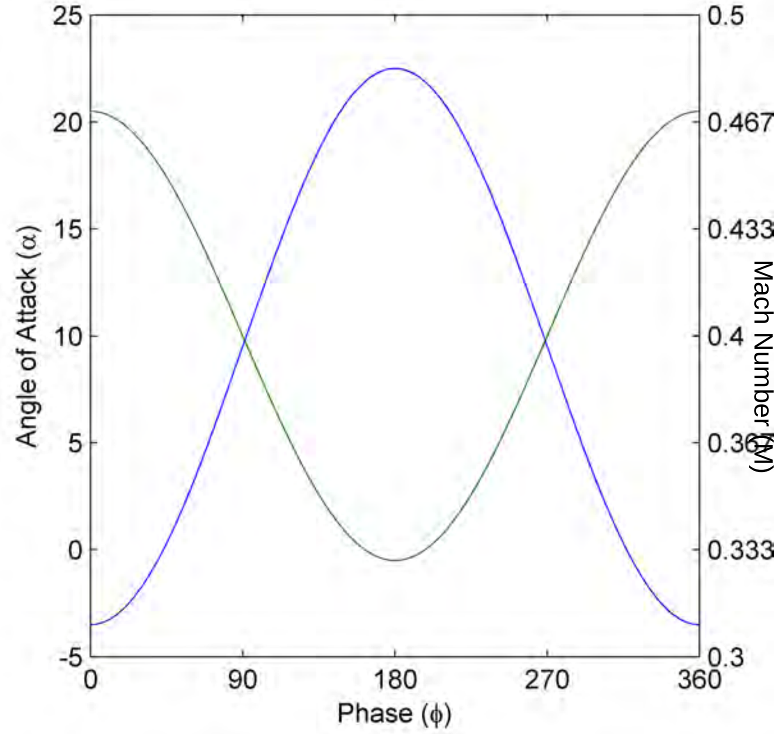


Gompertz, K., *et al*., 2011, "Modification of Transonic Blowdown Wind Tunnel to Produce Oscillating Freestream Mach Number," *AIAA Journal*, vol. 49, no. 11, pp. 2555-2563, **doi: 10.2514/1.J051090**

Experimental Setup:
Test Conditions

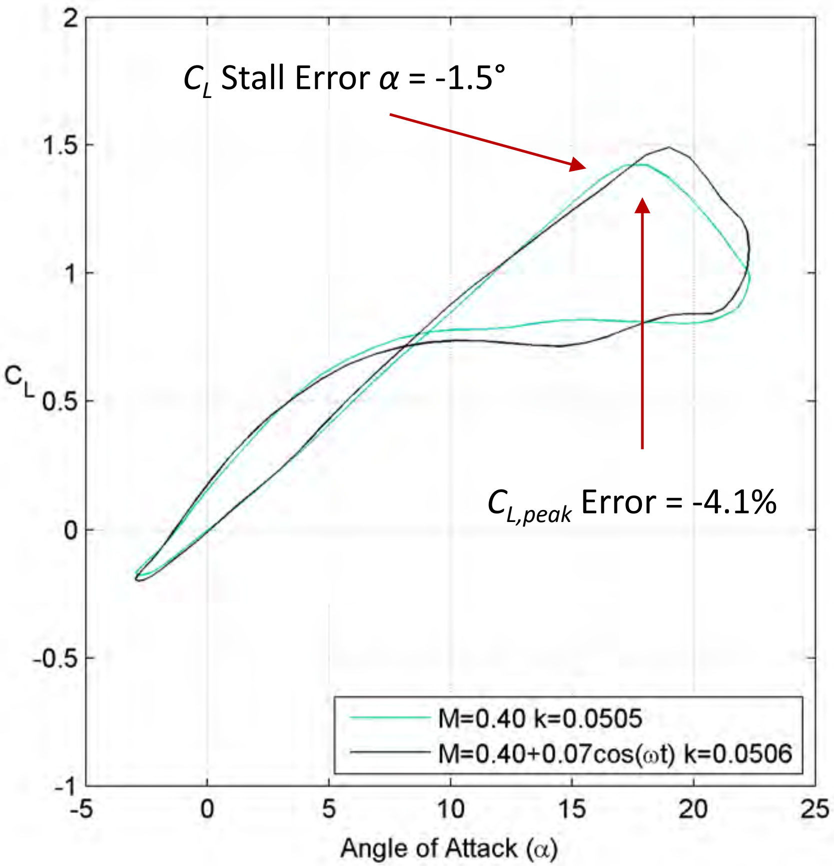
SSC-A09 Airfoil

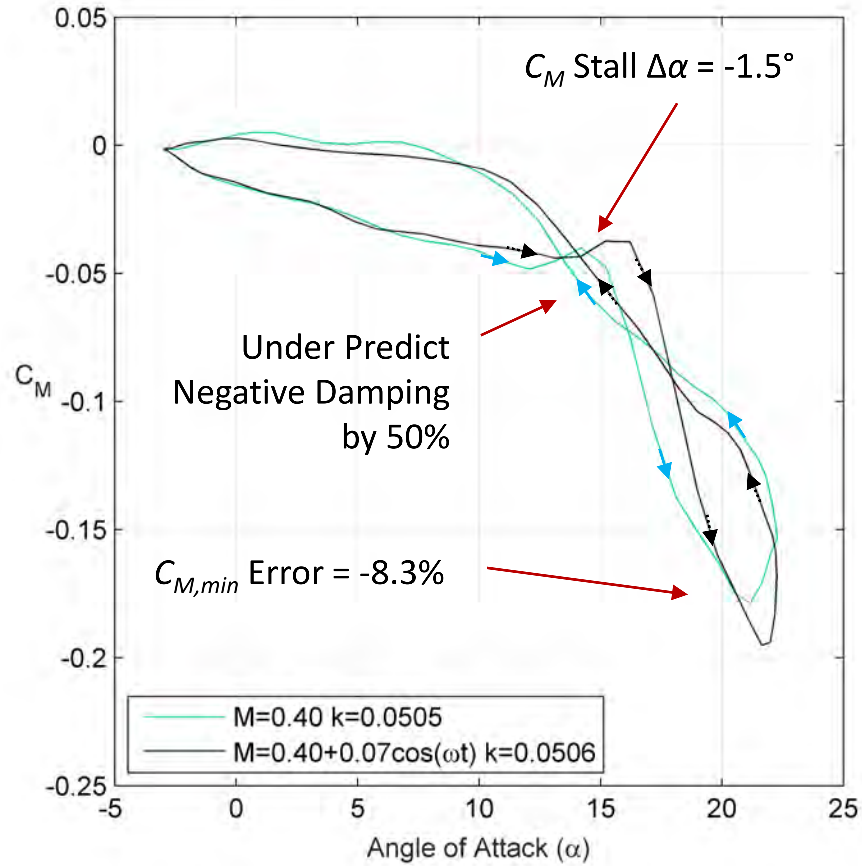




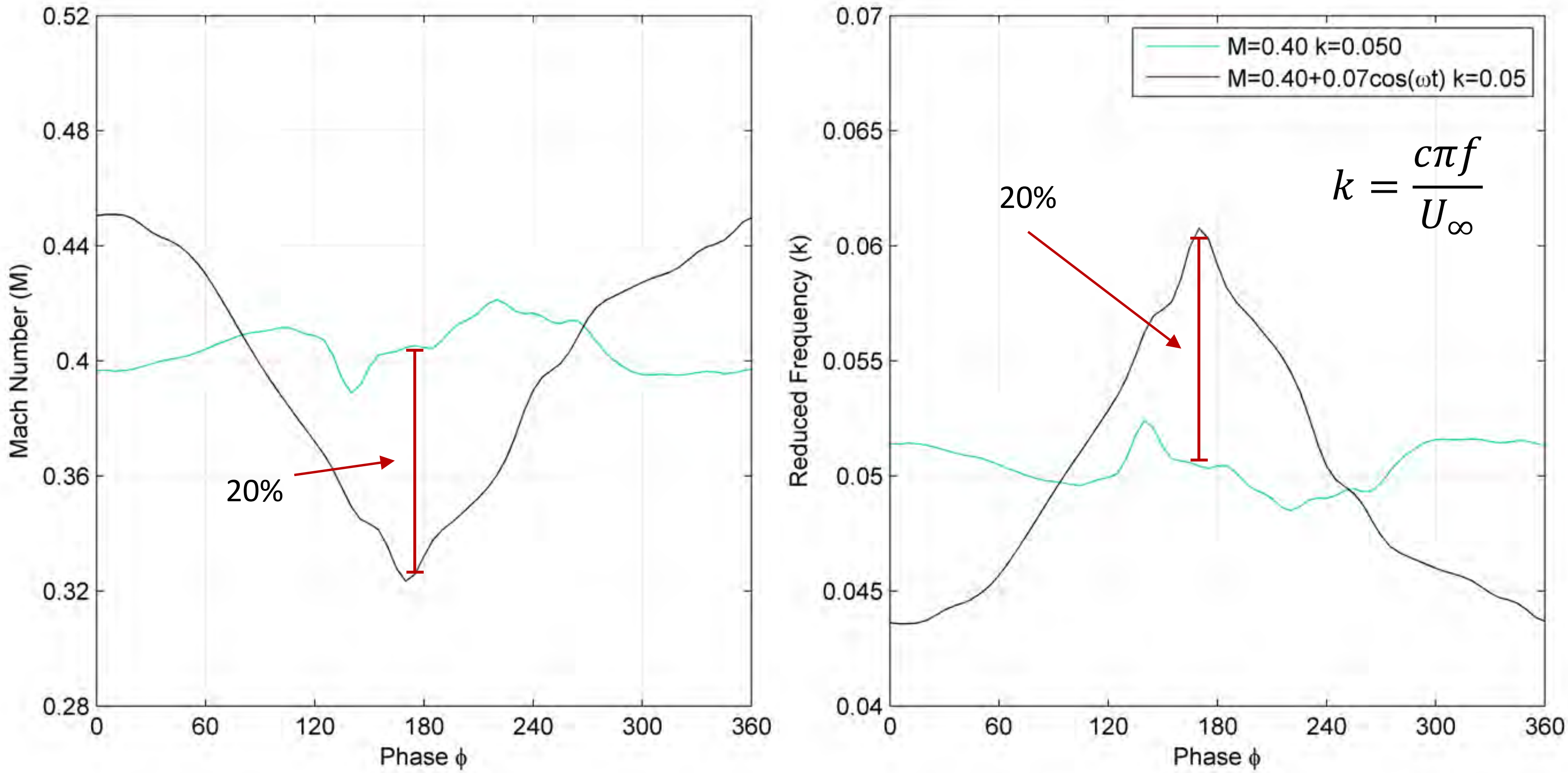
Conditions	Mach (M)	Reduced Frequency (k)	Reynolds Number (Re) ×10⁶	Angle of Attack (α)
Steady Freestream	$0.32 < M < 0.46$	$0.0220 < k < 0.0316$ $0.0441 < k < 0.0627$	$2.5 < Re < 3.5$	9° - 13 cos(ωt)
Unsteady Freestream	0.4 + 0.07 cos(ωt)	0.025 - 0.01 cos(ωt) 0.050 - 0.01 cos(ωt)	3.0 + 0.5 cos(ωt)	9° - 13 cos(ωt)

Results:
Matched Mean Conditions at k=0.050





Results:
Matched Mean Conditions at k=0.050



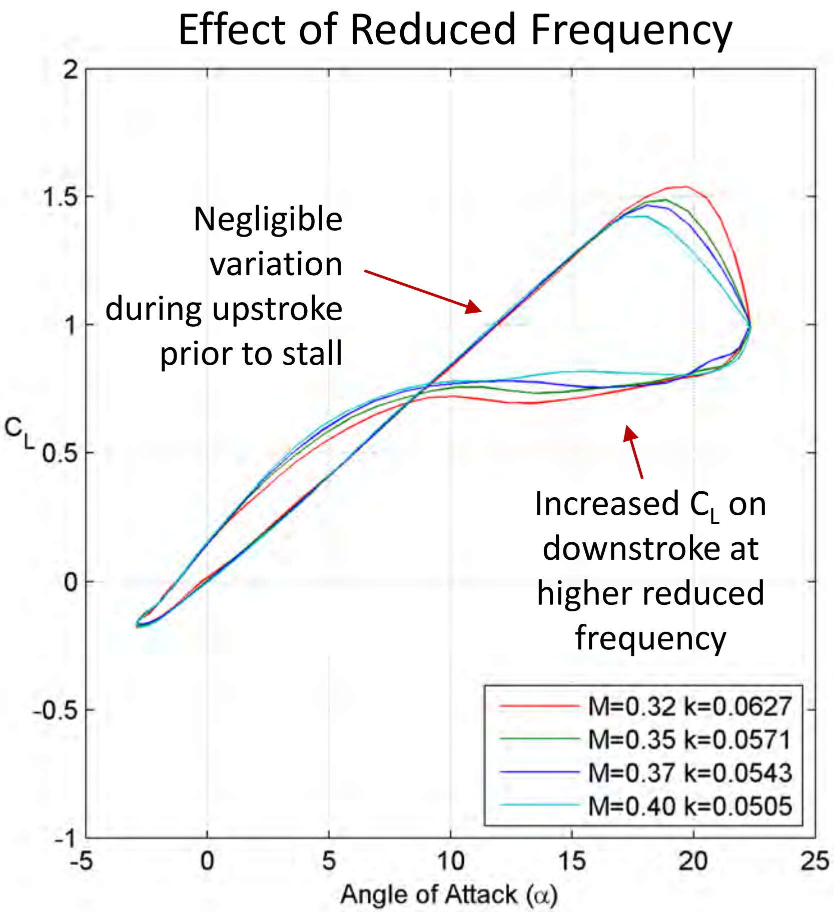
$$k = \frac{c\pi f}{U_\infty}$$

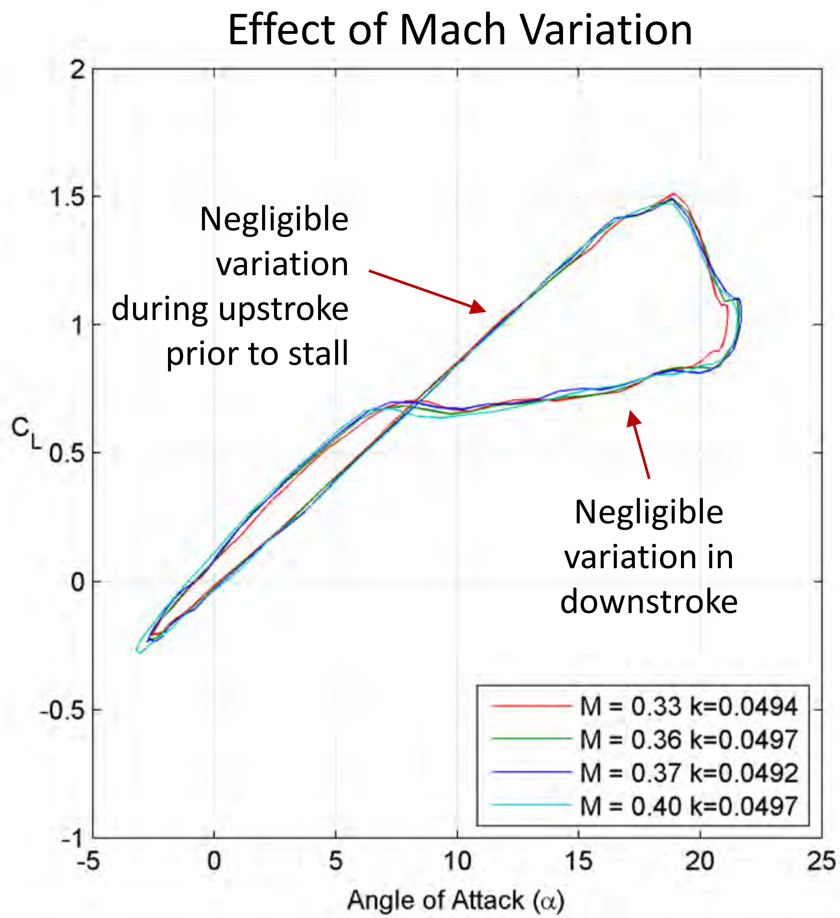
Mean values may be misleading, thus an equation may be more appropriate:

$k{=}k_0{-}k_\Delta\cos(\omega t)$

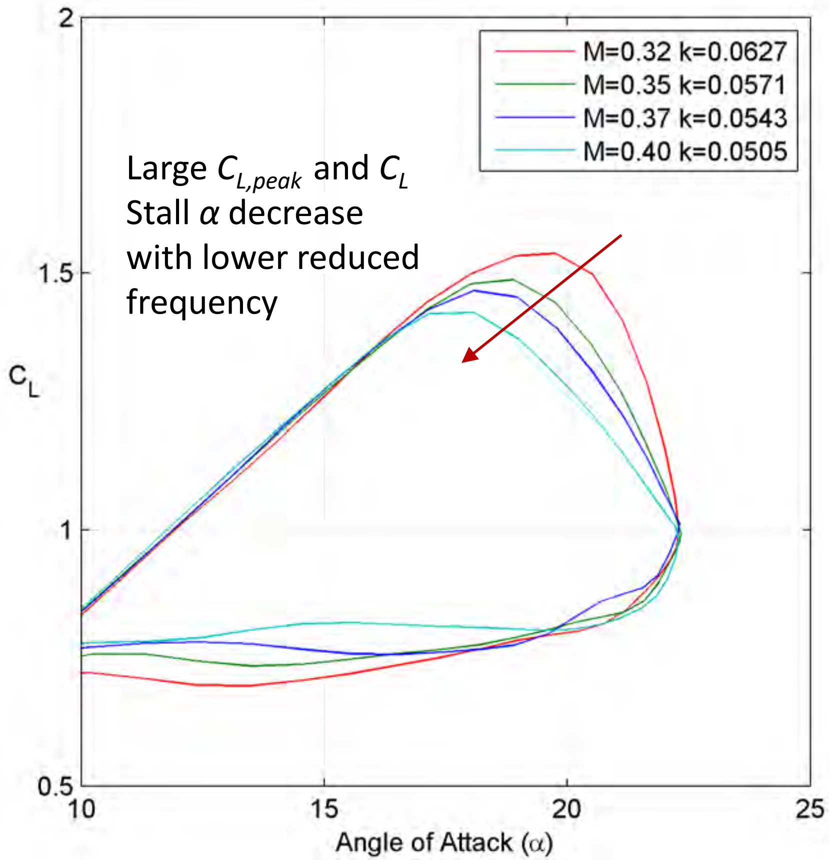
Results:

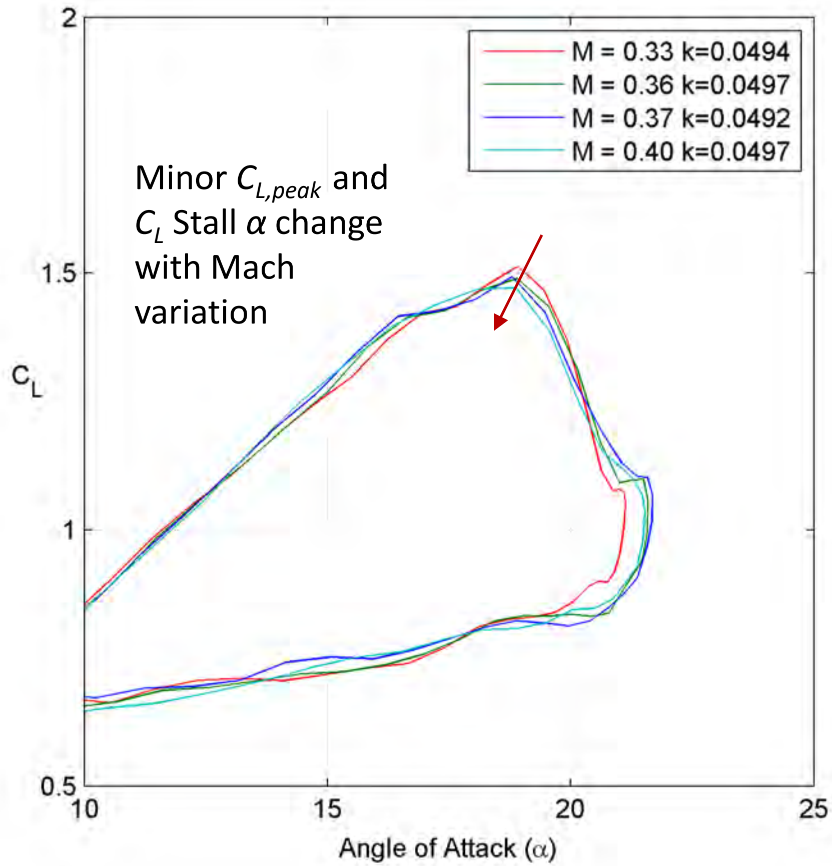
Non-dimensional Parameter Influence





Results:
Non-dimensional Parameter Influence

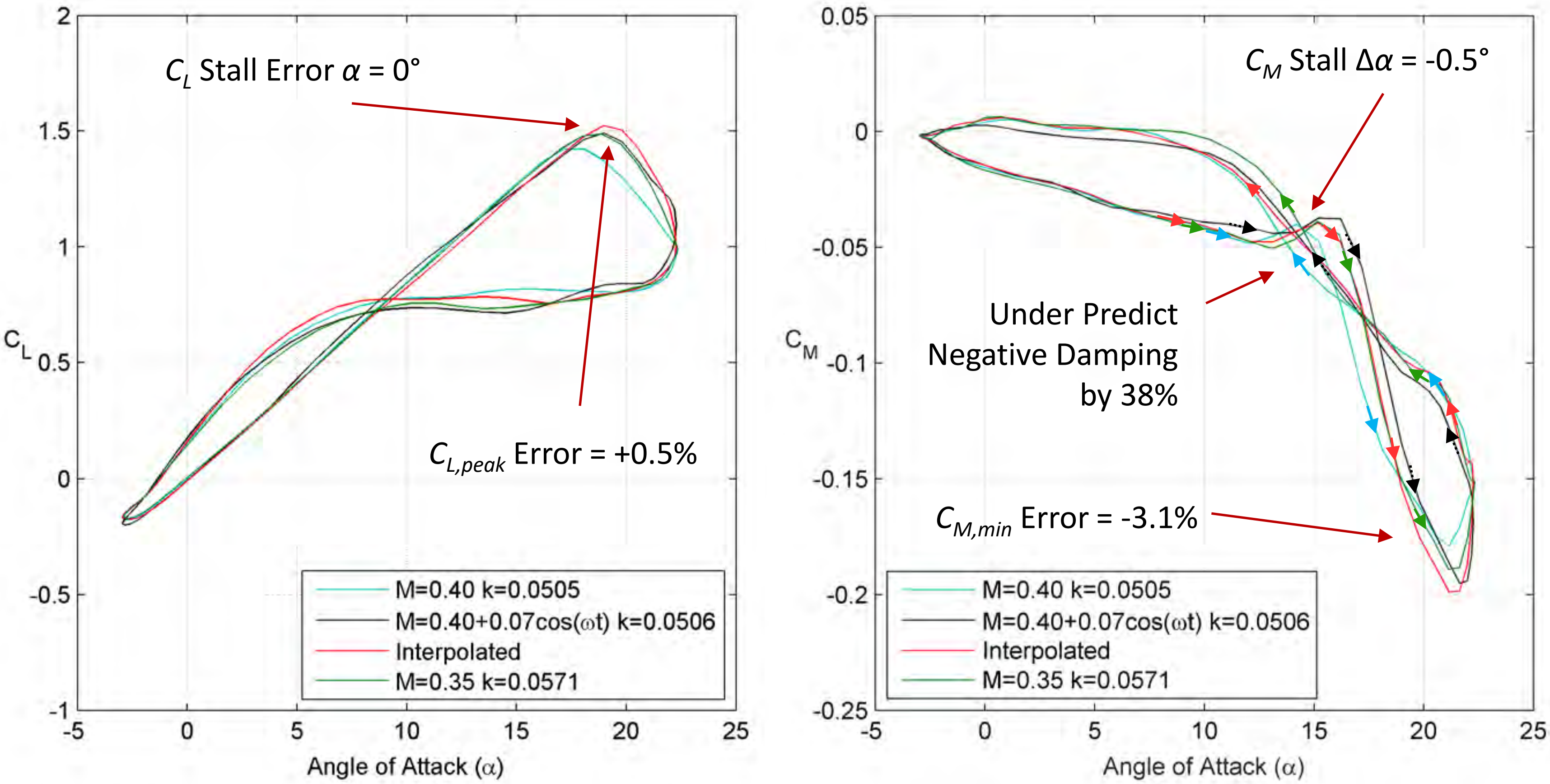




Primary dependency on reduced frequency, not Mach

Results:

Matched Instantaneous Value at Stall



Summary:

- Steady vs. Unsteady freestream:
  If steady is assumed, DSV sheds earlier and is weaker; severity of DS is under predicted.
- Matching the non-dimensional parameters at the stall event is a quick and better representation of airfoil loading than matching mean non-dimensional parameters.
- Interpolated steady freestream data can predict airfoil loading of the time-varied condition in a compressible flow.
- These methods cannot accommodate secondary airfoil loading oscillations (secondary DSV at lower *k*).
- The principal non-dimensional parameter for dynamic stall is reduced frequency: **instantaneous pitch rate at the point of stall is dominant**.
- Equation format such as $k=k_0+k_\Delta\sin(\omega t)$ and $Re=Re_0+Re_\Delta\sin(\omega t)$ are more descriptive.

Stall Alleviation using Magnetohydrodynamic Plasma Actuators

Jayant Sirohi

University of Texas, Austin

Question 1: What progress has been made?

What is the current state of the art in understanding dynamic stall for rotorcraft in your area (comp, exp, theor, control)?

Experiments: time history of pressure distribution over the airfoil is well understood.

Control: we know what works (e.g., 1/rev slats) and what doesn't work (e.g., blowing/ circulation control). Are there other approaches?

Who is advancing the state of the art and how are they doing it? (Names and places; what made you select their work?)

J. Gregory et al., OSU – dynamic stall experiments with harmonically varying freestream.

T. Schwermer et al., DLR – high cyclic pitch rotor test facility

What errors do you see the general community still making? (e.g., CFD papers that are still using 2D to model 3D separated flows)

Question 2: How does your current research fit in?

Magnetohydrodynamic plasma actuators:

Solid-state, high-bandwidth flow control device

Can introduce large transient momentum into the flow (comparable to combustion actuators) without needing cavities in the blade

- What question are you trying to answer?

What is the control authority of this type of actuator at full-scale Reynolds number and Mach number?

- Why is it important?

Can lead to an unsteady flow control device with minimum weight/ structural penalty

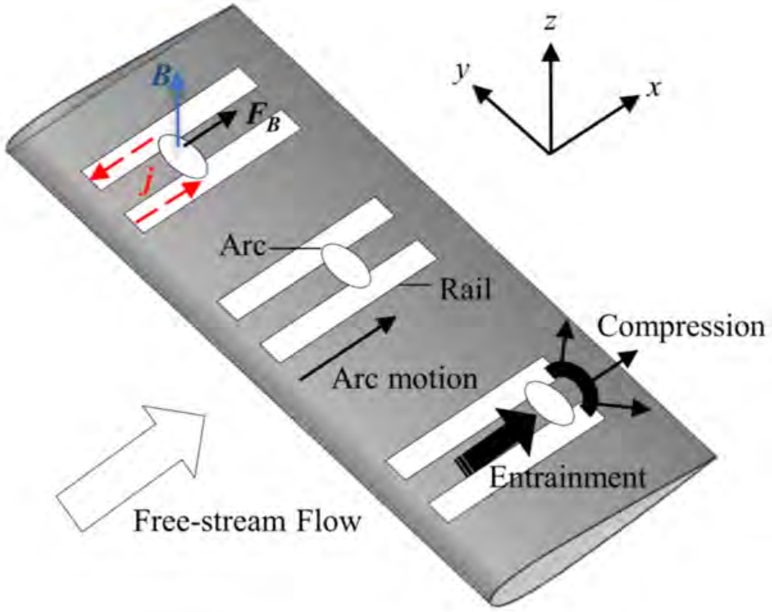
- Synopsis of your most promising/significant findings?

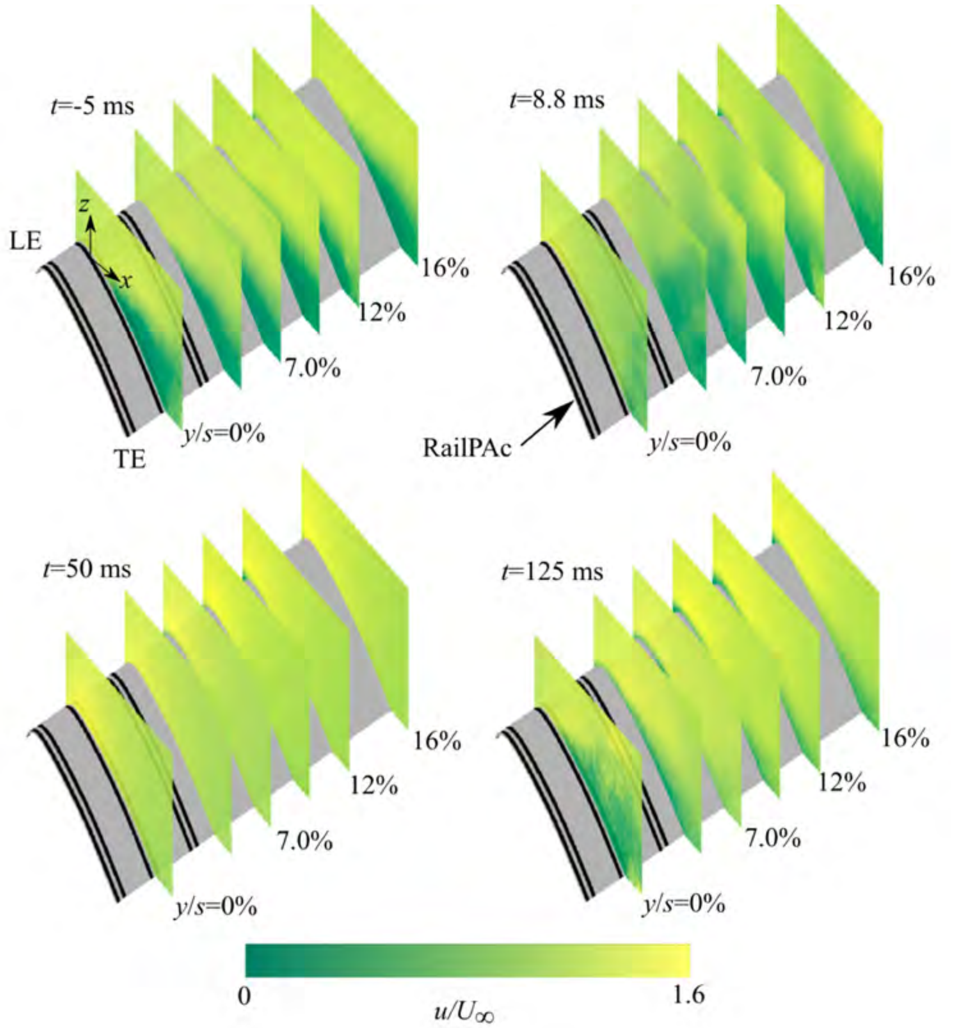
Question 2: How does your current research fit in?

- Synopsis of your most promising/significant findings?

Momentum imparted by the actuator has been measured – found comparable to combustion type actuators

Static stall alleviated at Re up to 90,000





U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

The Effects of Leading Edge Surface Roughness on Dynamic Stall at Low Reynolds Number

John Hrynuk

Research Engineer

Vehicle Technology Directorate

DD MMM YYYY

EXPERIMENTAL METHODS/SETUP

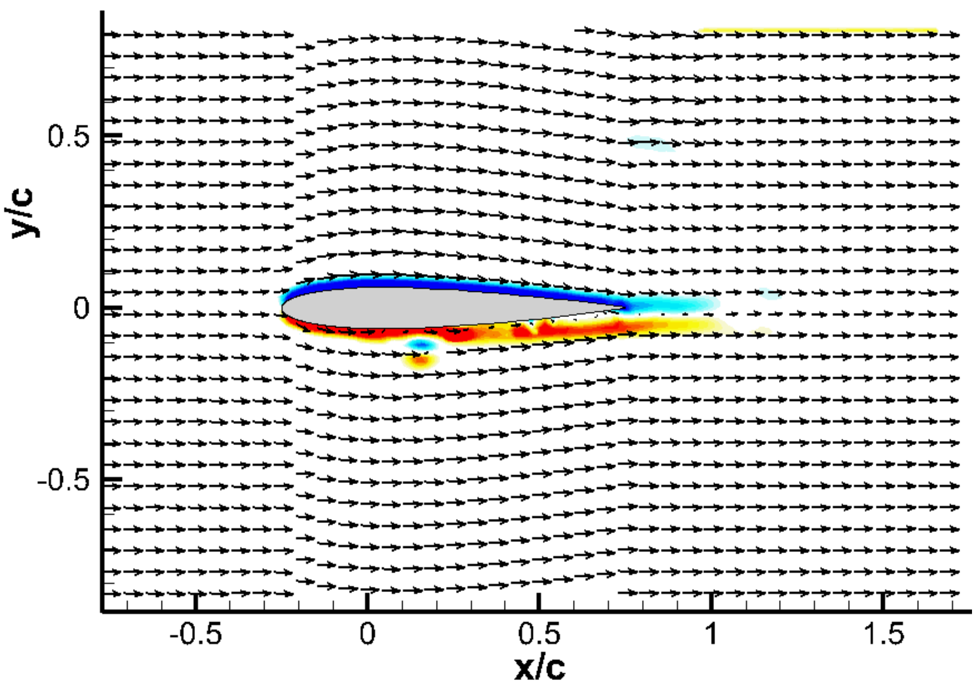
Motion Physics
Full Span NACA 0012 wing pitch and hold
Pitch axis: ¼ chord
$U_\infty = 1.5$ m/s
c = 12 cm
Re = 12,000
$\Omega = 0.1$

Flow field measurements via PIV @ 7 Hz
Phase averaged to 140 Hz,
nominally 1 data point every 1º
50 repeated trials (highly repeatable)
1/5th of vectors shown

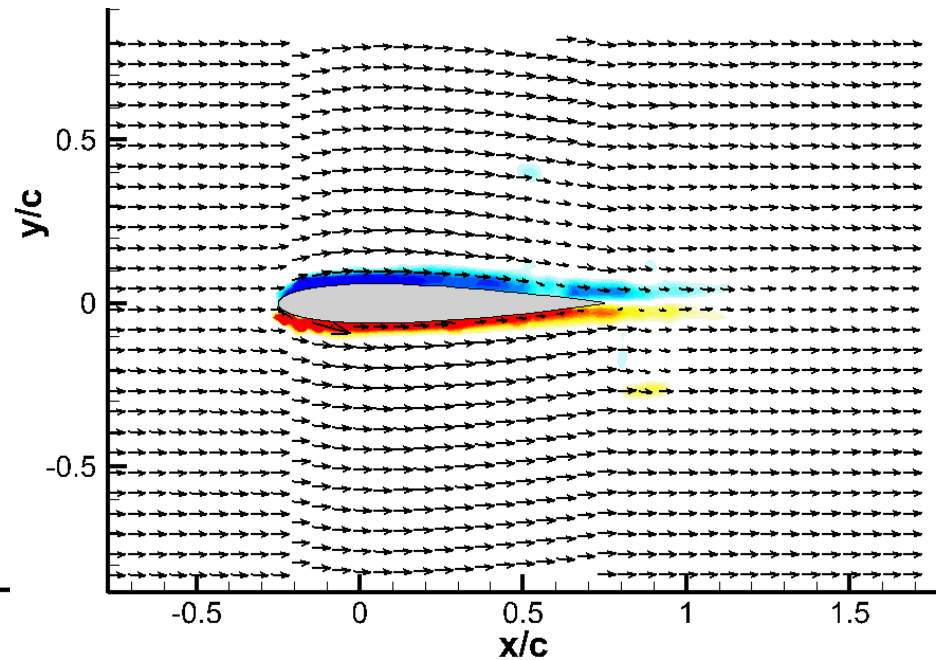
Roughness:
36 Grit sandpaper
Typical particle diameter = 530 microns ≈ 0.004c
Applied from LE to 0.25c on top and bottom surface

BASELINE VS ROUGH WING

- Contours of vorticity
- Reflections from roughness caused more noise near LE
- Time delay before rough wing DSV forms



Baseline



Rough

CLOSER LOOK

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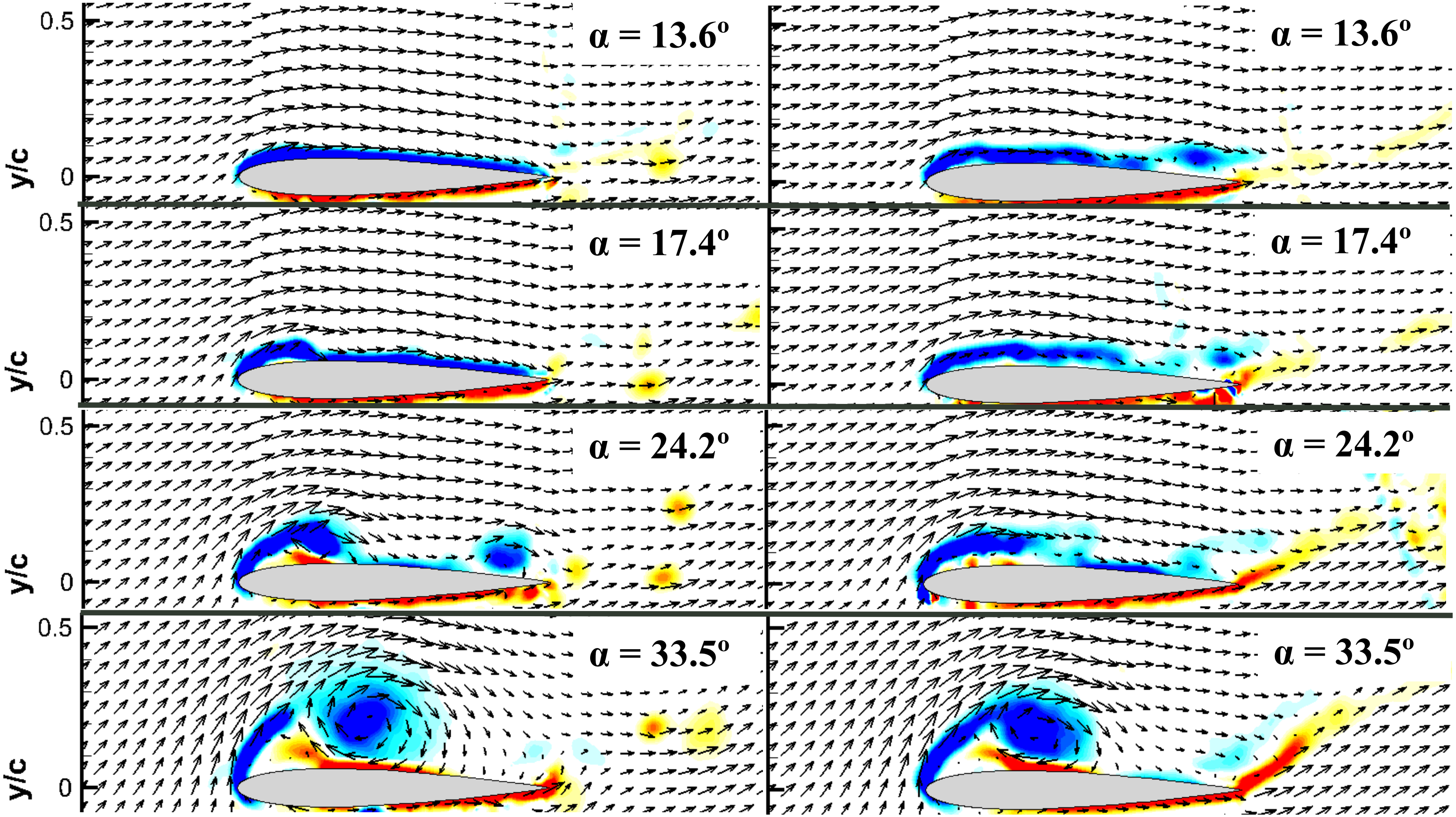
- **Delayed vortex formation, different shape**



VORTEX FORMATION ANGLE

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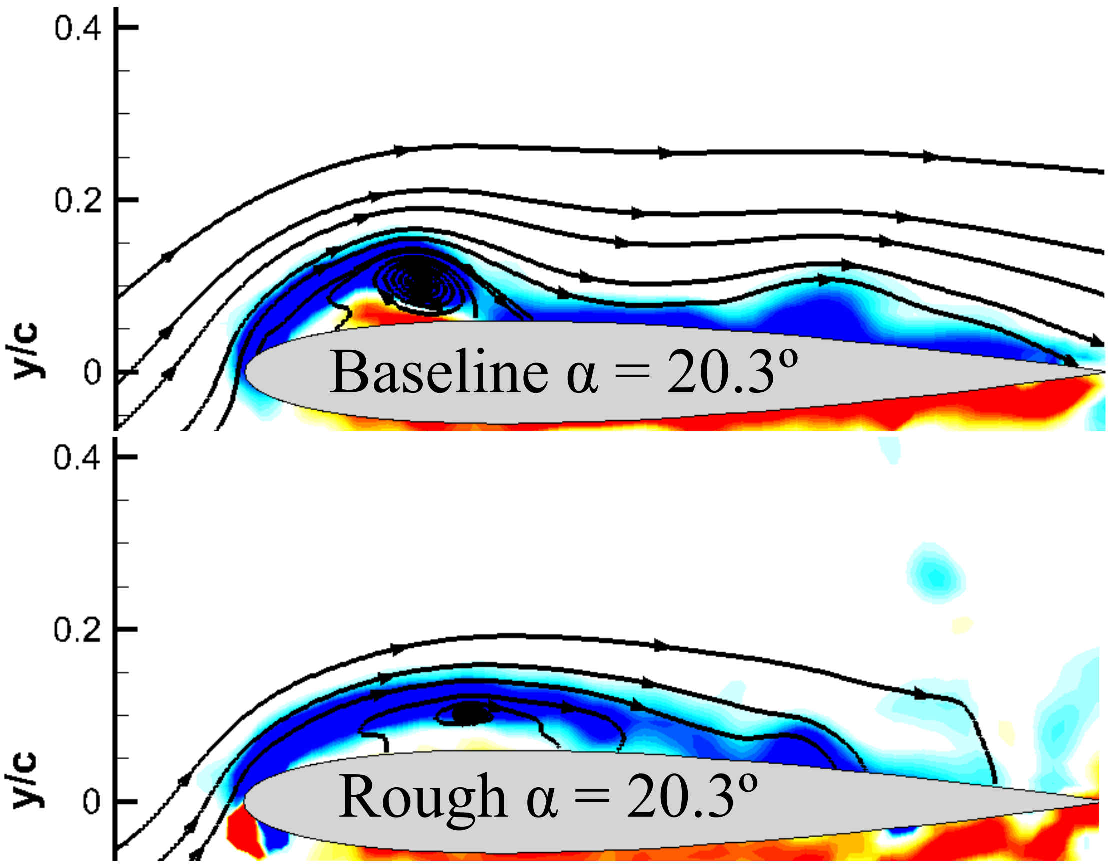
Pick formation angle using streamlines to ID vortex

Vortex formation angles:
- **Baseline 15.5º**
- **Rough 20.3º**

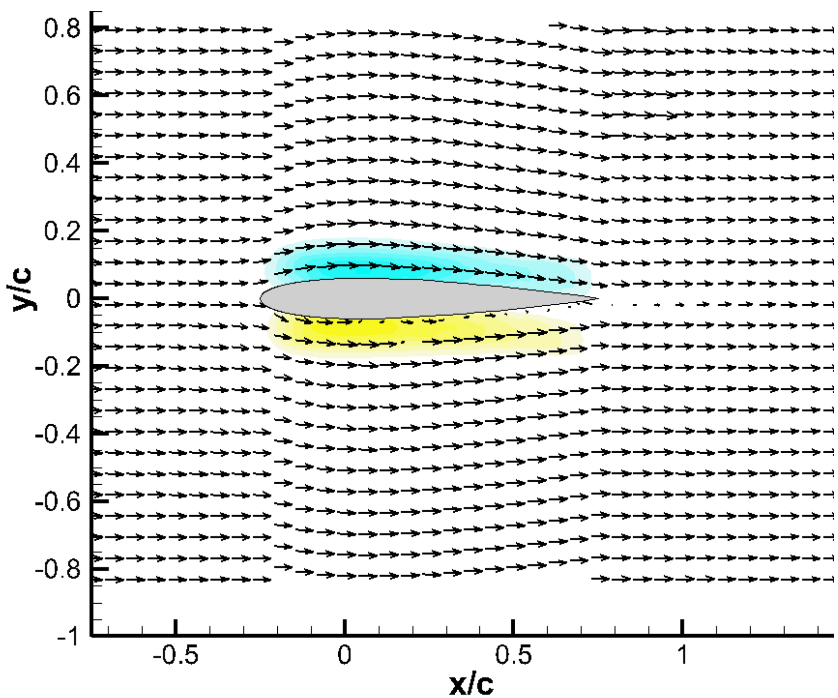
Compare Baseline, Rough at the Rough formation angle



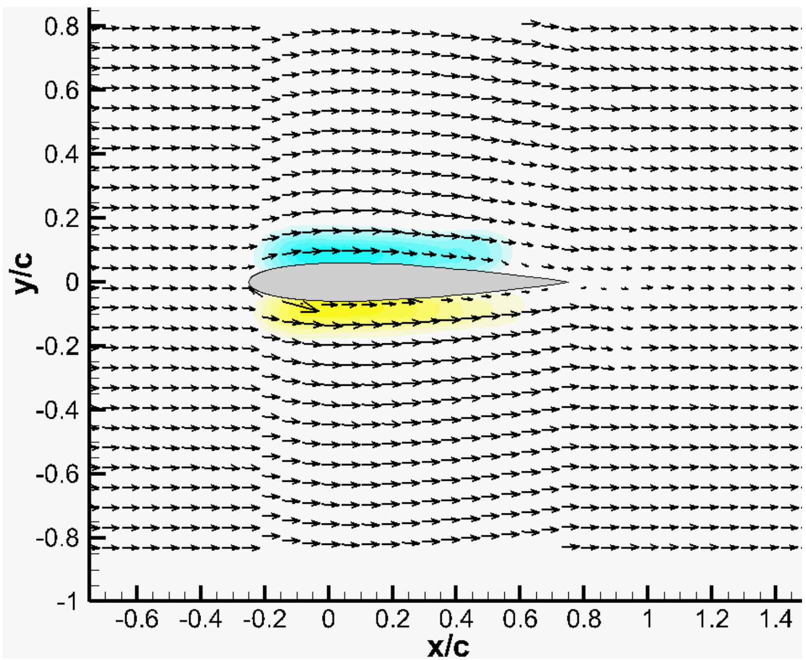
GAMMA CRITERIA FOR VORTEX TRACKING

Using Γ criteria for tracking
Best performing tracking metric on vortices of these types

$$\Gamma_1(P) = \frac{1}{N}\sum_S \frac{(PM \wedge U_M)\, z}{||PM||\;||U_M||} = \frac{1}{N}\sum_S \sin(\theta_M)$$



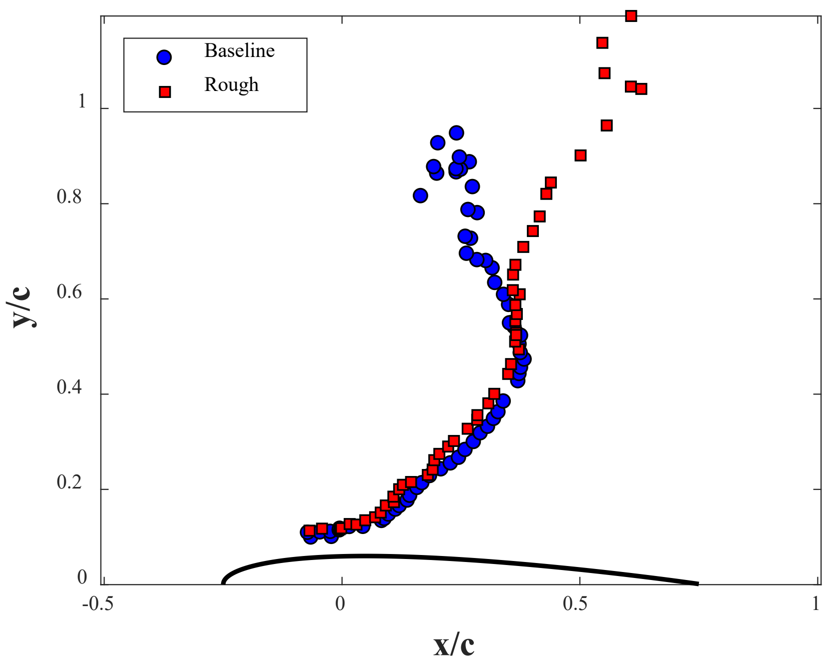
Baseline

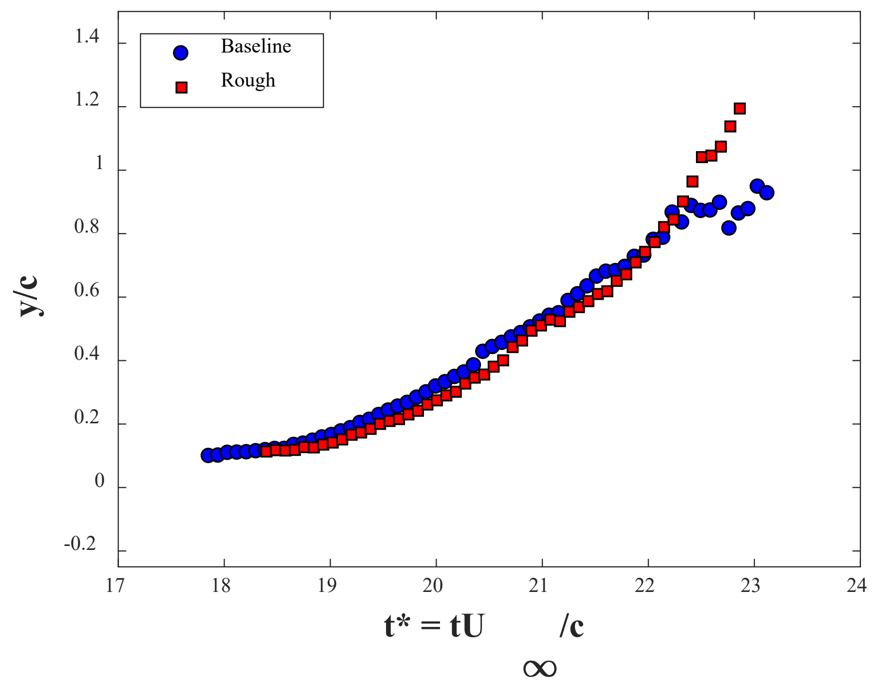


Rough

VORTEX PATH

- Vortex paths are very similar near the wing, deviate downstream
- Rough DSV forms roughly 0.5 convective times later, convects a little slower





VORTEX CIRCULATION

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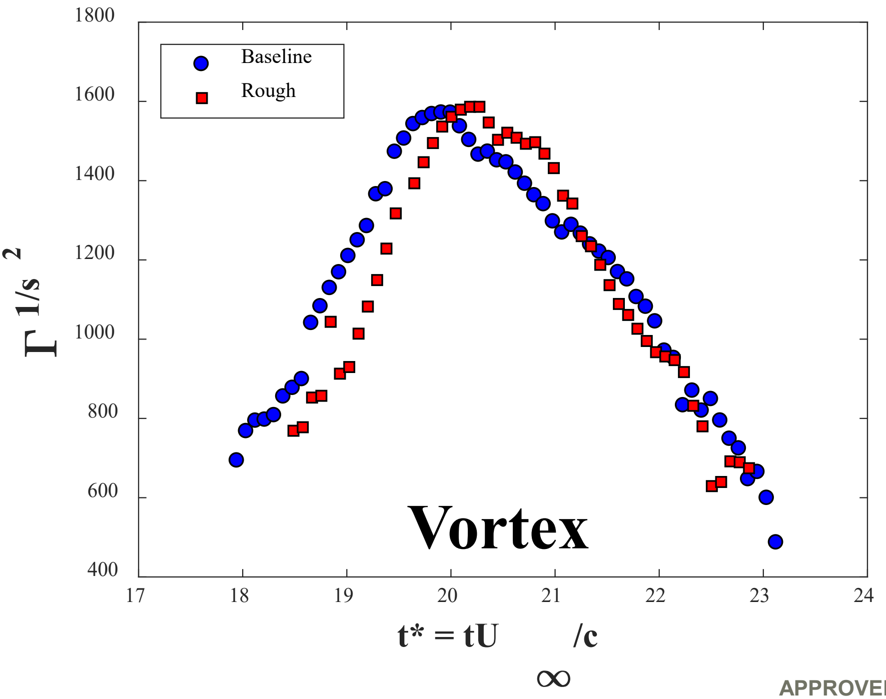
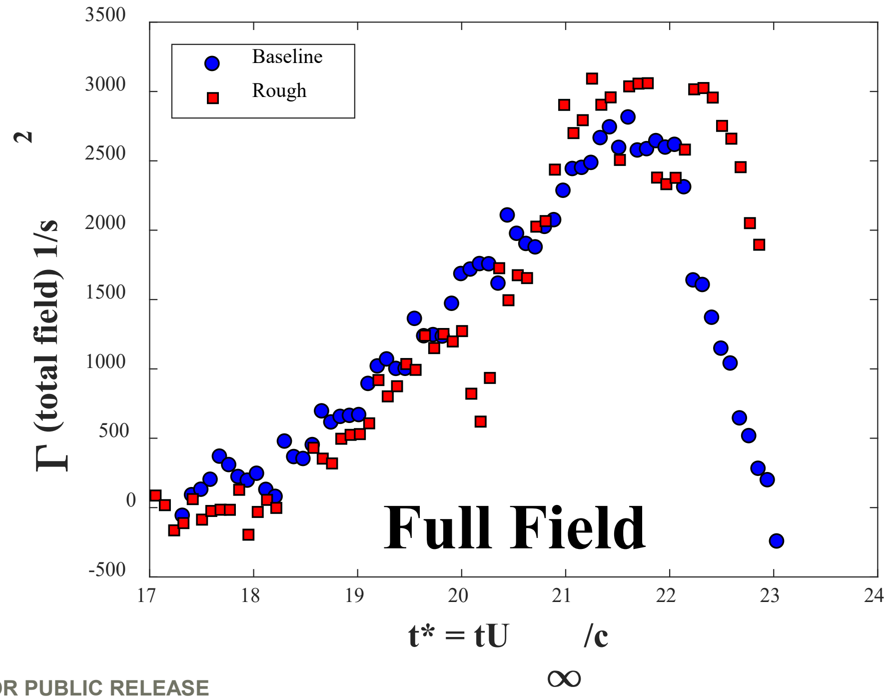
Vortex Circulation – negative circulation within a set radius (5cm) around the vortex

- **Delayed formation**
- **Flatter peak**

Total Circulation – sum of all circulation (+/-) in data

- **Delayed formation**
- **Higher total circulation**





CONCLUSIONS

At Low Reynolds number roughness causes:

- **A delay in vortex formation**
  - ~ 0.5 convective times
  - ~ 5^{o}
- **Slightly stronger peak circulation**
- **Different vortex convective path**

Surface roughness may be the source of variability in formation angle from experiment to experiment.

Areas of interest:
What are the Reynolds number effects?
Is this effect similar in water?
What effect does roughness have on direct lift measurements?

Other future work:
Dynamic stall in gusts
Turbulence effects on dynamic stall at low Reynolds numbers

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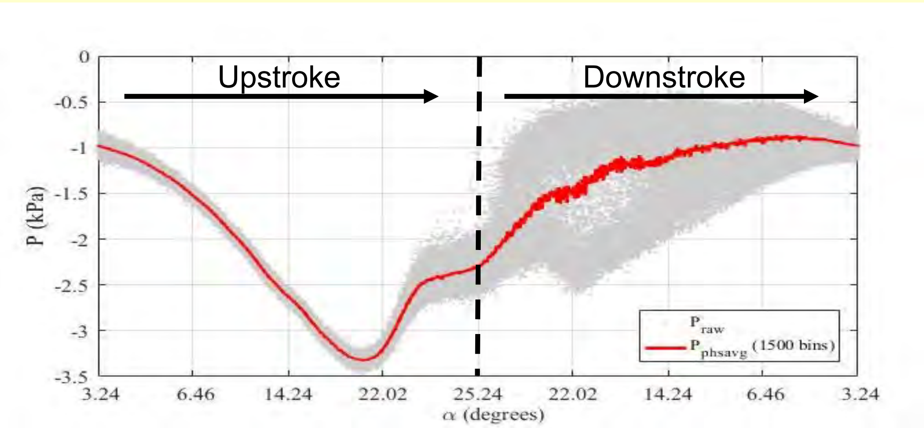
Cycle to Cycle Variation in Dynamic Stall

Jonathan W. Naughton
Professor, Department of Mechanical Engineering
Director, Wind Energy Research Center

Introduction/Previous Work

- **Introduction**
  - Dynamic Stall known to be unsteady
    - **The portion of the phase between separation and attachment shows the most variability in periodic flows**
  - The question is whether this unsteadiness is random

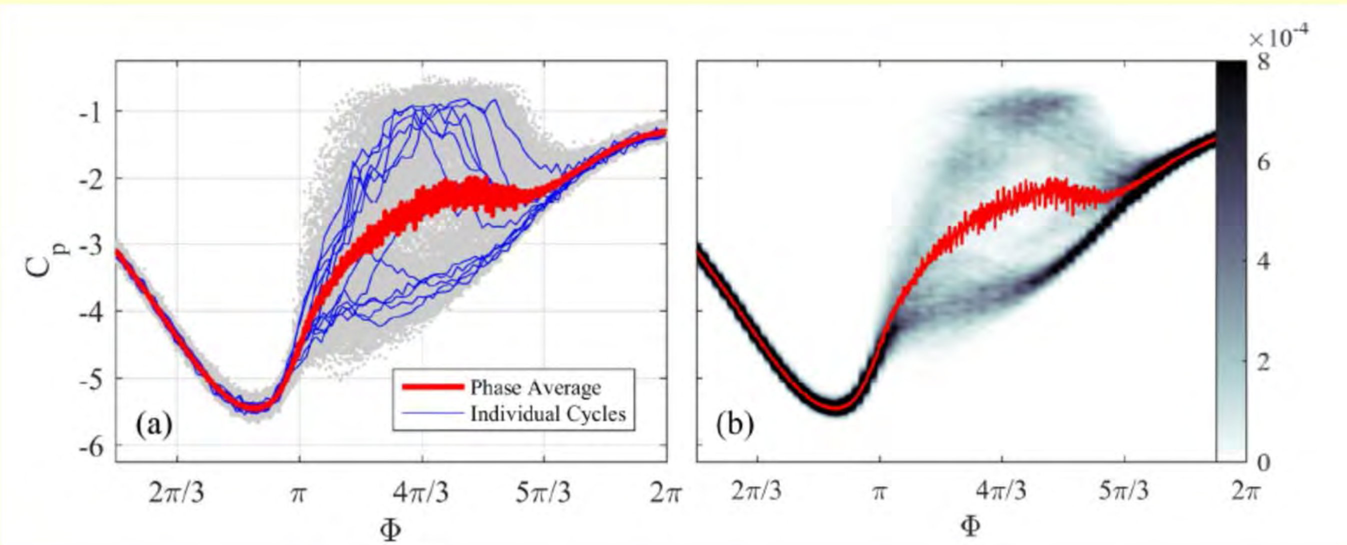


- **Previous Work**
  - Early work observing variations in flow-field
  - Recent work considering cycle-to-cycle variations
    - **Auburn**
      - Rhagav and Komerath
    - **U.S. Army ADD AMRDEC at NASA Ames**
      - Ramasamy et al.
    - **TU Berlin**
      - Lennie
    - **U. Wyoming**
      - Harms et al.

Evidence of Cycle-to-Cycle Variation

- **Scatter plot of pressure provides evidence of variability (100s of cycles plotted)**
- **Individual cycles do not appear to be random**
- **Few cycles follow phase average**

- **Joint probability distribution function clarifies these observations**
  - Two paths of higher probability
  - Phase average not representative



SC1094r8
$\alpha = 10^\circ \pm 6^\circ \sin(\omega t)$
k = 0.067, x/c=3.5%

Re=450,000
Tripped at 5% chord

Department of Mechanical Engineering
University of Wyoming Aeronautical Laboratories

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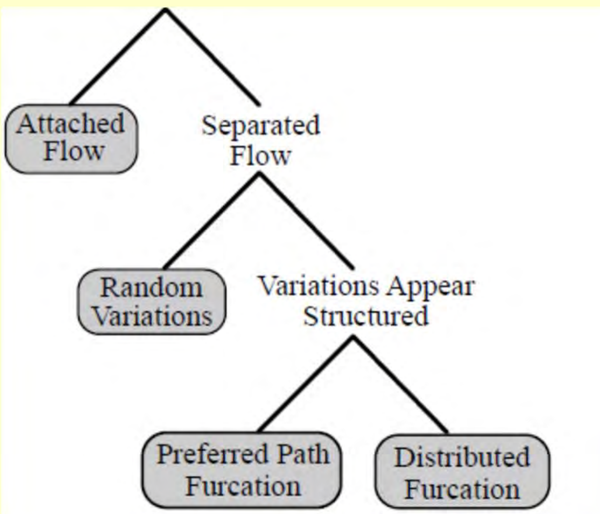
Cycle-to-Cycle Variation
Range of Variations

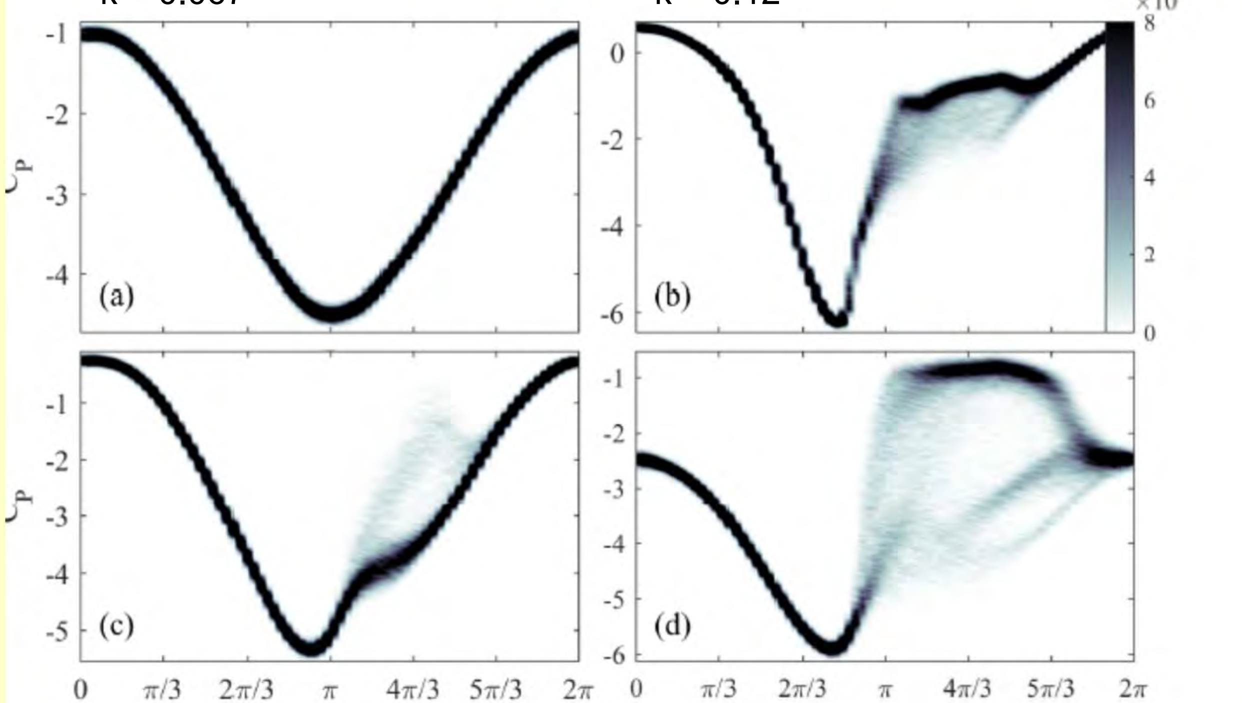
SC1094r8
x/c=3.5%

- **Different kinds of variability found in different cases**
  - No variability
  - Random variability
  - Two or more preferred paths



$\alpha = 8° \pm 5° \sin(\omega t)$
k = 0.067

$\alpha = 9° \pm 14° \sin(\omega t)$
k = 0.12



$\alpha = 8° \pm 8° \sin(\omega t)$
k = 0.067

$\alpha = 12° \pm 6° \sin(\omega t)$
k = 0.067

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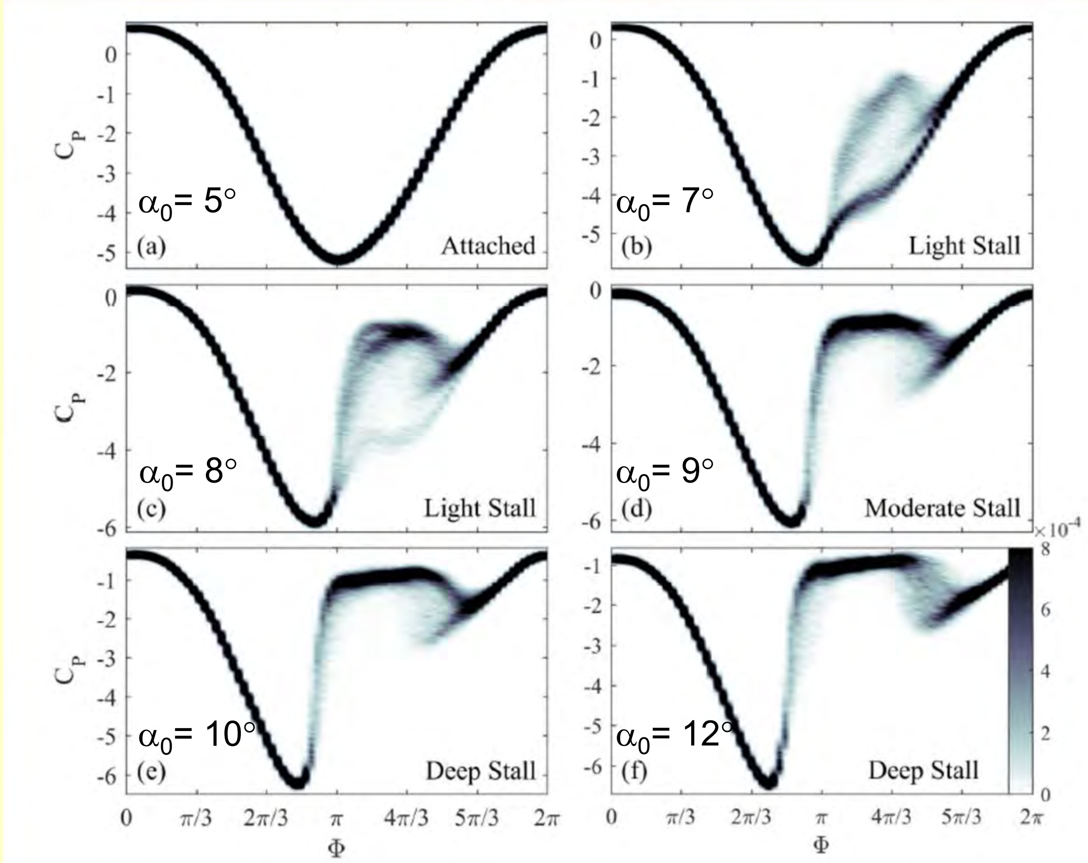
Cycle-to-Cycle Variation
Effect of Stall Type

SC1094r8
x/c=3.5%, α_1= 9°, k=0.067

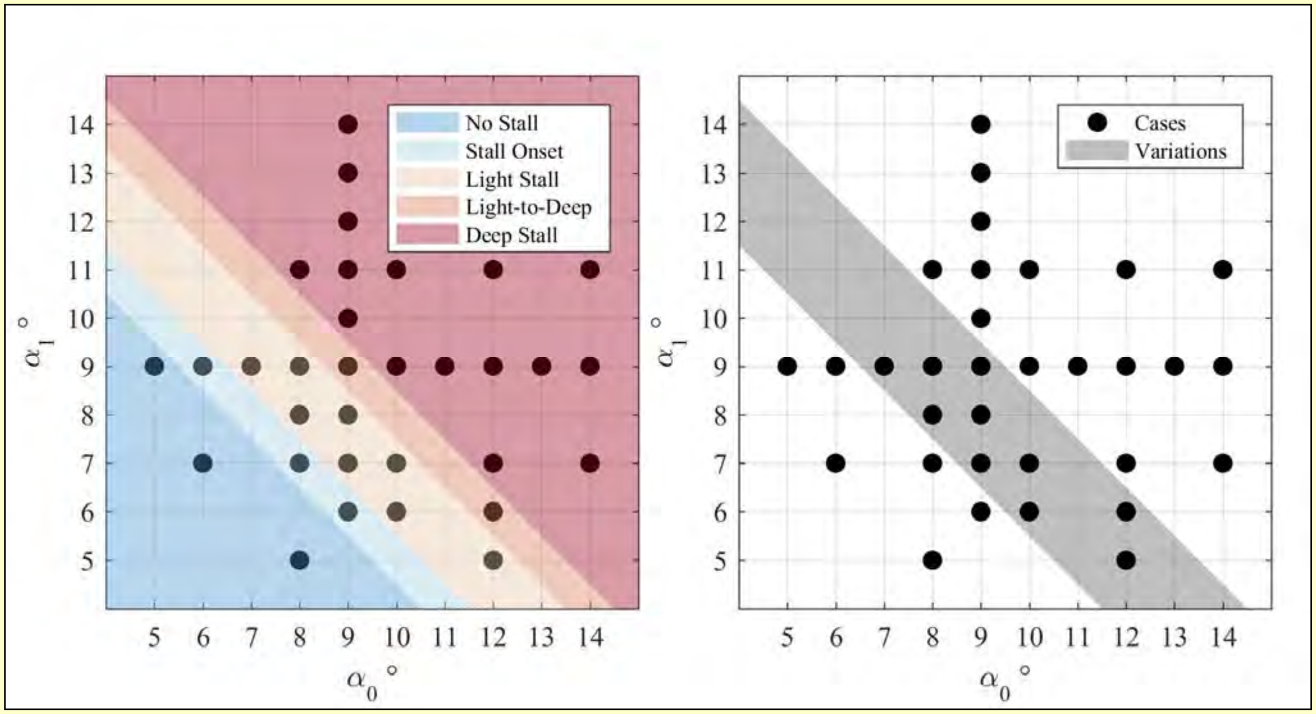
- **The type of stall appears to govern the variability observed**
  - Attached flow – no variability
  - Light stall – preferred path or distributed furcation
  - Moderate and deep stall – little variability
- **Stalled flow seems to take on 1 of 2 states in this case**
  - α_0=7° primarily exhibits low separation, but evidence of high separation exists
  - α_0=8° primarily exhibits high separation, but evidence of low sepration exists
  - α_0=9° primarily exhibits high separation



Cycle-to-Cycle Variation
Effect of Stall Type

- **Testing at many different conditions allows for the identification of where cycle-to-cycle variations are important**
- **Link between stall type and cycle-to-cycle variations can be mapped**
- **Cycle-to-cycle variations primarily associated with stall onset and light stall**
    - Most important parameter is maximum angle of attack
    - Lies in the operating conditions of typical applications

SC1094r8
k = 0.067



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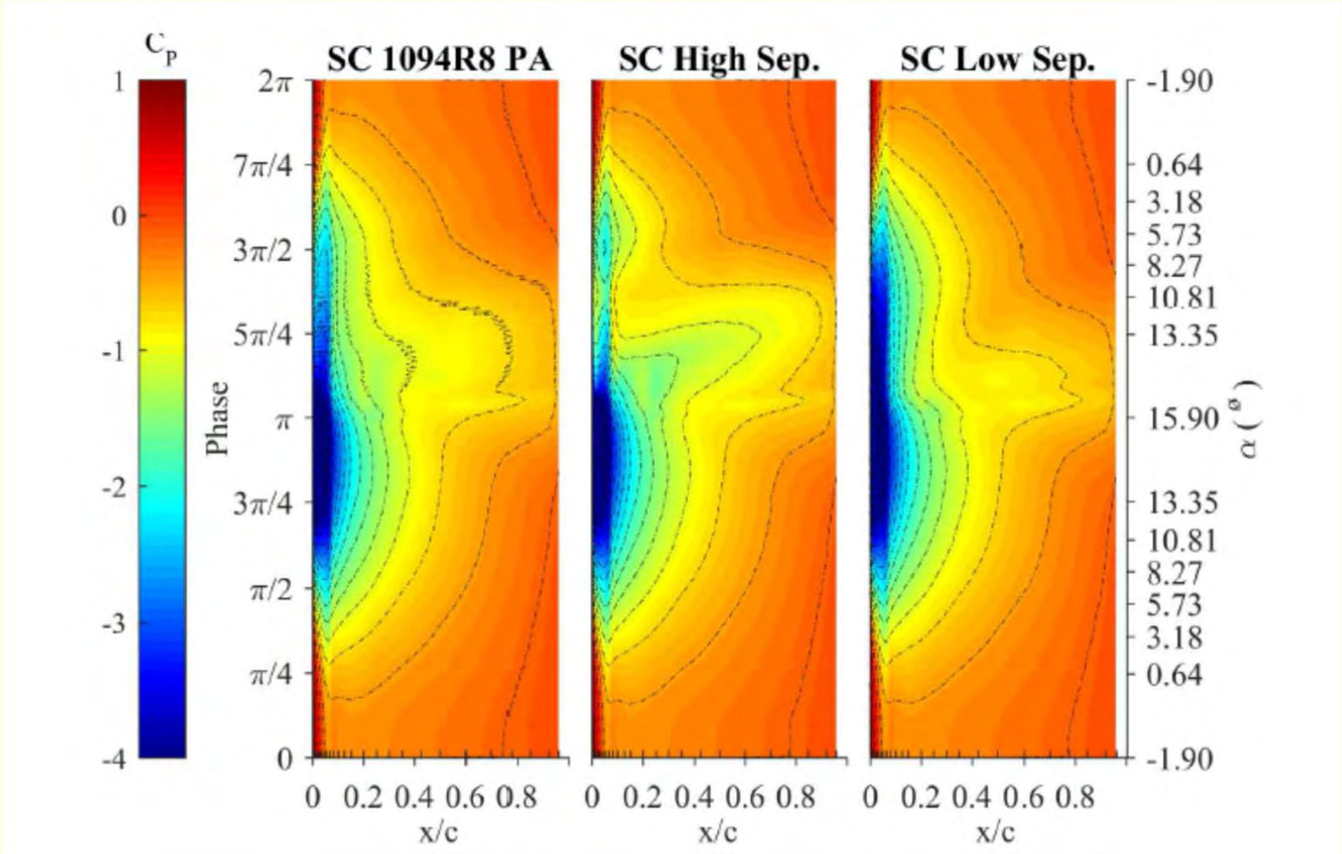
Cycle-to-Cycle Variations
Capturing Pressure Distribution Variation

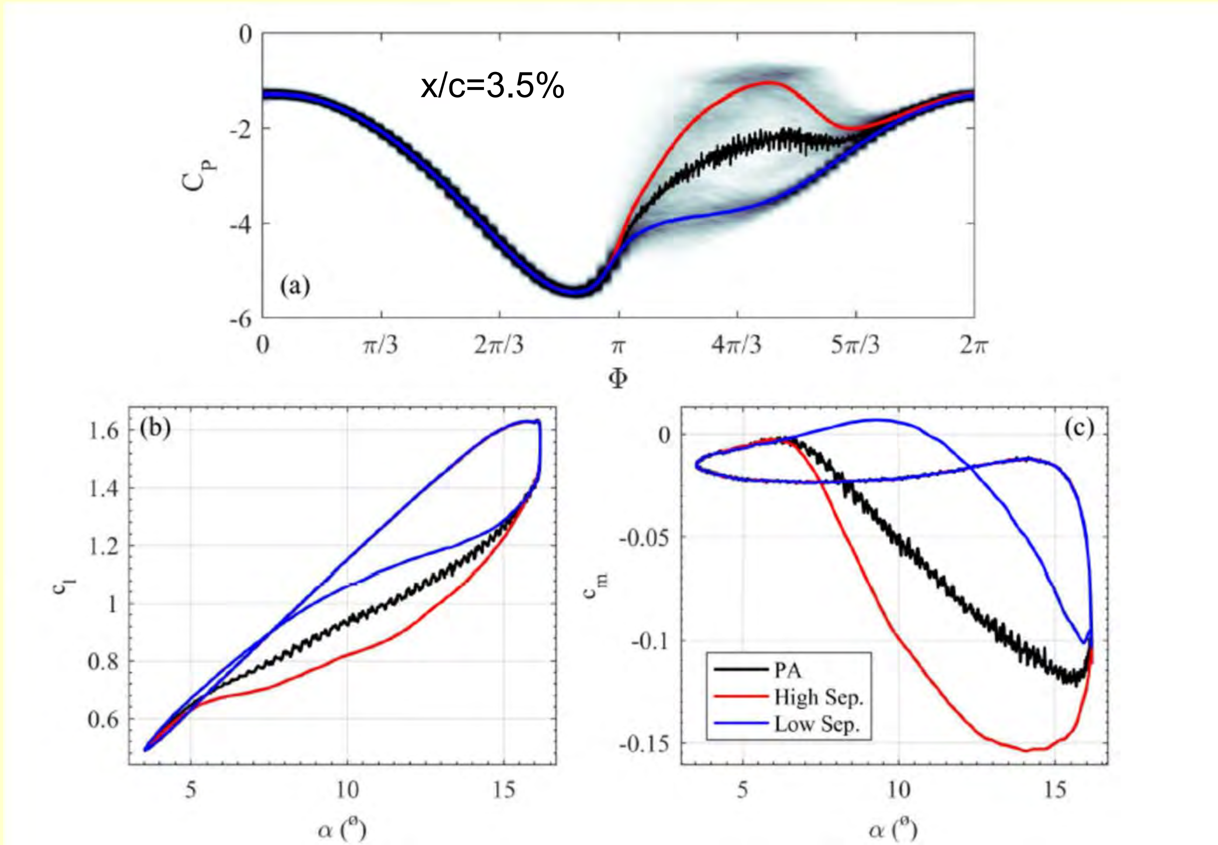
- **Individual cycles can be classified into groups**
  - High separation
  - Low separation
  - Others
- **Groups can be averaged to produce characteristic pressure maps**
  - Differences observed
    - **How much of the airfoils is stalled**
    - **Strength of stall vortex**
  - Integrate to determine impact on loads and moments



Cycle-to-Cycle Variation
Practical Impacts

SC1094r8
$\alpha = 10° \pm 6° \sin(\omega t)$
k = 0.067

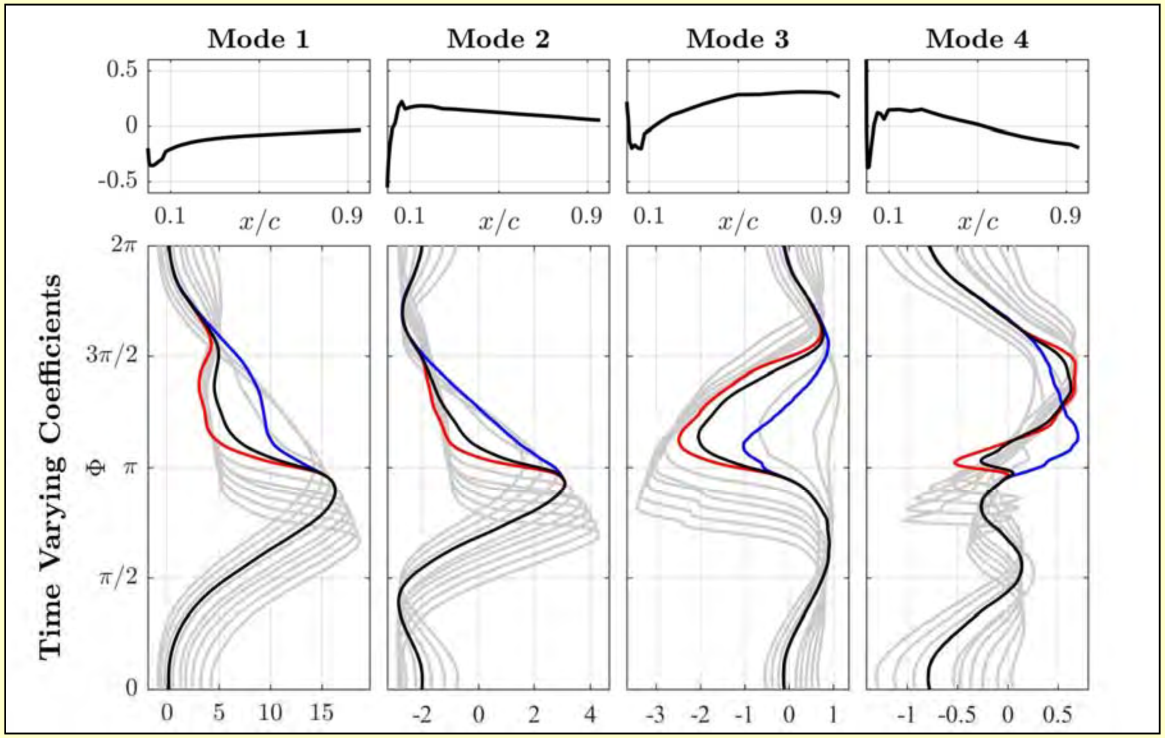
- **Cycle-to-cycle variations exist, but are they important to practical problems**
  - Lift curves show a larger impact for high separation case
  - Moment curves show an even larger impact
    - **Effect is most pronounced near the leading edge**
  - Phase-averaged pressures do not produce representative results



Cycle-to-Cycle Variations
Characterizing Cycles – Modal Analysis

SC1094r8
$\alpha = 8° \pm 9° \sin(\omega t)$
k = 0.067

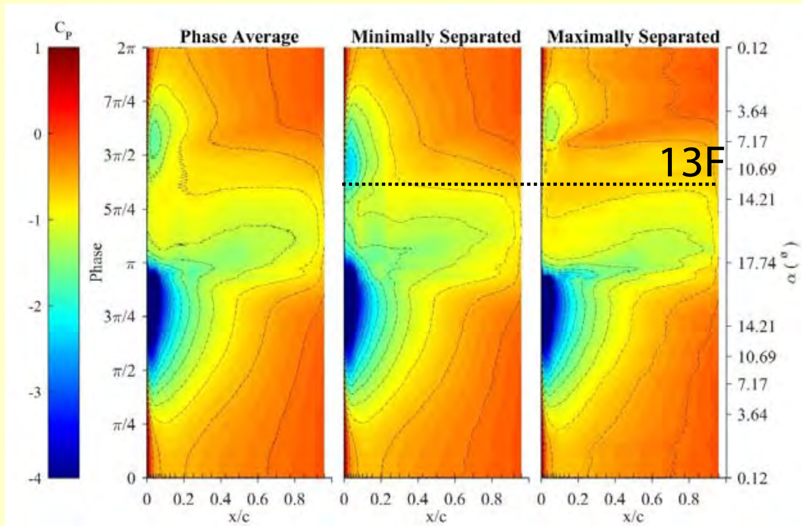
- **How do we characterize the variations over the entire suction surface?**
- **Use modal analysis to characterize changes in temporal behavior of mode coefficients**
  - Variations tend towards the path clusters
  - High separation resembles deep stall
  - Low separation resembles attached flow

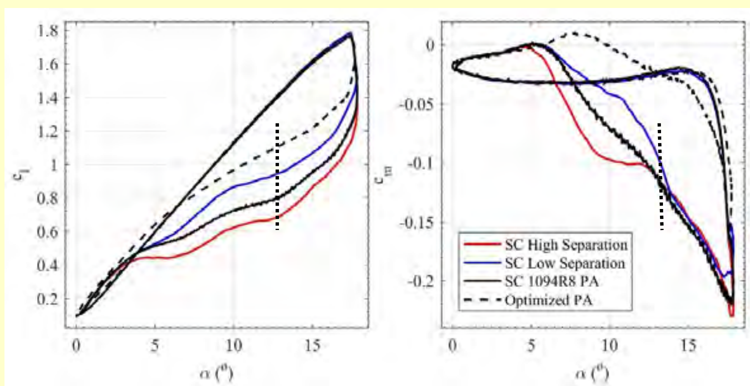


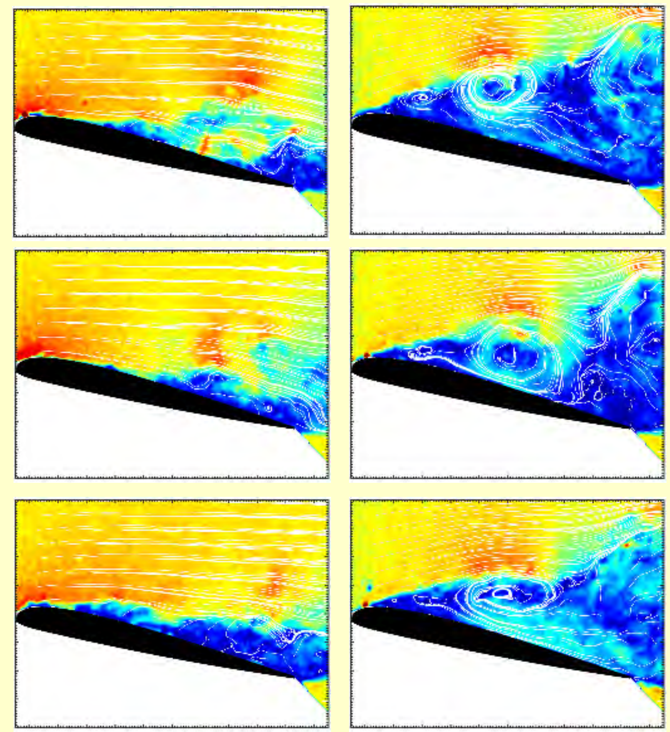
CTC Variability

SC1094r8
$\alpha = 9° \pm 9° \sin(\omega t)$
k = 0.067

- **Does flow-field show similar bifurcation?**
- **Flow-field separated into low and high separation cases**
  - Not simultaneous yet!
- **PIV confirms the low separation and high separation cases**
  - Low separation fails to reach leading edge and does not extend as far in the flow as expected



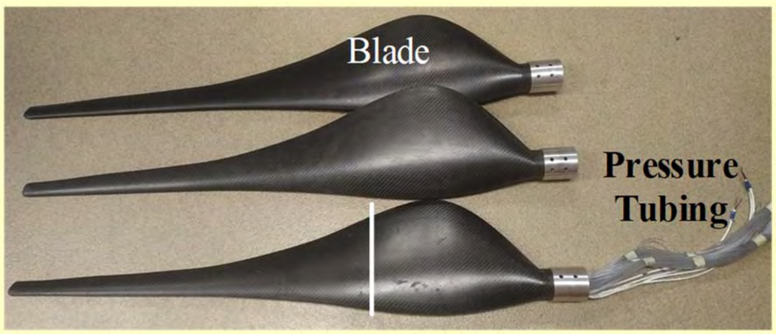




UNIVERSITY of WYOMING

Cycle-to-Cycle Variations
Summary / Ongoing and Future Work

- **Summary**
  - Cycle-to-cycle variations are prevalent in dynamic stall
    - **Stall onset and light stall are regions of concern**
      - Relevant to practical applications
    - **Impacts can be significant**
      - Forces and moments significantly impacted



- **Future Work**
  - Modal analysis
    - **Low dimensional modeling**
    - **Characterize state (see Ramasamy characterization schemes)**
  - Variations in the flow-field
  - Dynamic stall models
    - **Include cycle-to-cycle variations effects**
    - **Modal analysis encouraging**
      - A few modes appear to capture the variations
  - Cycle-to-cycle variations on blades
    - **Is it still important?**
    - **Where and when does it occur?**
  - Airfoil optimization to minimize cycle-to-cycle impacts (Ahuja)

Acknowledgements

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  - The University of Wyoming work was performed under sub-contract
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  - U.S. Department of Energy, Office of Science, Basic Energy Sciences, under Award # DE-SC0012671 monitored by Timothy J. Fitzsimmons
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  - Mark Potsdam
  - Mani Ramasamy
- **Students**
  - Tanner Harms
  - Pourya Nikoueeyan
  - Many other previous students contributed to the development of facility and diagnostics

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Dynamic Stall Detection Using Infrared Thermography

C. Christian Wolf, Anthony D. Gardner, M. Raffel

Helicopter Aerodynamics, German Aerospace Center, Göttingen

DLR

DIT: Differential Infrared Thermography

- Developed for BL transition detection
- Investigates surface temperature fluctuations/differences
- Enabled by recent developments in high-speed IR cameras

Advantages:

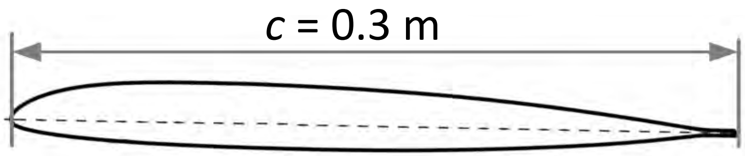
- „Easy-to-use“
- Planar measurement region
- No preparation required for CFRP models or rotor blades

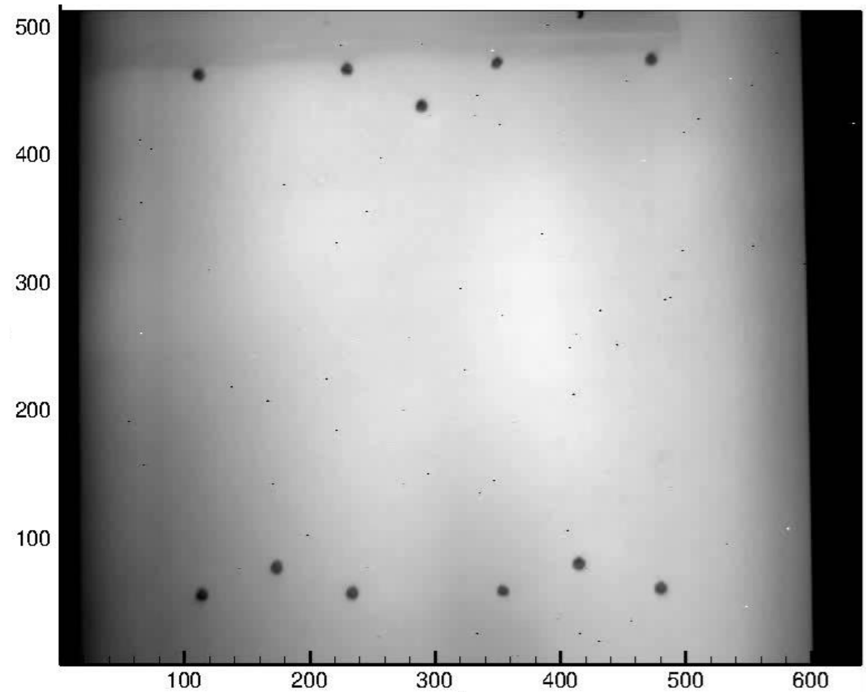
Performance of current IR cameras

Image exposure time	50 – 200 µs
Sensor pixel count	0.3 – 1.3 Mpix
Frame rate	0.1 – 1.0 kHz
Thermal resolution	< 50 mK

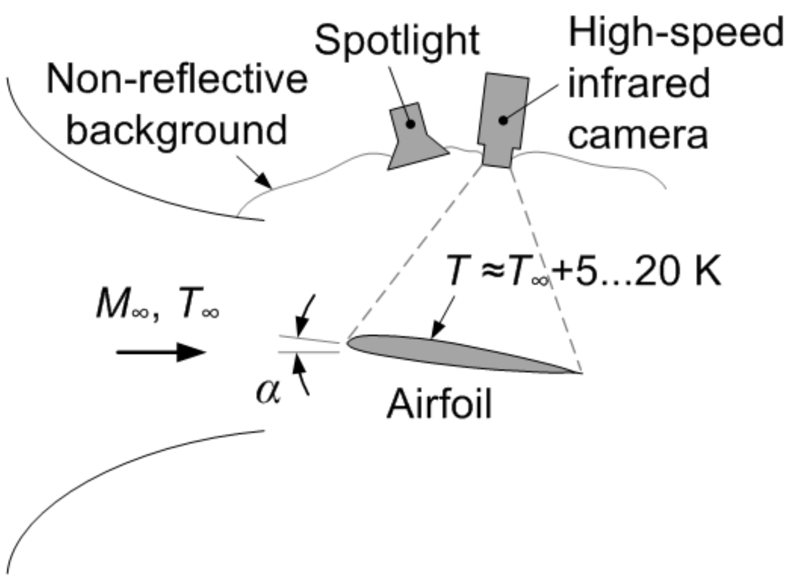
Application I: Pitching Airfoil Experiment

- DSA-9A airfoil
- Low-speed wind tunnel, M_∞=0.15
- Pitch test rig, Θ = 19°± 8°, f = 2.5 Hz (k = 0.047)





Sequence of raw IR images



Application I: Pitching Airfoil Experiment

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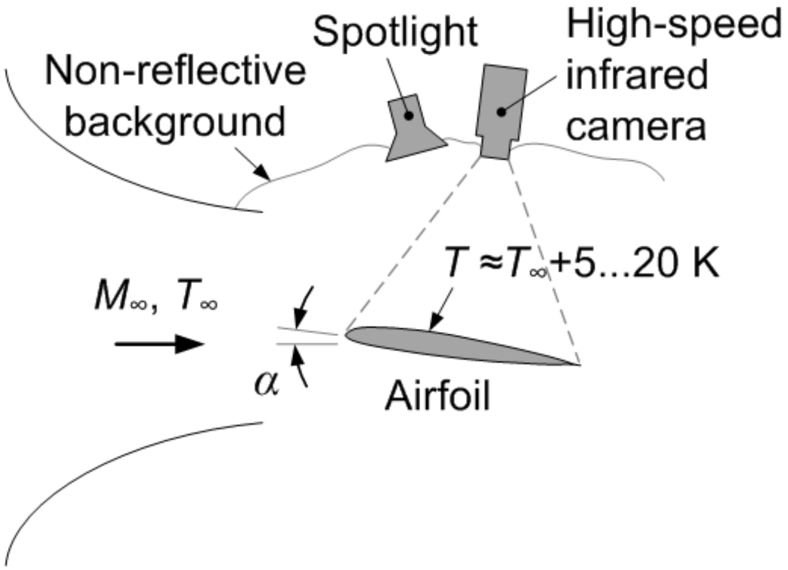
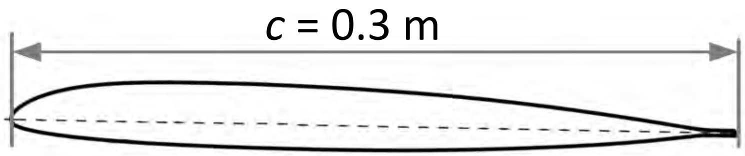
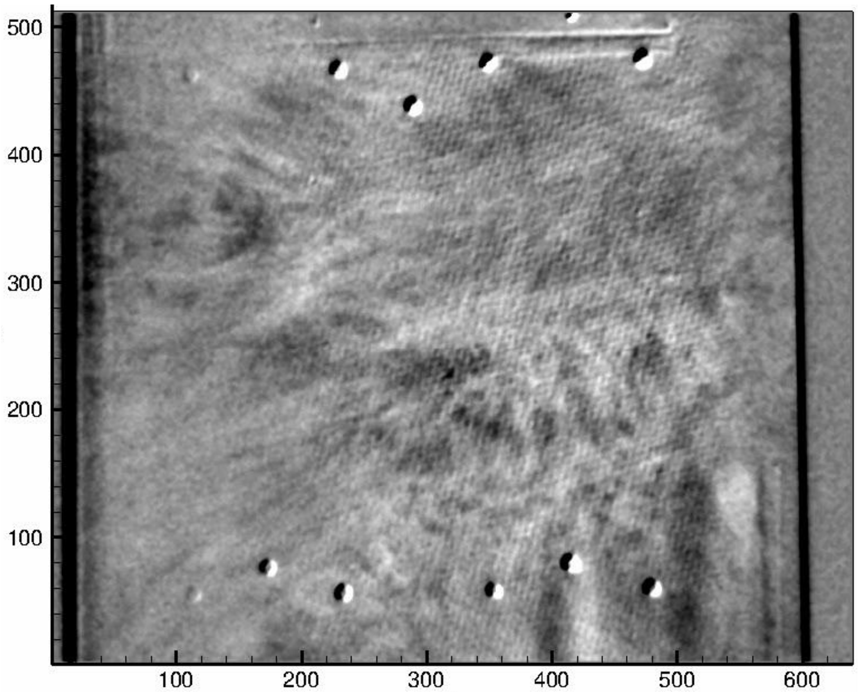


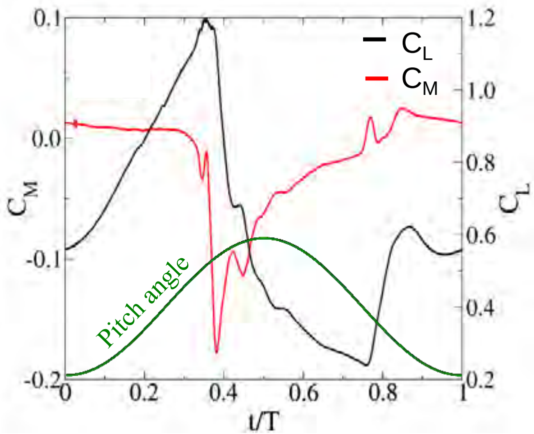




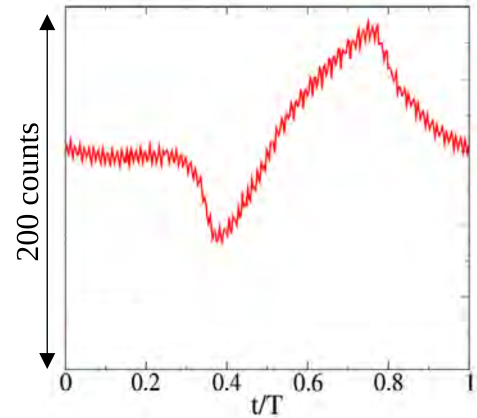
Sequence of raw IR images

Application I: Pitching Airfoil Experiment

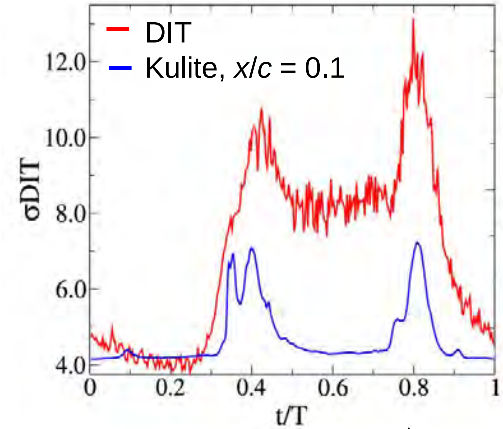
Phase-averaged C_L,C_M



Avg. surface temperature

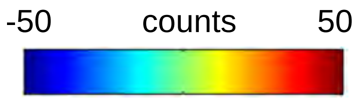


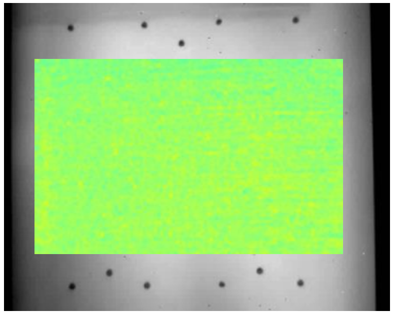
Cycle-to-cycle variation

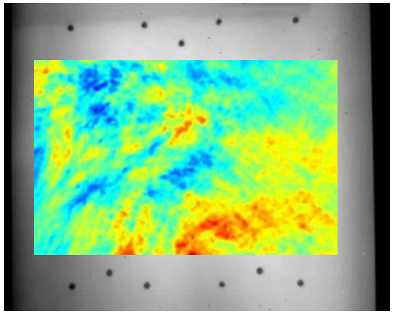


IR camera, odd frequency → Record multiple cycles → Phase-sorting → Differential images → Statistics

Cycle-to-cycle differences, attached flow (left) and separated flow (right)

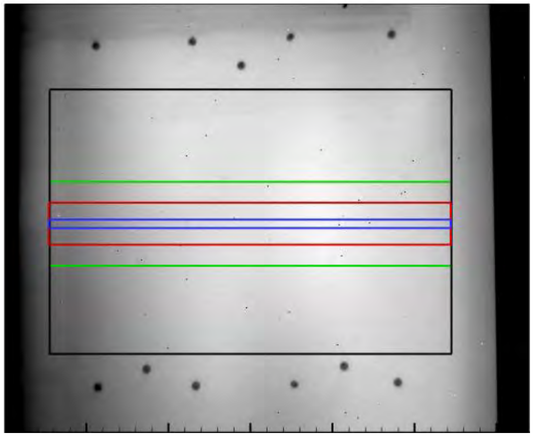


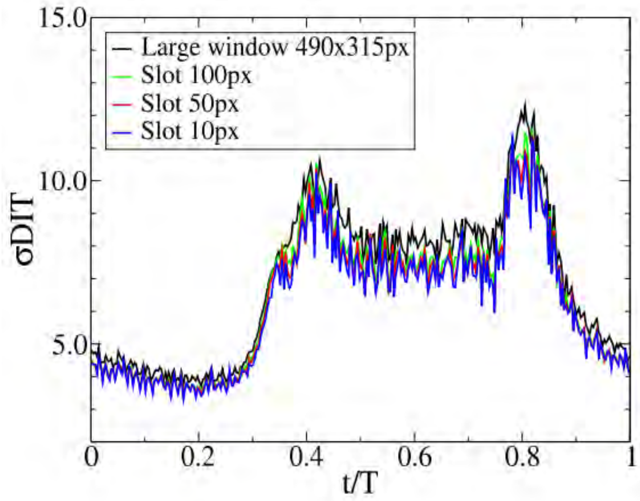




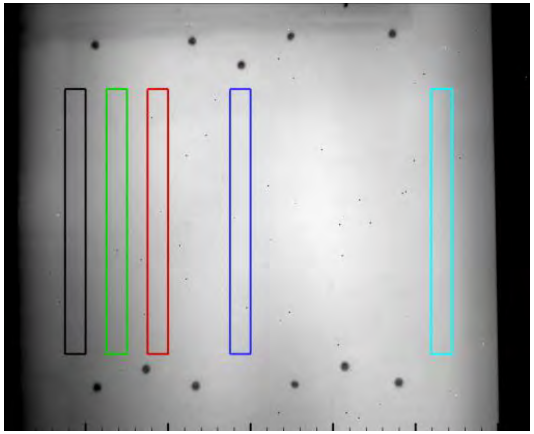
Application I: Pitching Airfoil Experiment

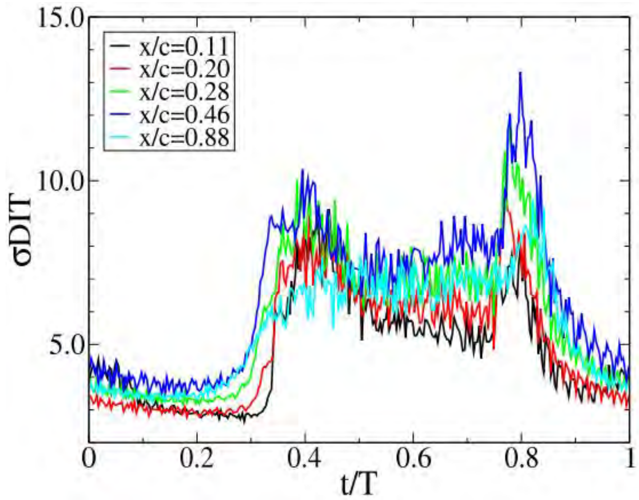
Spanwise reduction of interrogation window size





Different chordwise positions of interrogation window

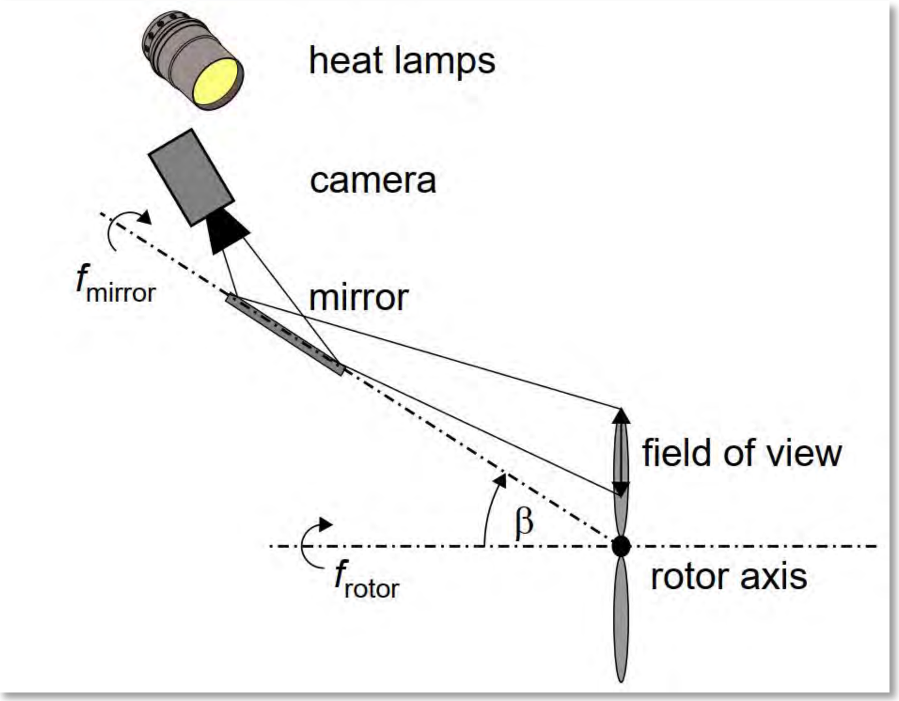




DLR

Application II: Rotor test facility Göttingen (RTG)

- Rotor diameter: 1.3 m, horizontal axis, slow axial inflow
- DSA-9A airfoil, 2 or 4 blades
- $M_{75} = 0.21$, $f = 23.6$ Hz ($k = 0.074$)
- Swashplate, $\Theta_{75} = 16° \pm 6°$

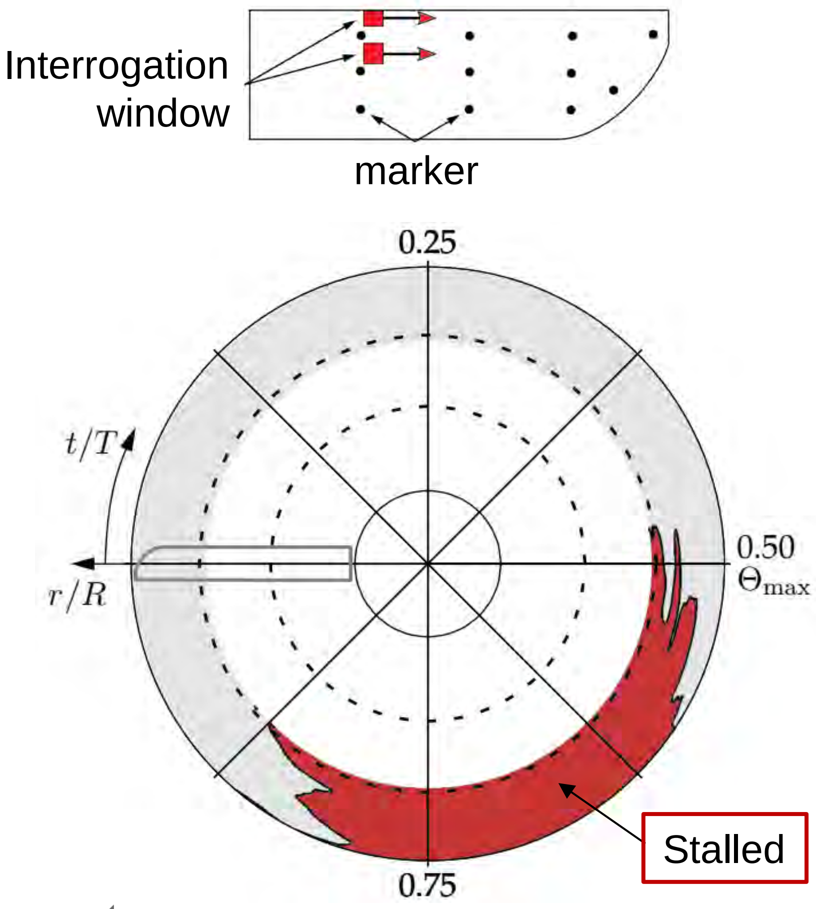


Rotor challenges:

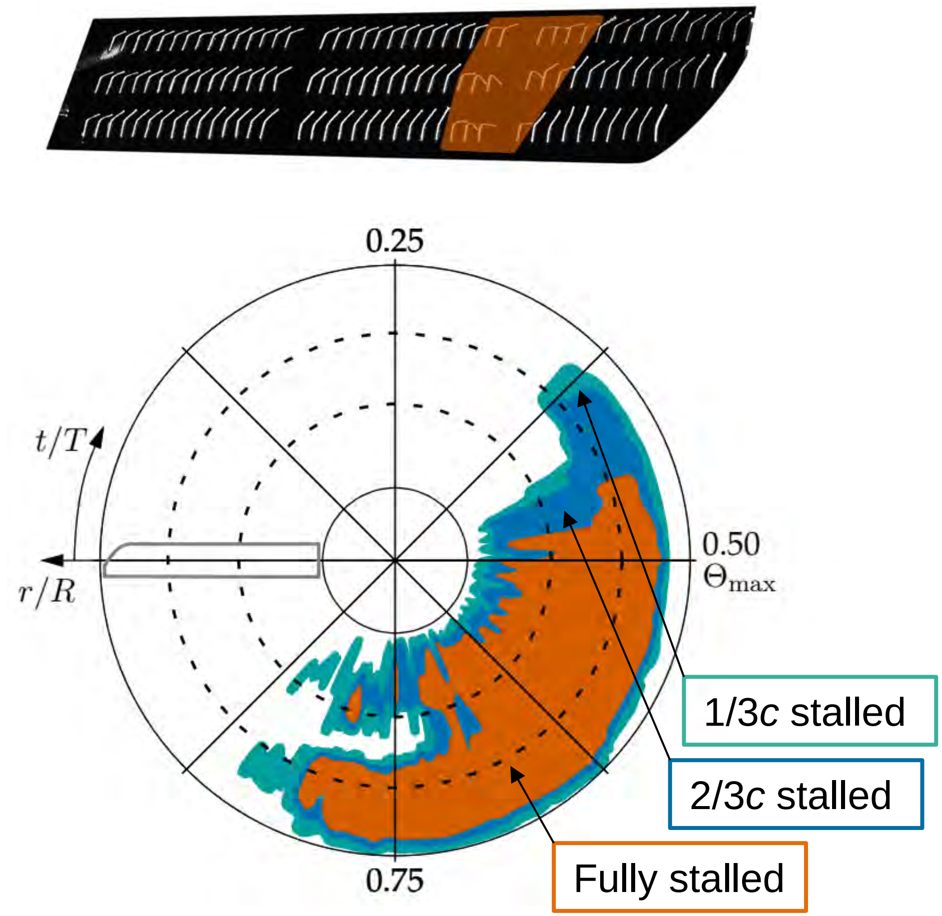
- Avoid motion blur
  → Rotating mirrors
- Oblique viewing direction and jitter of blade position
  → Image dewarping

Application II: Rotor test facility Göttingen (RTG)

DIT dynamic stall map



Tuft visualization dynamic stall map



Possible future application: Flight tests

- DLR/NASA formation flight tests (2018)
- First in-flight BL transition visualization
- Level flight at 80 kts → no dynamic stall

In-flight challenges:

- No extra heating, but azimuthal variation of the recovery temperature
- Very low spatial resolution
- Cloud reflections, weather, etc.
- Camera-to-rotor synchronization

Thank you for your attention!

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A Photonic Skin Friction and Wall Pressure Sensor for Unsteady Separated Turbulent Boundary Layers

Tindaro Ioppolo
NY Institute of Technology

Question 1: What progress has been made?

- Most of the experimental work involves pitching airfoils and provide a global flow field information and the measurements of the corresponding dynamic force and moment . These experimental setup do not allow high spatial and temporal resolution measurements of the unsteady boundary layer structure . These are important to fully understand the flow physics of the dynamic stall process.
- Real time wall measurements (wall pressure and skin friction) could give valuable information of the flow phenomena occurring above it. Unfortunately there are not available data of direct measurements of fluctuating skin friction.
- Wall measurements could be the only data that could be used to detect some precursor events that leads to dynamic stall. Only then a suitable control strategy can be applied.
- Due to the lack of instrumentation most of the past work on unsteady turbulent separation focus on velocity measurements and higher order moments.

Question 2: How does your current research fit in?

- The goal of this research is to implement a photonic skin friction and wall pressure sensor that will be used to investigate the structure and the dynamics of unsteady separated turbulent boundary layers, that mimic dynamic stall. Currently we are implementing the sensor and we do not have data in unsteady separated turbulent boundary layer. However in the next phase we are planning to carry out:
- Streamwise and spanwise fluctuating skin friction and wall pressure.
- Detailed velocity mapping using hot-wire anemometry, Laser Doppler velocimetry and particle image velocimetry
- The measurements will be carried out in the development region and in and out of the separated region of the unsteady turbulent boundary layer. This is the first time that these types of measurements are undertaken and could reveal new important flow physics relevant to dynamic stall.

- Many unanswered questions remain such us:
- What are the parameter that we should consider to predict the onset and extent of stall in unsteady separated turbulent boundary layer?
- What is the signature of the streamwise and spanwise fluctuating skin friction that indicates the onset of separation?
- Is there any correlation between the fluctuating skin friction and the fluctuating wall pressure that can be used to indicate the onset and extent of stall in unsteady separated turbulent boundary layers
- Wall measurements could be the only data that could be used to detect some precursor events that leads to dynamic stall. Only then a suitable control strategy can be applied.

Question 3: What is Next?

- Detect signatures in the skin friction and wall pressure (or other wall measurements) that indicates the onset of dynamic stall
- The measured events should be detected earlier enough so that a control strategy can be applied. This is challenging since it is a very abrupt event.
- Currently it is impossible to cover the lifting surface with sensors, therefore a small number of sensors should be placed in an intelligent manner to detect the onset of dynamic stall. These require a fully understanding of the flow structure behind dynamic stall.

Development of a Novel Rotating Volumetric Velocimetry Technique

Abbishek Gururaj, Mahyar Moaven, Zu Puayen Tan, Brian Thurow, Vrishank Raghav

Department of Aerospace Engineering – Auburn University

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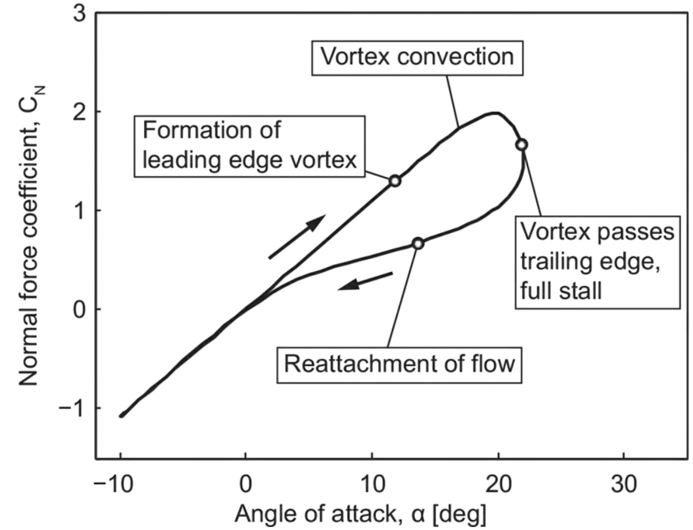
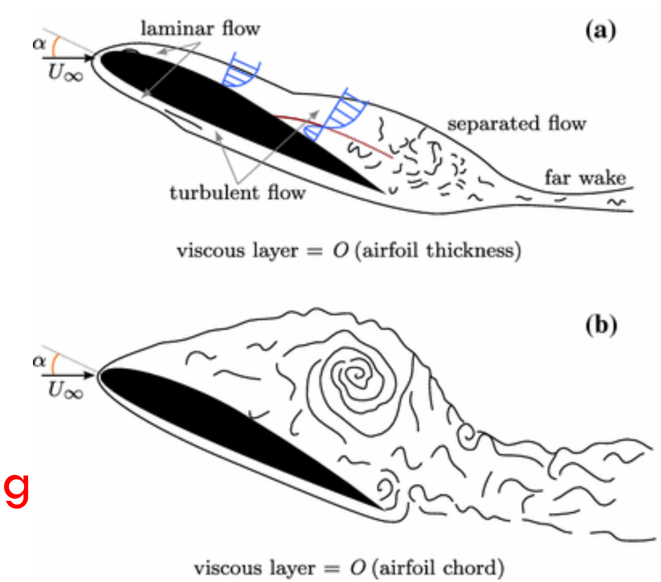
MOTIVATION

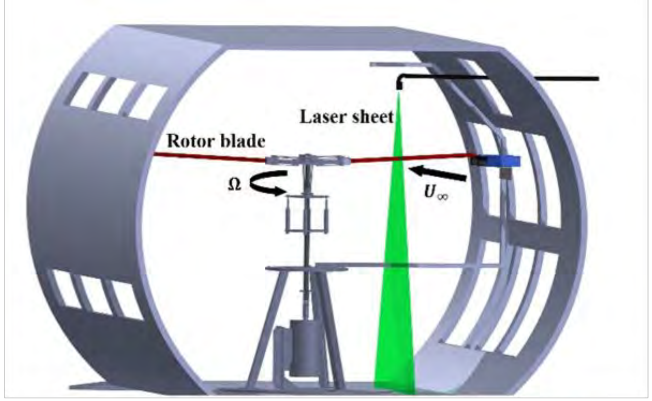
- Unsteady flow separation
  - Unsteady aerodynamic loading
  - Dynamic stall
    - High vibrations and poor handling qualities
    - Reduces max speed and maneuverability
    - FVL calls for helicopters without dynamic stall
- Significant work dedicated to this problem
  - Vast majority use 2D approximations
  - Flow physics and control concepts explored
  - Yet our comprehension is limited
- There is a need to consider additional critical flow physics
  - Centripetal and Coriolis accelerations in a rotating flow field



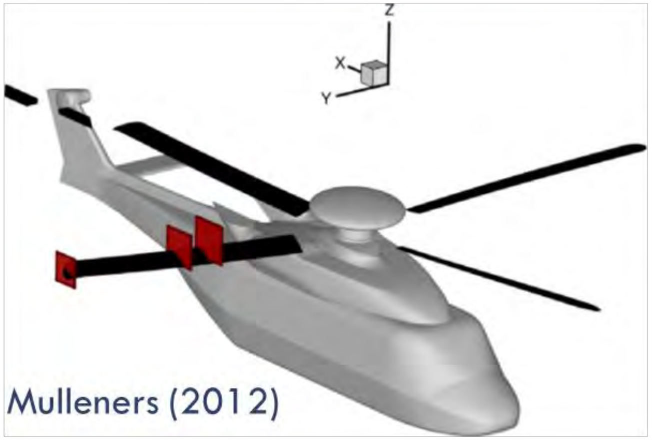


BACKGROUND

- Rotating wing investigations
  - Laboratory frame of reference velocimetry
    - Phase-averaged or Time-resolved
  - Three-dimensional and high cycle-to-cycle variations



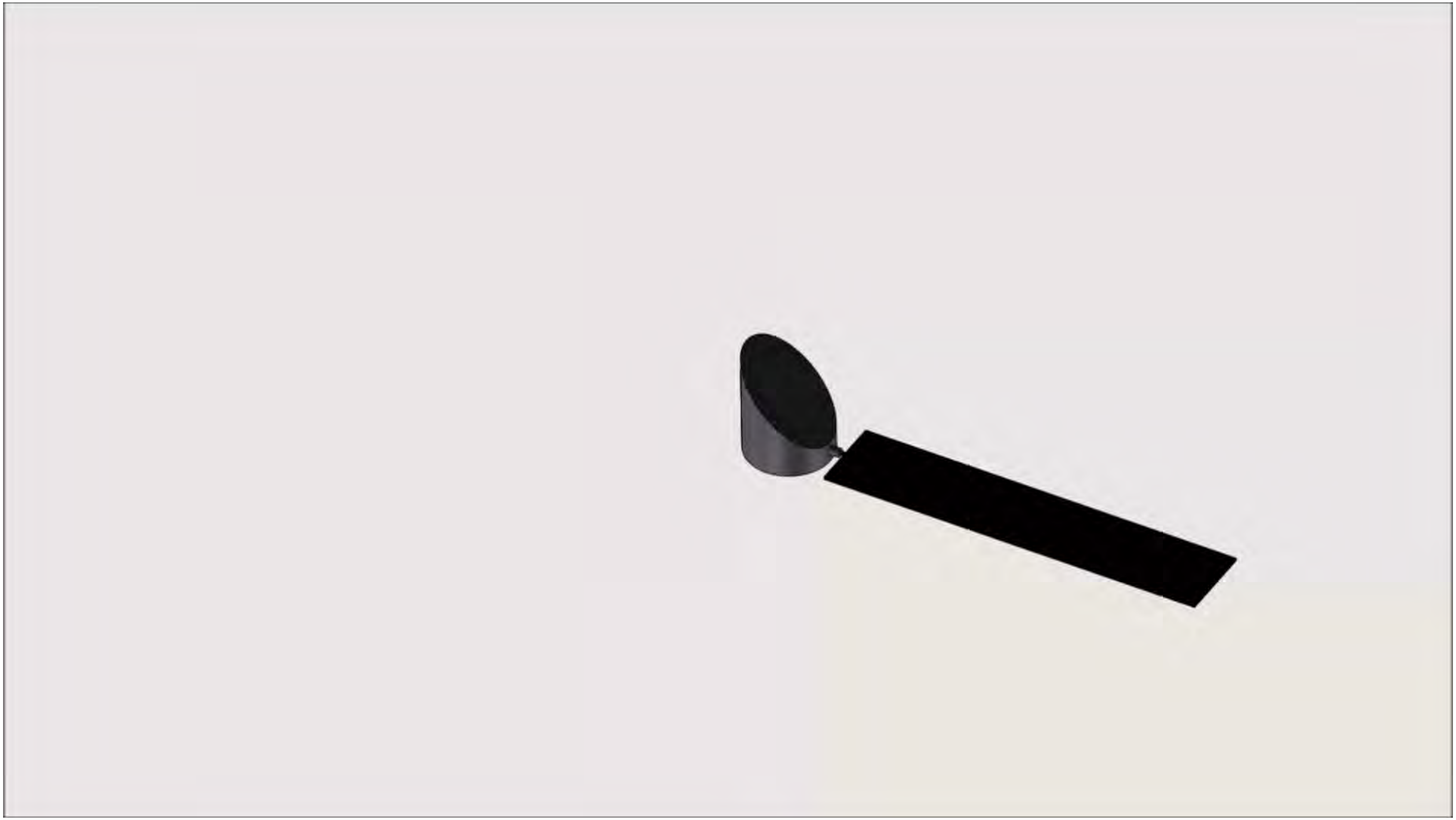
Raghav (2013)



Mulleners (2012)

- Blade cannot be tracked over a range of azimuths

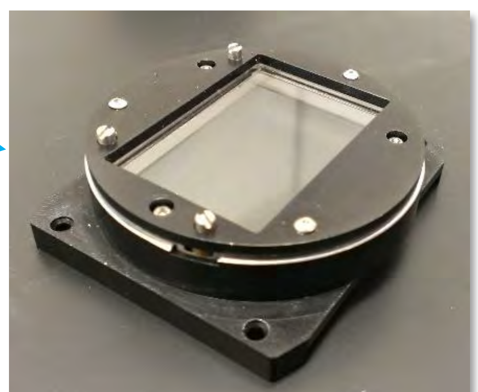
Rotating 3D Velocimetry



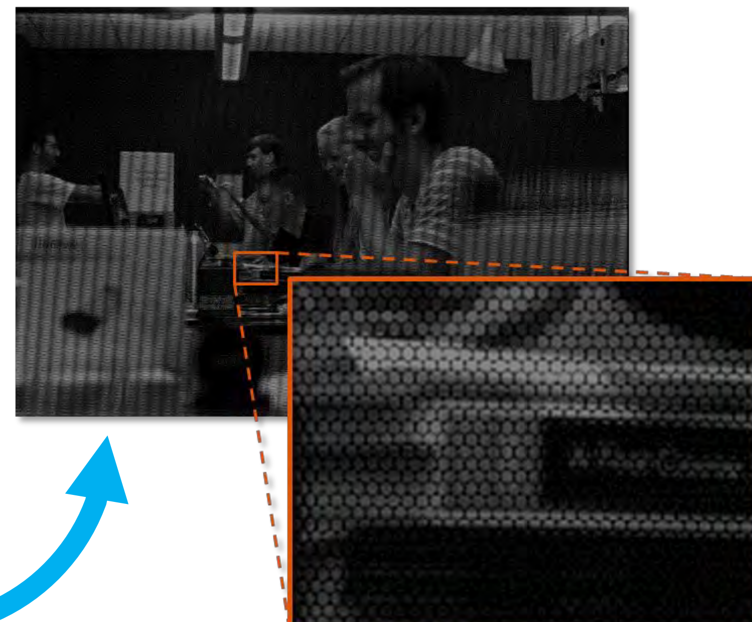
Plenoptic Imaging

- Novel 3D Imaging technique using a single camera
- Relatively less time consuming and financially economical

High resolution camera – 29 Megapixel



Microlens array between main lens and image sensor



Captures both spatial and angular information

What does this enable?

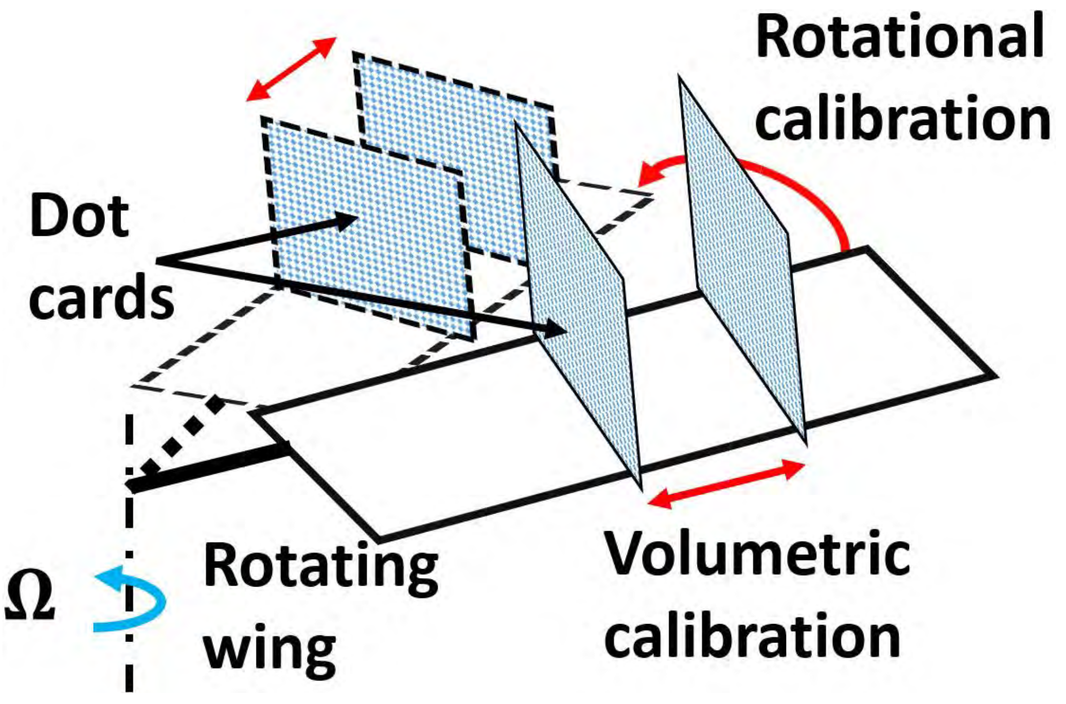
- Navier-Stokes equation in non-inertial rotating frame of reference

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla \mathrm{p} + \nu\nabla^2\boldsymbol{u} - \boxed{\boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times r) - 2\boldsymbol{\Omega} \times \boldsymbol{u}} - \dot{\boldsymbol{\Omega}} \times r$$

- Explicitly measure Coriolis, centripetal accelerations in experiments
- Address some of the hypotheses on the effect of Coriolis and centripetal acceleration

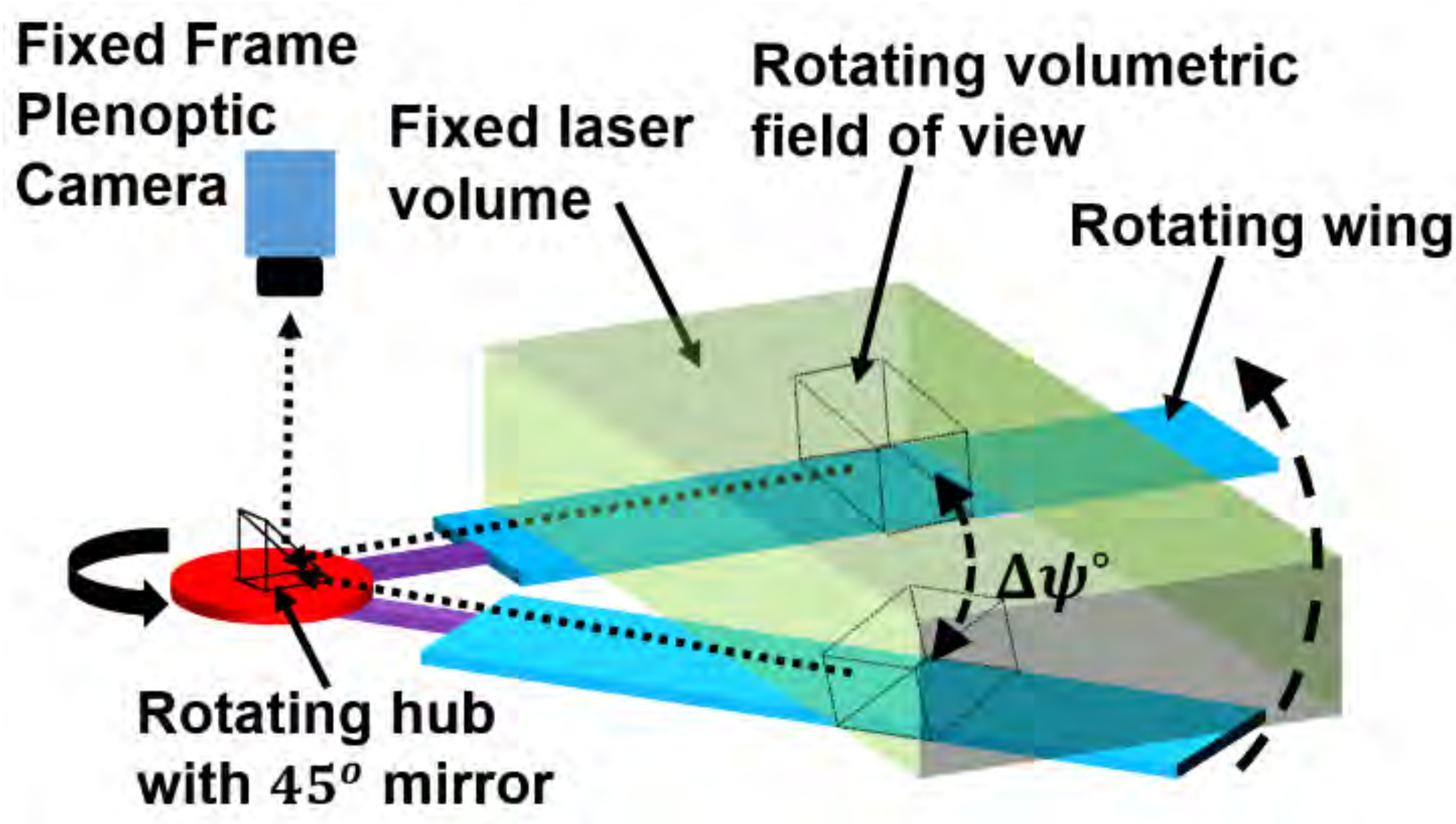
Current work

- *Implement and validate the rotating 3D velocimetry (R3DV) technique*
  - *Rotational calibration*
  - *Validate using fixed frame camera*



Current work

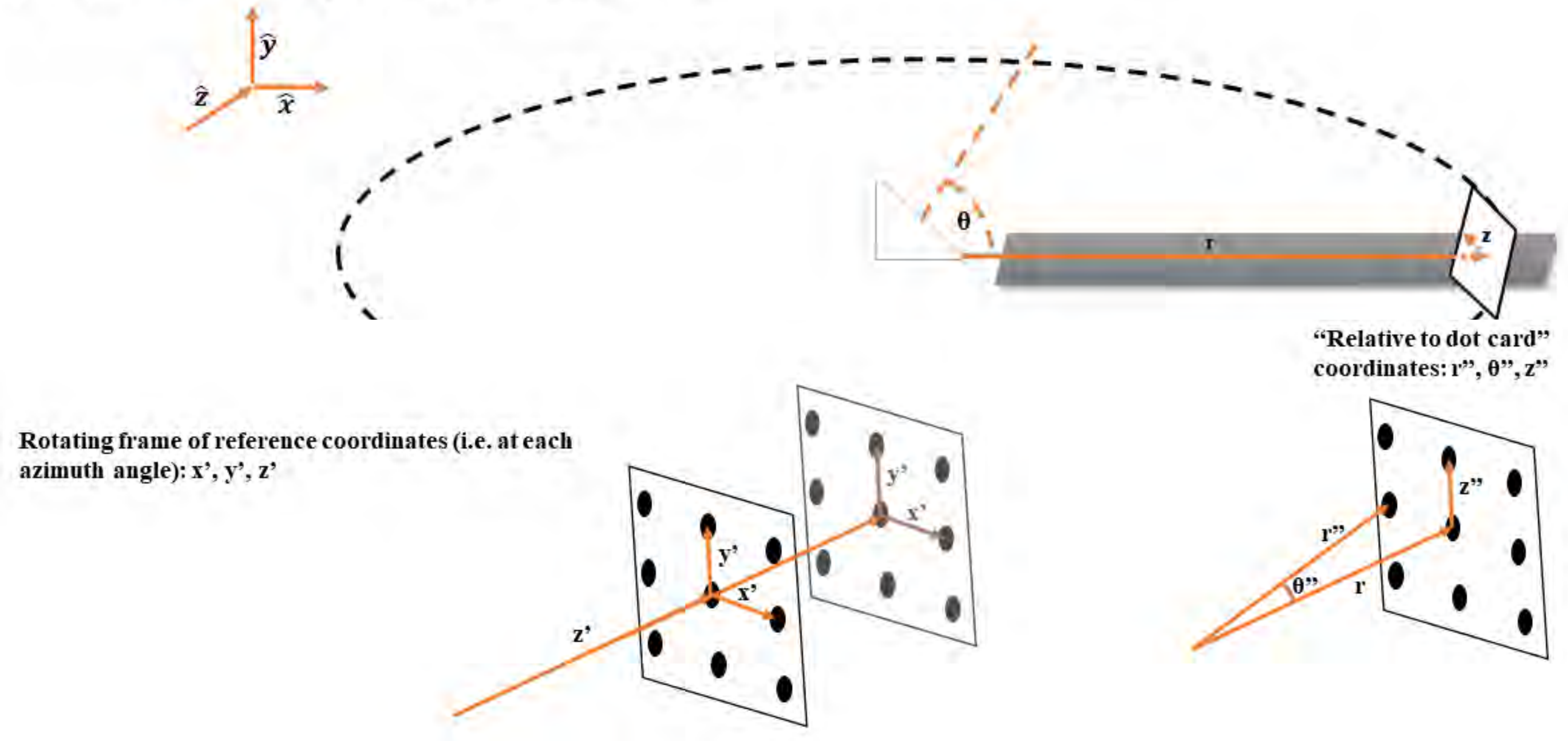
- ***Framework to implement R3DV***



Current work

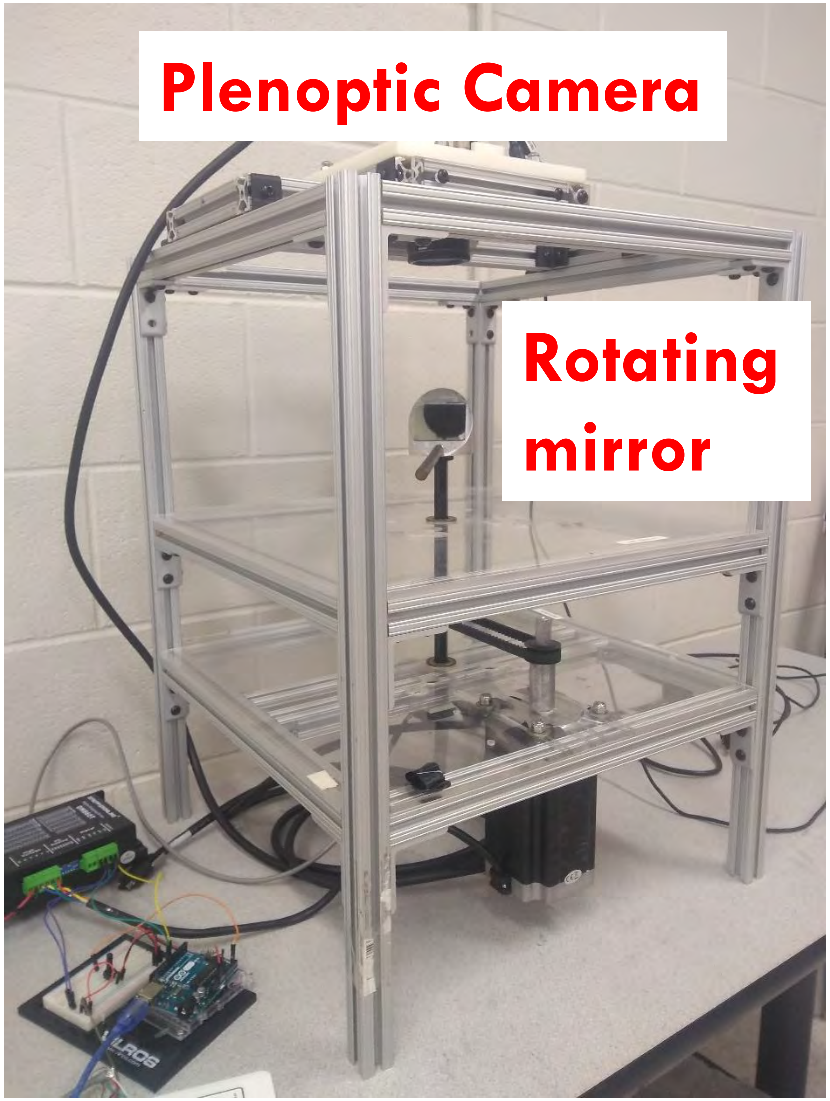
- **Framework to implement R3DV**

Real world coordinates: $\hat{x},\hat{y},\hat{z}$ for fixed frame of reference



Current work

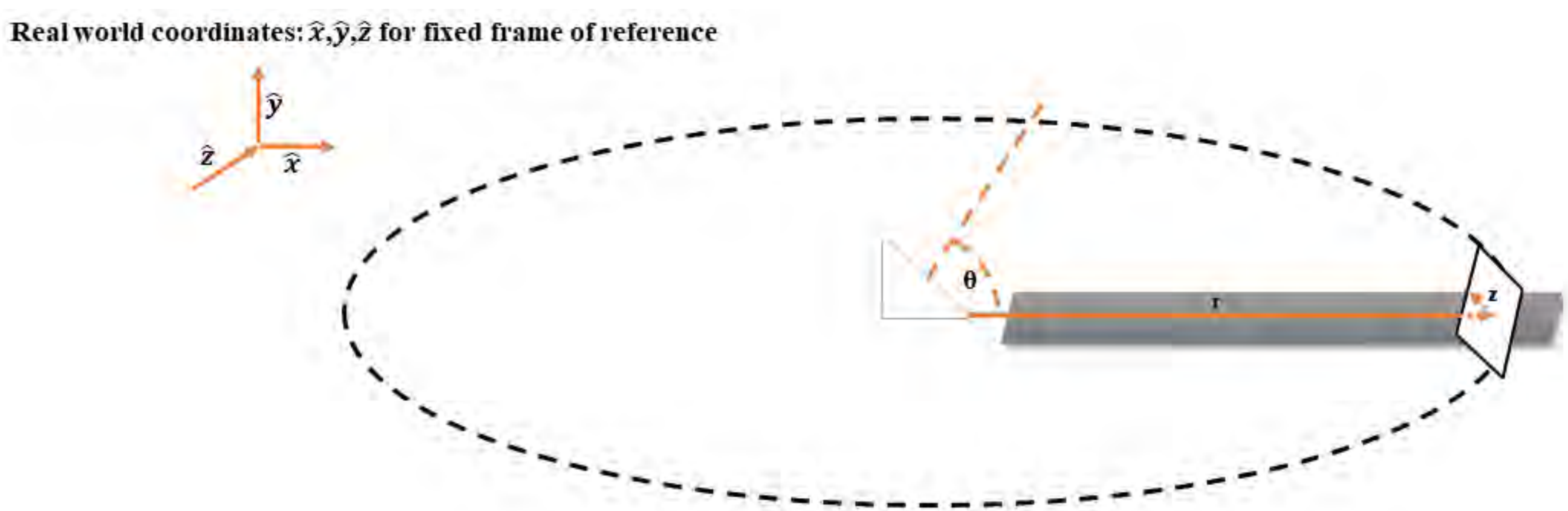
- *Bench-top rotational calibration*
- *Rotating frame*



Current work

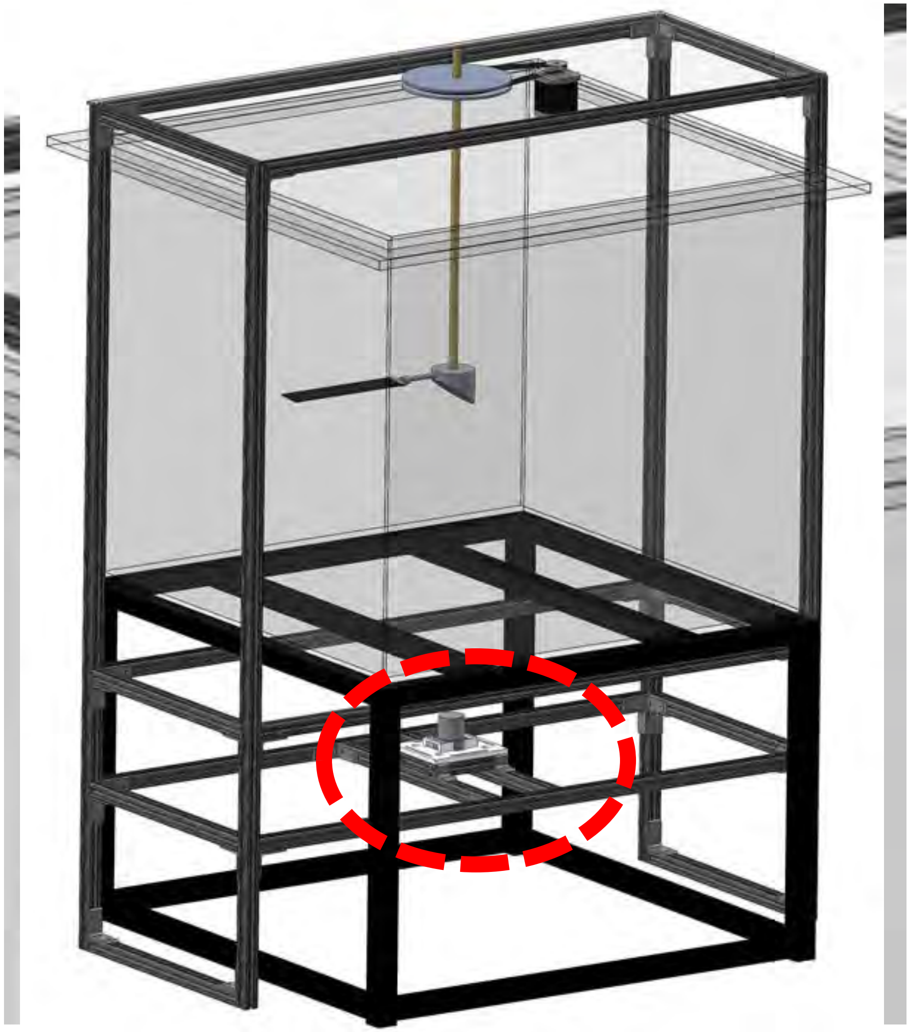
- *3D rotational calibration matrix*

$$C = f\left(\begin{bmatrix} r_1 & \cdots & r_m \\ \vdots & \ddots & \vdots \\ r_n & \cdots & r_{m,n} \end{bmatrix}\begin{bmatrix} \theta_1 & \cdots & \theta_m \\ \vdots & \ddots & \vdots \\ \theta_n & \cdots & \theta_{m,n} \end{bmatrix}\begin{bmatrix} z_1 & \cdots & z_m \\ \vdots & \ddots & \vdots \\ z_n & \cdots & z_{m,n} \end{bmatrix}\begin{bmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{bmatrix}\right)$$



Ongoing work

- ***Facility development***
  - $1.2 \times 1.2 \times 1.2\ m$ water tank
    - Low vibrations
    - Better SNR for PIV data
  - Simultaneously rotating and pitching wing
    - Instrumented with load cell
  - Plenoptic camera mounted at bottom
    - Zoom lenses to control working distance
    - Ensure high magnification



Future goals

- *Identify the spatial location and timing of initiation of flow separation and subsequent progression*
- *Investigate the cause for cycle-to-cycle variations in the initiation and evolution of flow separation on the rotating wing*
- *Characterize the spatio-temporal flow dynamics on the rotating wing after flow separation*

QUESTIONS?

Vrishank Raghav
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Low-Order Modeling and Theory

Theoretical and Lower-Order Modeling of Dynamic Stall

Marilyn Smith, Georgia Tech

David Peters, Washington Univ

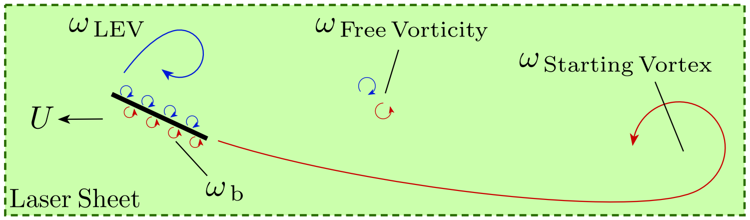
Holger Babinsky, Univ of Cambridge

How do we model dynamic stall at present?

- Rotor models based primarily on unsteady aerodynamics with significant empirical tuning
  - Leishman-Beddoes
  - ONERA
- “Best” approach and in almost every comprehensive modeling solver used in rotorcraft (and wind energy)
- The empirical-based constants have been determined from multiple experiments based on traditional rotors
- Their performance with new rotors, advanced configurations, and varying Reynolds numbers have been reported as inconsistent
- Development across multiple groups focuses on the use of experiments, CFD, unsteady linear theory, etc. to more accurately focus on physics rather than empirical data and reduce number of user inputs

Mistakes observed in analyses

- “Linear superposition” is not physically valid in this nonlinear regime
- Potential approach towards better dynamic stall models is to analyze the unsteady flow field vorticity development to extract (low-order) force models, BUT:
  - Added mass ‘creates’ bound vorticity on body surface but this is not circulatory
  - When analyzing the particle image velocimetry (PIV) data, the body kinematics are often ignored
  - Not all of the vorticity located in the flow field is included in the analysis of PIV flow fields (sometimes CFD as well)
    - Vorticity has left the flow field and is not accounted for
    - Portions of the vorticity flow field are simply ignored
    - ‘Mechanical circulation’ attributed to the solid body rotation of an object is not included

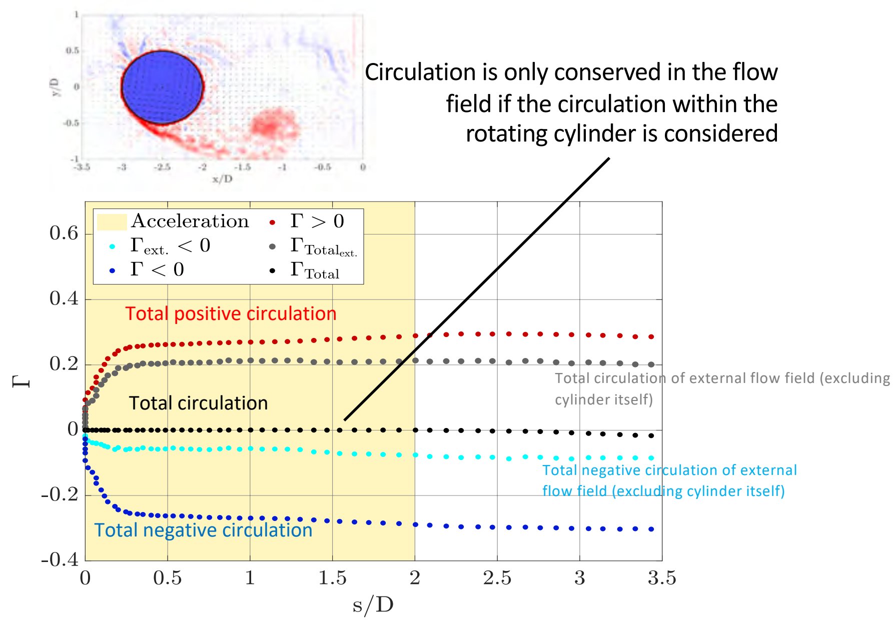


Complete flow field that needs to be analyzed

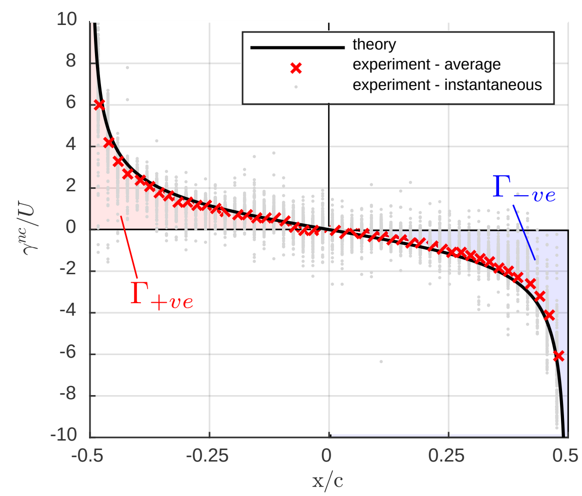
Babinsky

Mistakes observed in analyses

Circulation around rotating and translating cylinder



Non-circulatory added mass vortex sheet



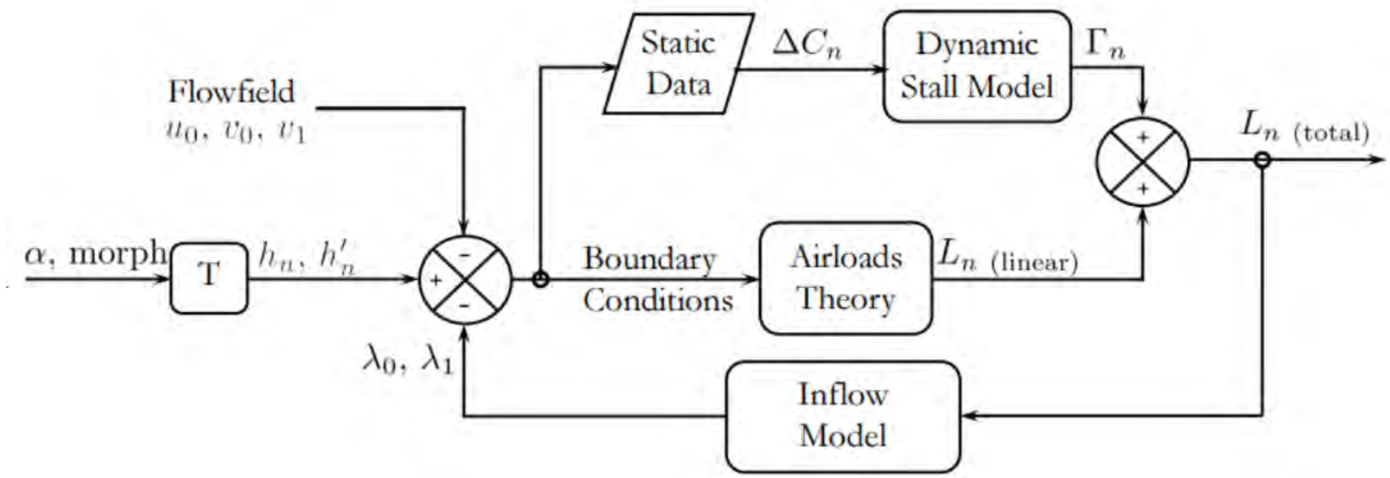
$$\Gamma_{+ve} - \Gamma_{-ve} = 0$$

Babinsky

Current Endeavors : Unified Aerodynamics

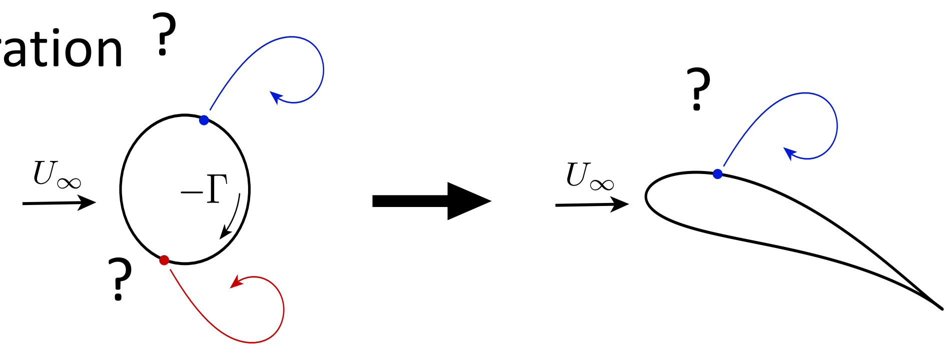
- Unified Aerodynamic Theory (Peters, Washington University)
  - Use of steady nonlinear aerodynamics (Aerodynamic C81 tables) with corrections based on unsteady aerodynamics
  - Mathematical functions provide responses
  - Minimal number of constants
  - Unsteady freestream, double dynamic stall, three-dimensional effects, compressibility effects, reverse flow
  - Being implemented into ART software
  - Validated with a number of experimental (and CFD) results
  - Approach also very accurate for bluff bodies with additional physics (Smith)
  - "…impressively versatile for being able to handle a large range of flow situations including reverse flow" (Workshop input)

Unified Aerodynamic Model



Current Endeavors : Circulation-based analysis

- Circulation-based Analysis (Babinsky, University of Cambridge)
- Experimental (Cambridge) with collaboration with computational (Smith, GT) assessments
- Understand how to use vorticity to calculate and decompose forces
- When and where does unsteady separation occur?
- How much vorticity is shed at the separation locations?

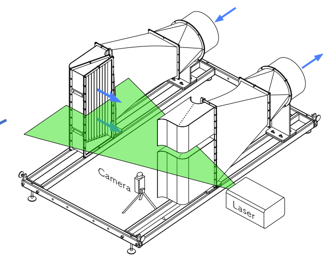


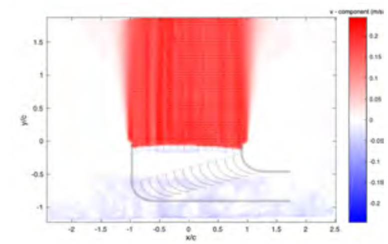
The ability to predict / estimate the above could lead to new low-order models

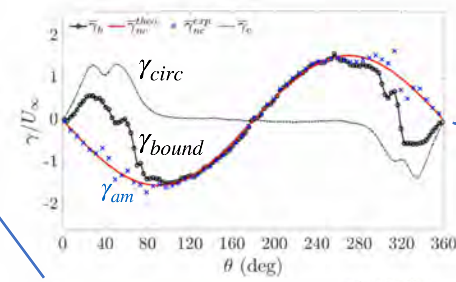
Experimental Approach

- Designed/built tow-tank rig to study top-hat gust encounters
- Identified different contributions to boundary-layer vorticity
    - Added mass is strictly attributed to the kinematic motion of an object
    - In an accelerating fluid, the ‘added mass’ vorticity contribution to the boundary layer comes from the mirror image of vorticity created externally in the flow field
    - A correct understanding of the origin of vorticity in the flow field prevents ‘double counting’ during forces computations.
- Predict the strength of shed vorticity, purely from interrogating the boundary layer; even when this is under-resolved
    - Crucial to inform low-order model development
    - Helpful in flow field analysis where the amount of shed vorticity is of interest but where it is difficult to measure the shed shear layer

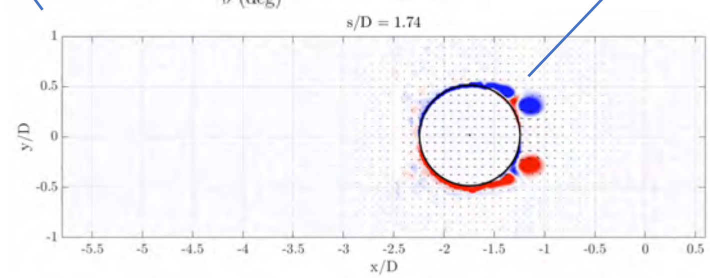
Gust rig and flow field





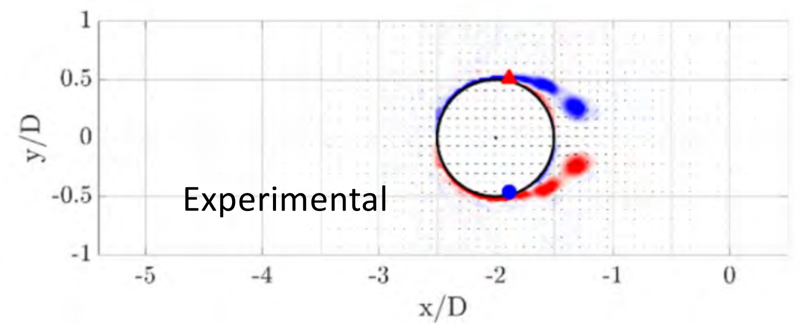


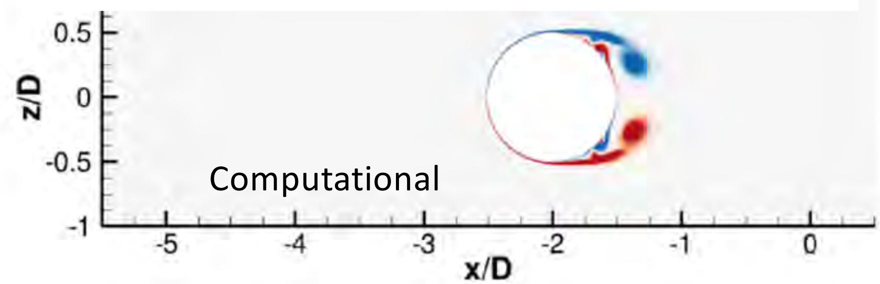
Boundary layer vortex sheets around cylinder

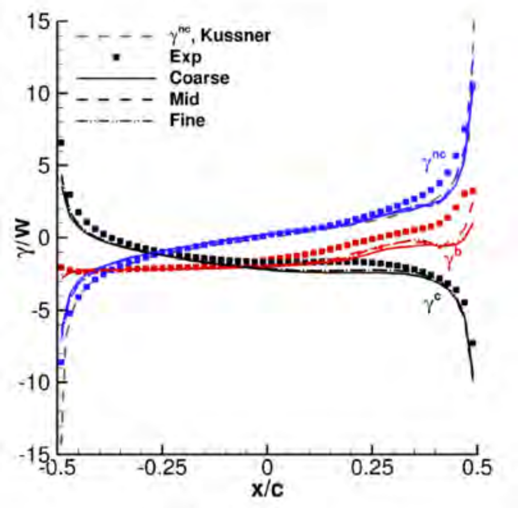


Computational Approach

- Model the test rig and the motion of the body through the gusts
- Three-dimensional analysis interrogated to obtain two-dimensional results
- CFD permits the rapid analysis of sensitivity to scaling and similarity parameters





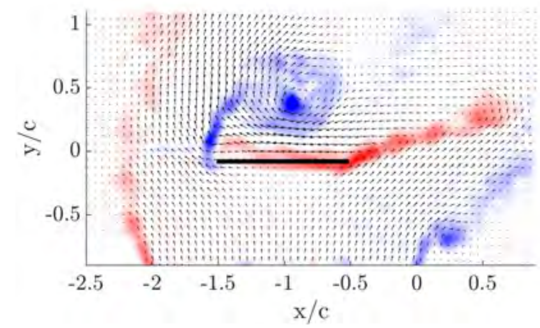


- LES and hybrid RANS-LES to determine physics with URANS to understand limitations of different approaches
- Analysis of circulatory components applied using same codes
- CFD provides full and "experimental" details

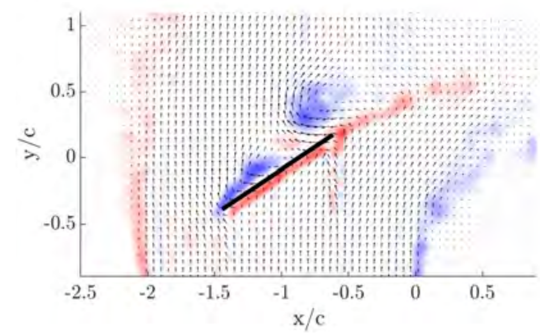
When does unsteady flow separation occur?

- Low-order model to predict unsteady flow separation
  - Subsequent low-order model allows kinematics and geometry to be optimized to improve dynamic stall response
  - Requires understanding of unsteady flow separation
- Negate gust encounter by dynamically pitching wing
  - Wing kinematics informed from low-order model predicting forces
  - Based on the understanding of how the unsteady vorticity field impacts the force response

Gust Encounter



Gust encounter with modified kinematics to reduce unsteady force response

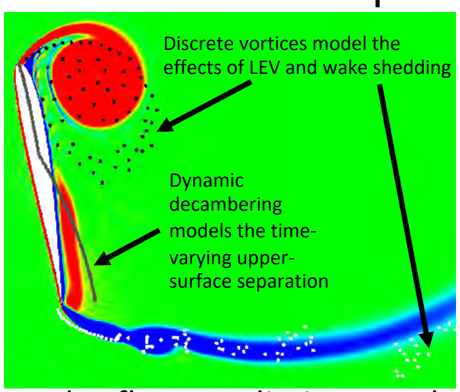


Current Endeavors : Leading Edge Vortex Analysis

- Multiple interest: Gopalarathnam (NC State), Ringuette (Univ of Buffalo)
- There has been good progress on low-order models including LEV behavior, many types are available (see, e.g., Eldredge & Jones *Annu. Rev. Fluid Mech.* 2019).
- Experimental Support: Phil Ansell (UIUC), Mulleners (EPFL), Jones (UMD)
- Computational Support (High Fidelity): Visbal et al. (AFRL)

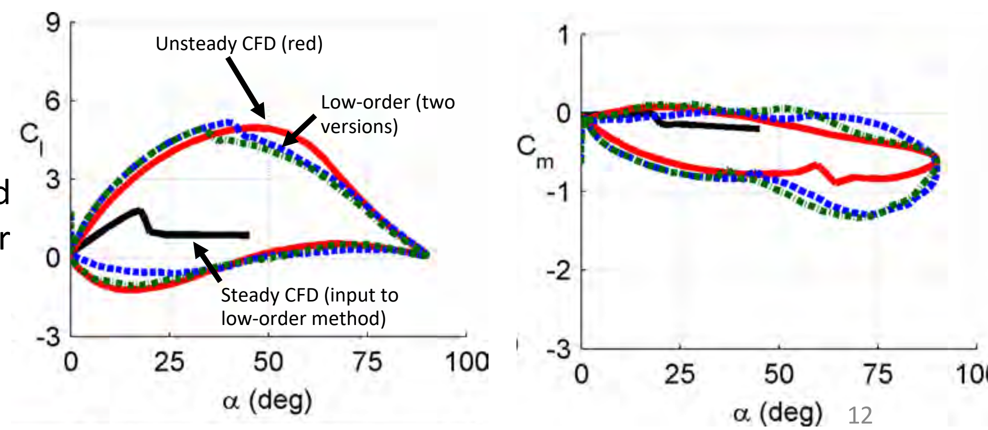
Gopalarathnam (NC State)

- Augmentation of theoretical method to model dynamic stall
  - Develop fast low-order method that predicts the loads and flow features with reasonable accuracy while being fast enough for use in design and simulation.
  - Use CFD and experimental results to extract the main flow physics with which to augment classical theory (like unsteady thin airfoil theory) and create an effective low-order prediction method.
  - Low-order method uses leading-edge suction parameter (LESP) to modulate intermittent LEV shedding and dynamic decambering to model time-varying upper-surface flow separation.



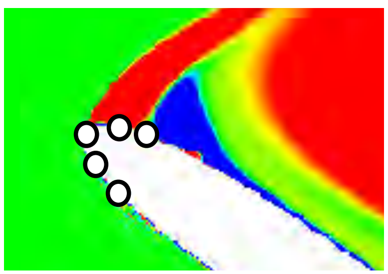
Low-order flow prediction overlaid on CFD vorticity contour plot

Low-order force prediction of lift and pitching-moment coefficients compared with unsteady CFD for an airfoil pitching up from 0 deg to 90 deg and back.



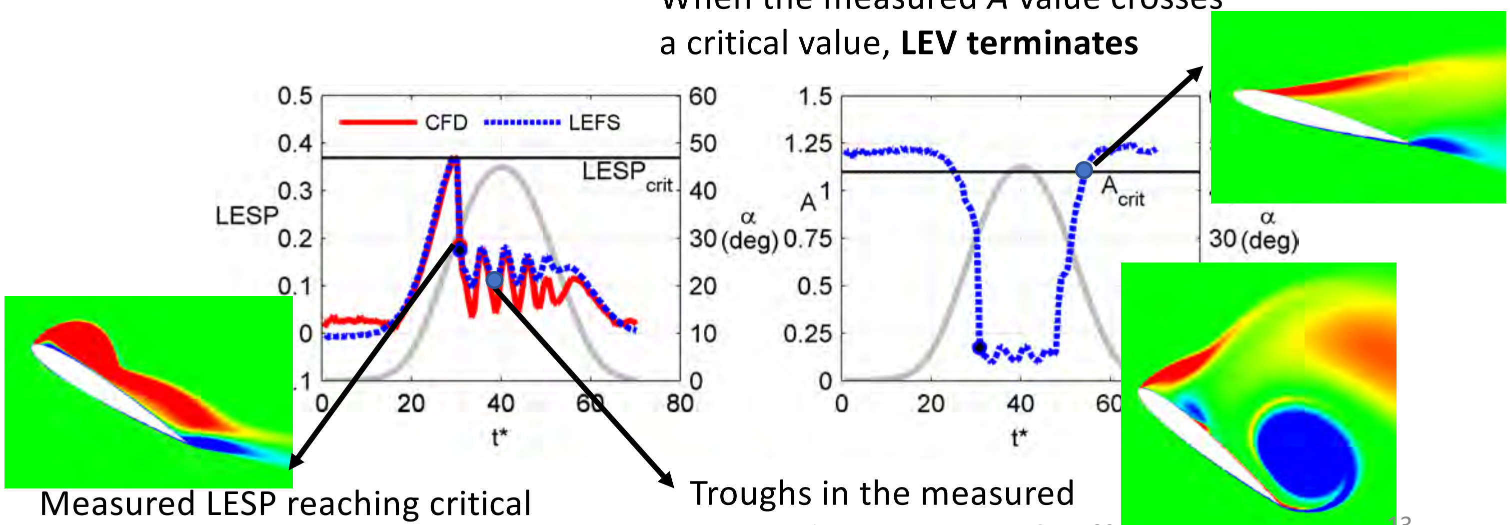
Gopalarathnam (NC State)

- Leading-edge flow sensing for dynamic stall
  - New leading-edge flow sensing (LEFS) approach for aerodynamic parameter estimation of unsteady flows
  - Uses pressure measurements at the leading edge to calculate the LESP and another parameter (*A*) which relates to velocity scaling compared to exact solution over a parabola.
  - By monitoring the *LESP* and *A*, we can detect initiation and termination of LEV formation and pinch off of LEVs



Use of five pressure measurements at leading edge in the LEFS approach

When the measured *A* value crosses a critical value, **LEV terminates**



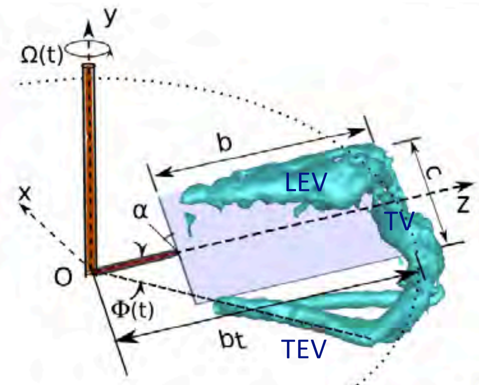
Measured LESP reaching critical value indicates **LEV onset**

Troughs in the measured LESP indicate **LEV pinch-off**

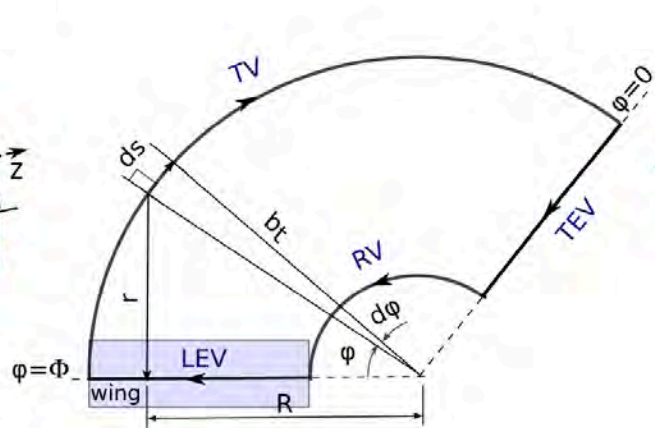
Ringuette (Buffalo)

Chowdhury, J. & Ringuette, M., *JFM* (accepted)

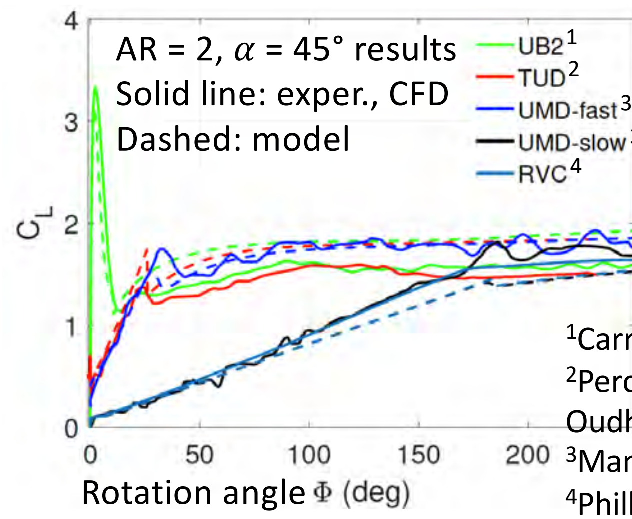
- Goal: develop a simple, 3D analytical model for the unsteady lift of low-AR, high-α rotating wings.
- Motivation: inexpensive design tool, physics-based flow control.
- Assume: single tilted loop—attached LEV, tip vortex (TV), trailing-edge-vortex (TEV), root vortex (RV).



PIV visualization of 3D loop, AR=2 (Carr, DeVoria, Ringuette, *JFM* 2015)



Top-view schematic of loop model



[1]Carr *et al*. 2015
[2]Percin & van Oudheusden 2015
[3]Manar *et al*. 2016
[4]Phillips *et al*. 2016

- Momentum balance gives loop circulation Γ; flow deflection past wing and induced loop velocity determine loop tilt angle.
- Lift = ρd/dt(ΓS_{hor}) + potential-flow added-mass force; S_{hor} = top-view loop area.
- Reasonably-good prediction of unsteady C_L, also α behavior; limited to AR ≤ 4, single-revolution.

Questions to be Answered

- Model Development:
  - How does rotational acceleration impact these predictive capabilities?
  - How to predict strength and separation of dynamic stall vortex
  - Why does suction force drop after LEV formation?
  - What is the role of vortex breakdown in dynamic stall?
  - What modeling differences are needed (if any) for reverse flow dynamic stall.
  - How should tip effects be approached? Strip theory?

Questions to be Answered

- What dynamic stall events are important to model in design with these low-order methods/theory?
  - While causal mechanisms may be different – are responses similar enough to use one model?
- Can these methods be extended to new rotors and physics without user inputs (that may be wrong)?
- Can a low-order modeling approach/theory correctly predict the onset of dynamic stall so it can be controlled?
  - Smith/Grubb: Stagnation pressure behavior
  - Gopalarathnam: Pressure at LE

Improved Understanding of Flows Past Round Edges for Modeling & Sensing of Vortex Shedding and Stall

Ashok Gopalarathnam
NC State University
agopalar@ncsu.edu

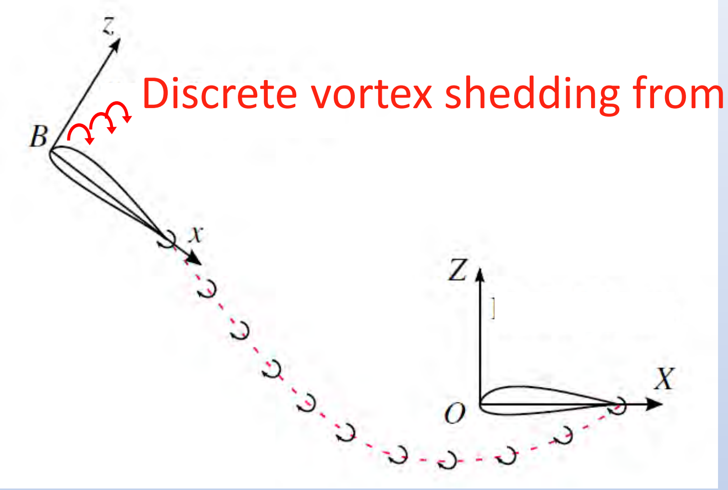
ARO Dynamic Stall Workshop, 10-11 September 2019

Georgia Institute of Technology

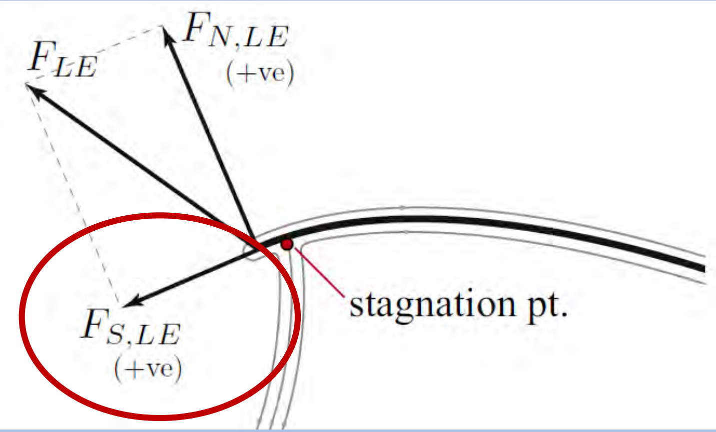
Background: Low-order modeling of unsteady airfoil aerodynamics at low-Re (2010-2014, AFOSR-funded)

- Extended an unsteady thin airfoil theory to handle LEV formation

$$\gamma(\theta, t) = 2U(t)\left[A_0(t)\frac{1+\cos\theta}{\sin\theta} + \sum_{n=1}^{\infty} A_n(t) sin(n\theta)\right]$$



- Introduced Leading-Edge Suction Parameter, *LESP* = A_0

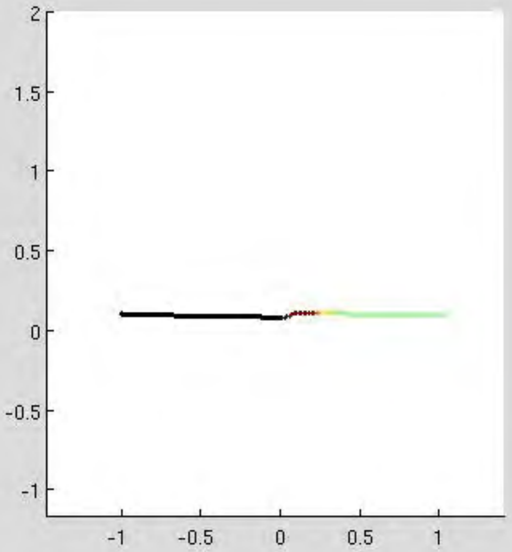


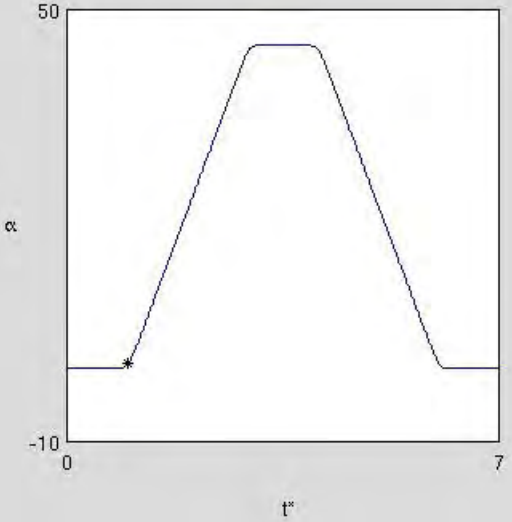
- LEV shedding occurs only when LESP > critical LESP
- LESP maintained at critical value during LEV shedding
- Critical LESP is independent of motion kinematics

Background: Low-order modeling of unsteady airfoil aerodynamics at low-Re (2010-2014, AFOSR-funded)

- Can model intermittent LEV shedding
- Good force and flow comparison with experiment and CFD
- Example video →
- More details in:

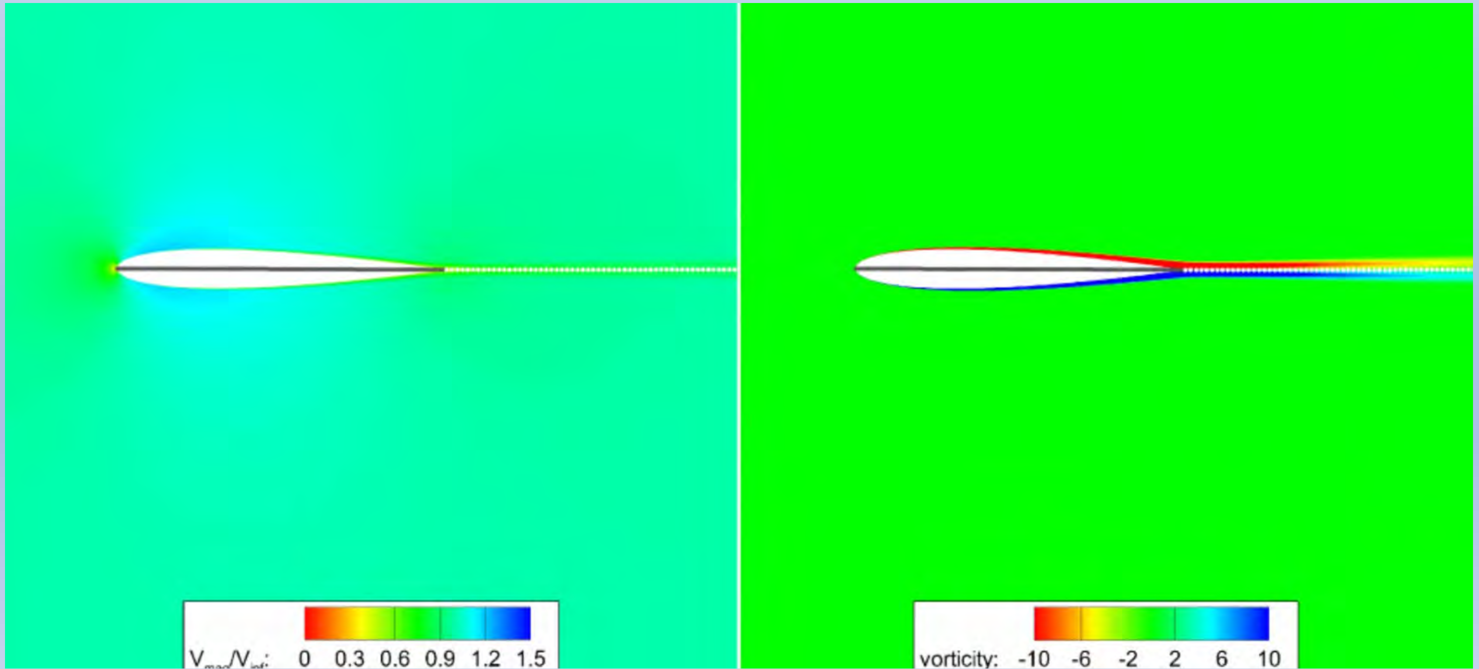
Ramesh, Gopalarathnam, Granlund, Ol, and Edwards, "Discrete-vortex method with novel shedding criterion for unsteady aerofoil flows with intermittent leading-edge vortex shedding," *Journal of Fluid Mechanics*, Volume 751, July 2014, pp 500-538.





Recent work: Low-order modeling of dynamic stall (2013-2017, ARO-funded)

- Extended earlier effort to handle trailing-edge separation using a time-varying decambering model
- Extended to higher Reynolds numbers
- Details in Narispur et al., AIAA Paper 2018-0813 and *AIAA Journal* (2019, Vol. 57, No. 1)

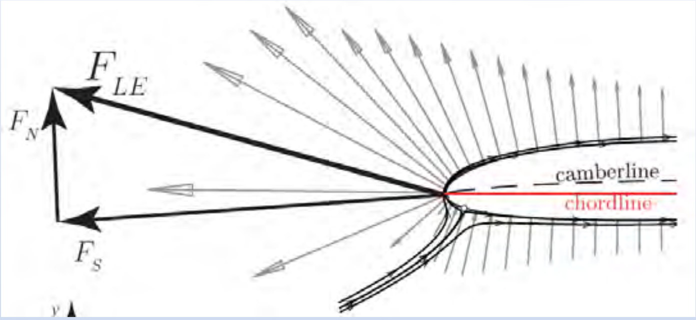


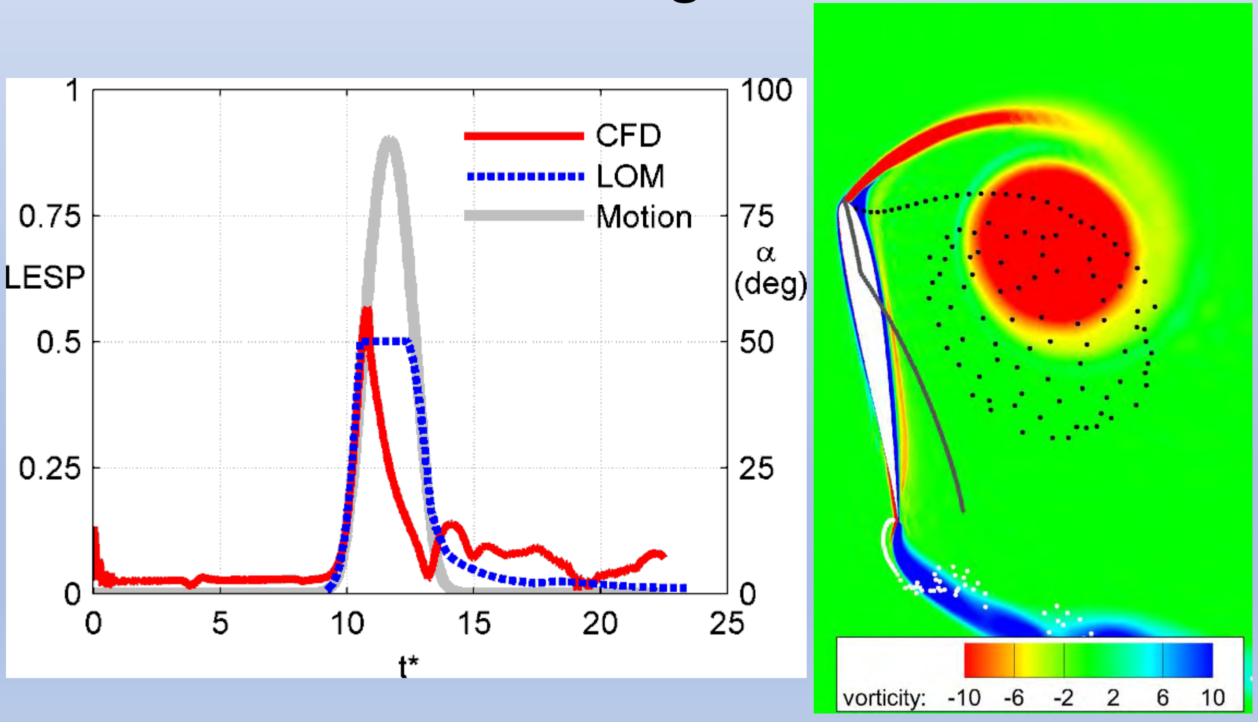
Narsipur, Gopalarathnam, Edwards, “Low-Order Modeling of Airfoils with Massively Separated Flow and Leading-Edge Vortex Shedding,” AIAA 2018-0813.

Narsipur, Gopalarathnam, Edwards, "Low-Order Model for Prediction of Trailing-Edge Separation in Unsteady Flow," *AIAA Journal*, Volume 57, Issue 1, 2019.

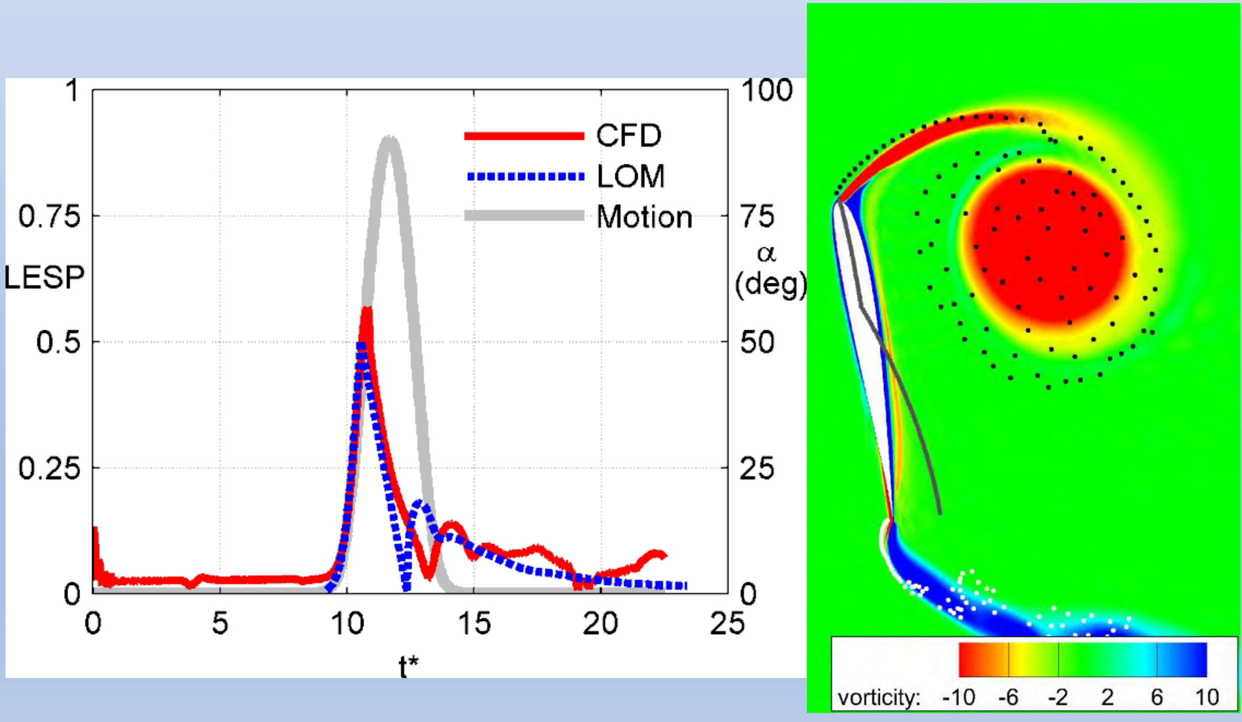
New Insight: LE Suction Behavior after Stall

- LE suction was calculated from RANS CFD results for large number of cases
- <u>New insight:</u> LE suction goes to near-zero after LEV shedding starts





Earlier model



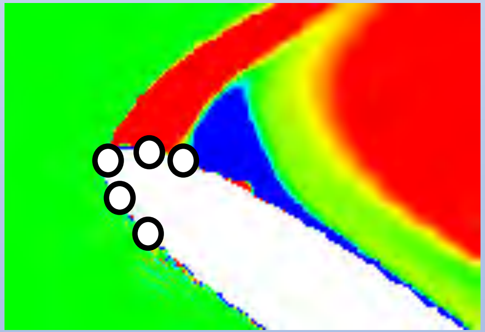
Improved model

New research: LE Flow Sensing (LEFS) for Airfoil Vortex Shedding and Dynamic Stall

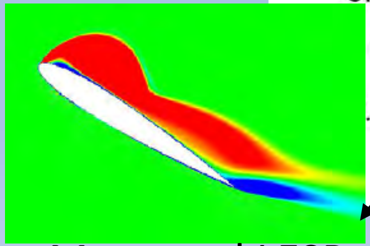
- LEFS uses a few pressure measurements at the leading edge to calculate the leading-edge suction parameter (*LESP*) and another parameter (*A*) which relates to velocity scaling compared to exact solution over a parabola.
- The *LESP* and *A* from LEFS compare well with CFD results.
- By monitoring the *LESP* and *A*, we can detect initiation and termination of LEV formation and pinch off of LEVs

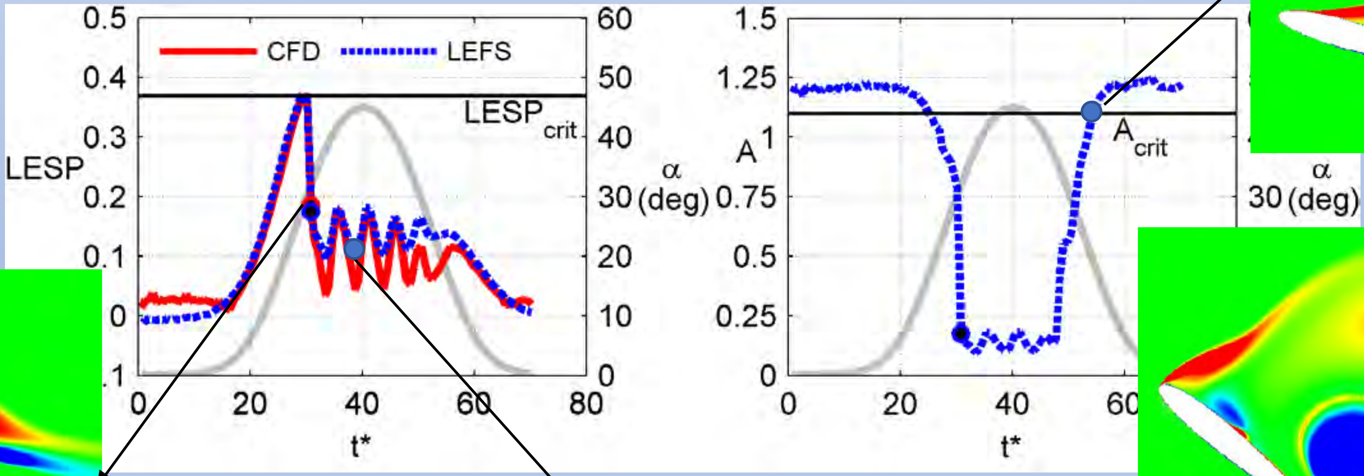
LEFS for steady flow documented in Ref. 4 on last slide

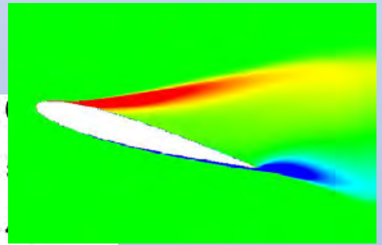
When the measured *A* value crosses a critical value, **LEV terminates**

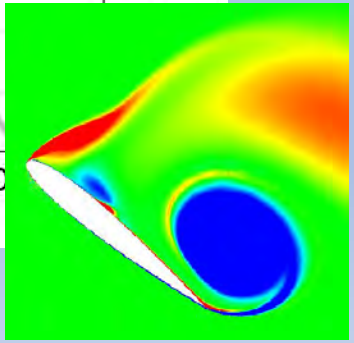


Use of five pressure measurements at leading edge in the LEFS approach







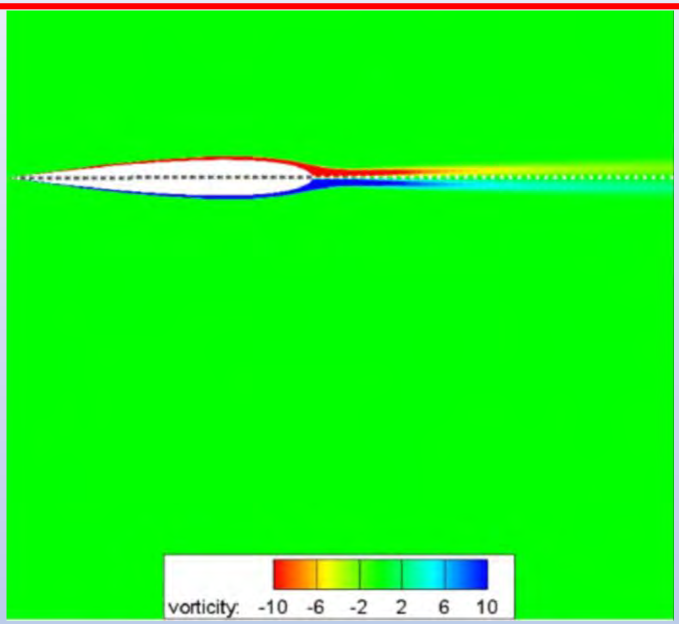


Measured LESP reaching critical value indicates **LEV onset**

Troughs in the measured LESP indicate **LEV pinch-off**

New research: Reverse Flow, Wake Impingement

- Early efforts to extend low-order method to reverse flow has produced good results
- Our method has been extended to handle wake impingements

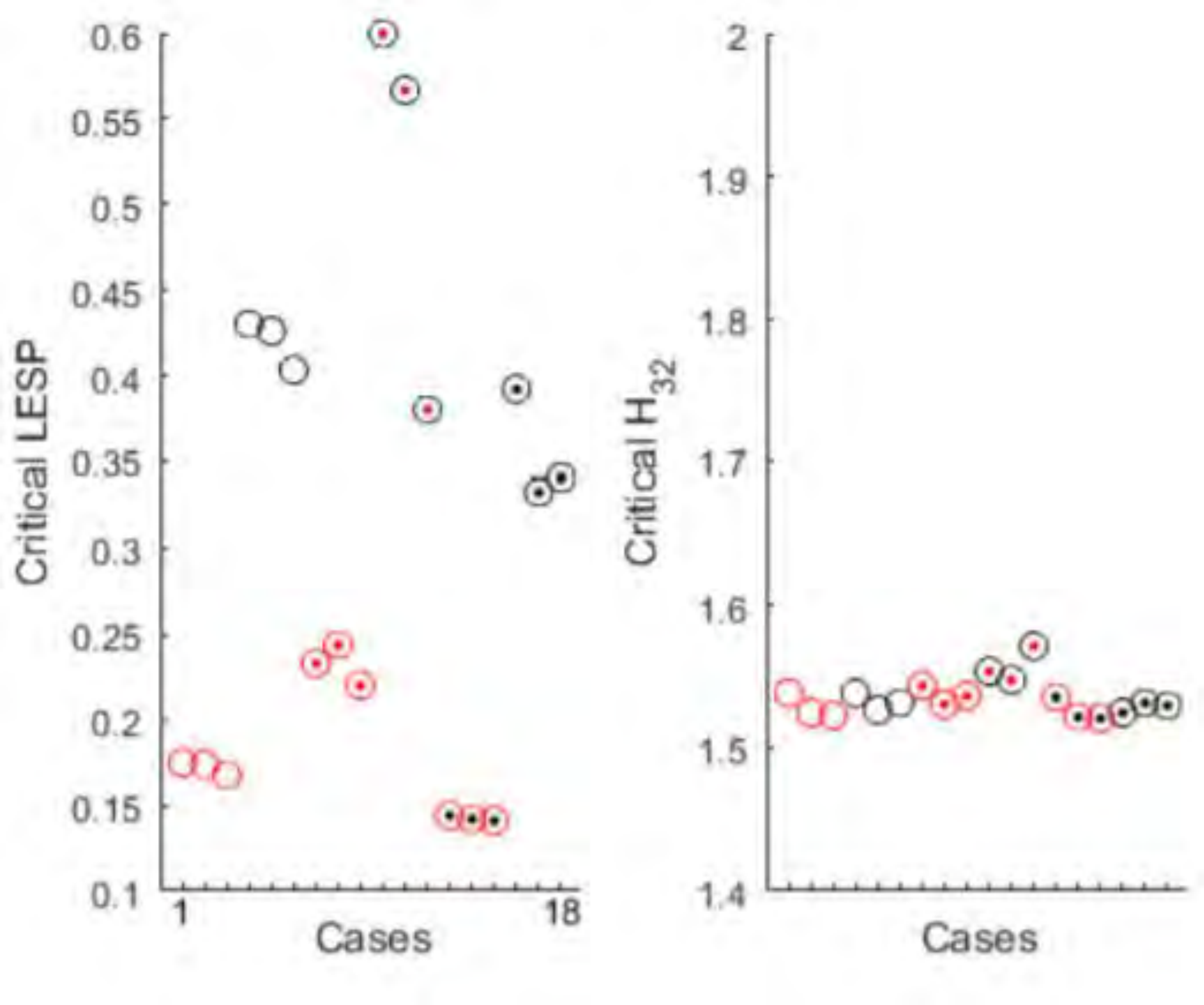


Medina, Suresh Babu, Rockwood, Gopalarathnam, and Ahmed, “Theoretical and Experimental Study of Wake Encounters on Unsteady Airfoils,” AIAA 2019-0898, January 2019.

New research: Going beyond LESP

- $\text{LESP}_{\text{critical}}$ depends on airfoil and Re. Can we go beyond LESP and find a parameter that will work across airfoil shapes and Reynold numbers. Early efforts to find a critical boundary-layer shape factor are showing promise.

Early efforts documented in: Ramanathan, Narsipur, and Gopalarathnam, “Boundary-Layer Characteristics at the Onset of Leading-Edge Vortex Formation on Unsteady Airfoils,” AIAA 2019-3590, June 2019.



Conclusions and Next Steps

- Leading-edge flow physics and the behavior of LE suction are clearly important for modeling and explaining DS behavior
- Need for fundamental investigations (CFD, experiment, low-order) to understand reasons behind LESP behavior
  - Why does LESP drastically go to near zero after vortex shedding starts?
  - Effect of airfoil shape
  - Effect of Reynolds number
  - Collapsing them using boundary-layer shape factor
  - Effect of rotation rates in second-order LESP changes with pitch rate
- A few pressure measurements near the LE with the flow sensing algorithm gives useful information even about off-surface flow events. This may be useful in wind-tunnel and flight test experiments, if not in routine operations
- Integrated experiment, CFD (including higher-order CFD), and low-order theory investigations are helpful for unraveling the flow physics of these situations

Acknowledgments

- AFOSR grant FA 9550-10-1-0120 (2010-2013), PM: Dr. Douglas Smith
- ARO grant W911NF-13-1-0061 (2013-2016), PM: Dr. Matthew Munson

- Collaborators
  - Dr. Michael Ol and Dr. Kenneth Granlund, AFRL
  - Dr. Jack Edwards, NC State
  - Dr. Albert Medina and Dr. Matt Rockwood, AFRL
- Former PhD students:
  - Dr. Kiran Ramesh
  - Dr. Shreyas Narsipur
  - Dr. Arun Vishnu Suresh Babu
  - Dr. Pranav Hosangadi

References

1. Ramesh, Gopalarathnam, Granlund, Ol, and Edwards, “Discrete-vortex method with novel shedding criterion for unsteady aerofoil flows with intermittent leading-edge vortex shedding," *Journal of Fluid Mechanics*, Volume 751, July 2014, pp 500-538.

2. Narsipur, Gopalarathnam, Edwards, "Low-Order Model for Prediction of Trailing-Edge Separation in Unsteady Flow," *AIAA Journal*, Volume 57, Issue 1, 2019.

3. Narsipur, Gopalarathnam, Edwards, “Low-Order Modeling of Airfoils with Massively Separated Flow and Leading-Edge Vortex Shedding,” AIAA 2018-0813.

4. Saini and Gopalarathnam, "Leading-Edge Flow Sensing for Aerodynamic Parameter Estimation," *AIAA Journal*, Volume 56, Issue 12, 2018. (LEFS for steady flow)

5. Kakumanu, N., “Low-Order Simulation of Unsteady Airfoils Operating in Varying Freestream Velocity Including Reverse Flow,” MS Thesis, North Carolina State University, 2017.

6. Medina, Suresh Babu, Rockwood, Gopalarathnam, and Ahmed, “Theoretical and Experimental Study of Wake Encounters on Unsteady Airfoils,” AIAA 2019-0898, January 2019.

7. Ramanathan, Narsipur, and Gopalarathnam, “Boundary-Layer Characteristics at the Onset of Leading-Edge Vortex Formation on Unsteady Airfoils,” AIAA 2019-3590, June 2019.

High-Fidelity Computations

US Army Research Office (ARO) – Georgia Tech

Dynamic Stall Workshop

September 10-11, 2019

Georgia Tech, Atlanta

State of the Art in Dynamic Stall Computational Predictions

Rohit Jain
Aviation Development Directorate
(CCDC AvMC), US Army

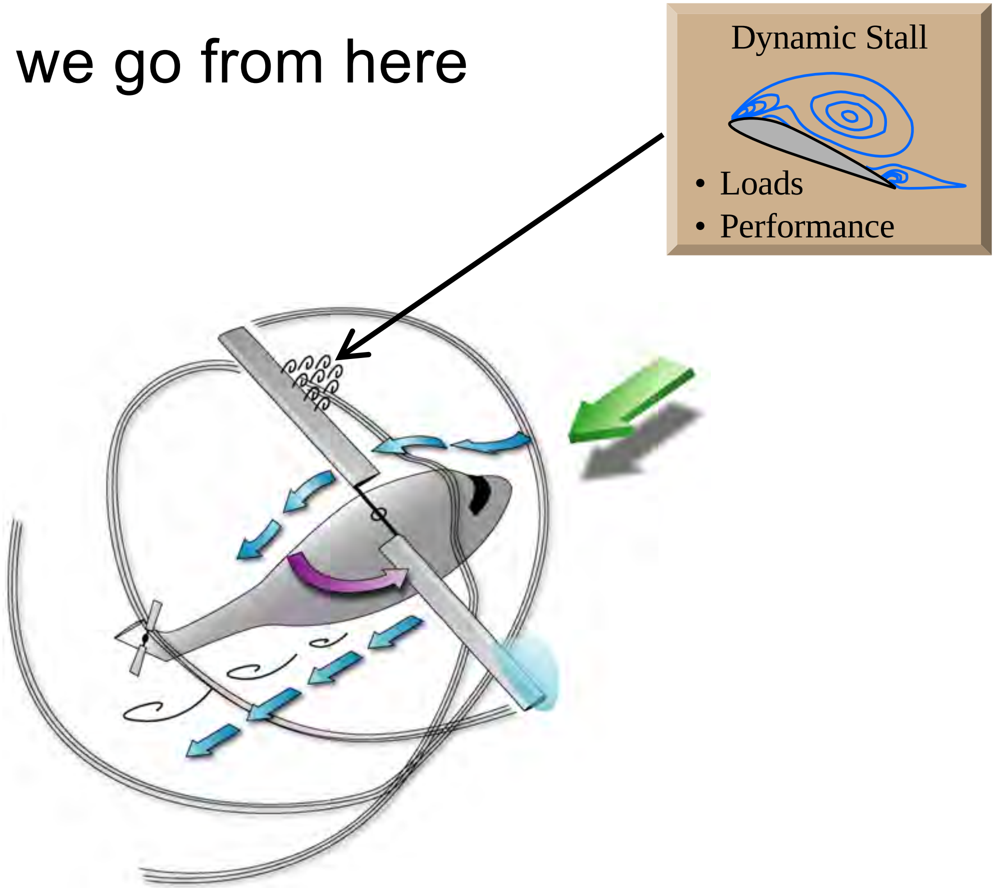
François Richez
ONERA, France

Anthony Gardner
DLR, Germany

Marilyn Smith
Georgia Tech, USA

Outline

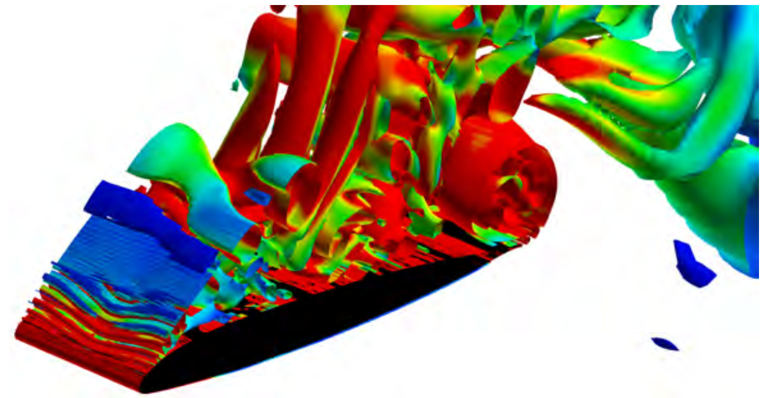
- Computational Fluid Dynamics (CFD) predictions/validations
- Lessons learned
- Discussion – where do we go from here



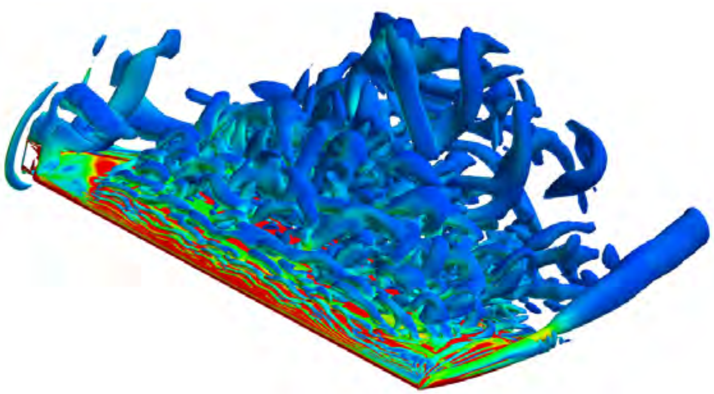
CFD studies of dynamic stall

- Two-dimensional (2-D) airfoils/wings
- 3-D finite-span wing
  - Examples of test datasets/measurements
  - List of recent studies
  - Examples of predictions
- Isolated and installed rotors
  - Similar examples as for 3-D wing

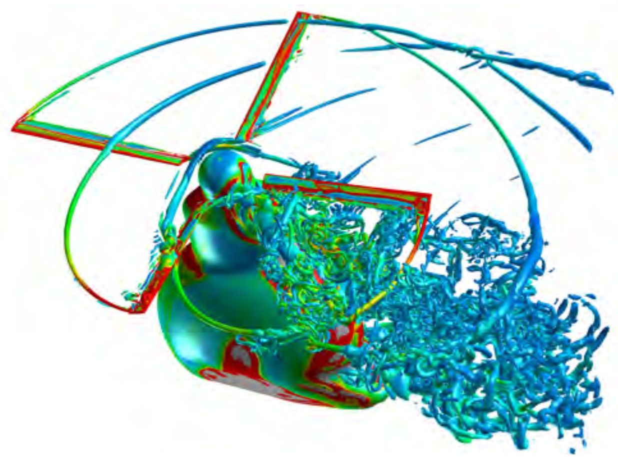
2-D Airfoil Wing



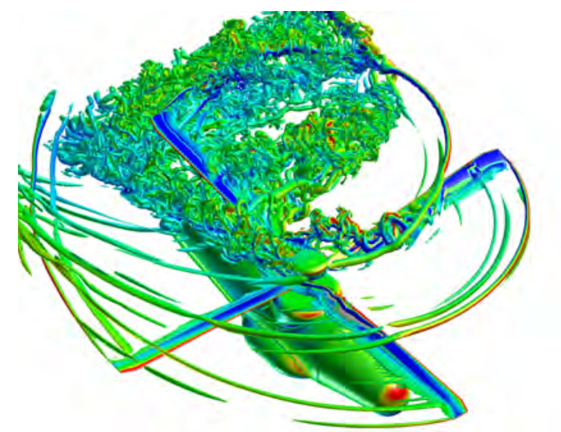
3-D Wing



7A Rotor

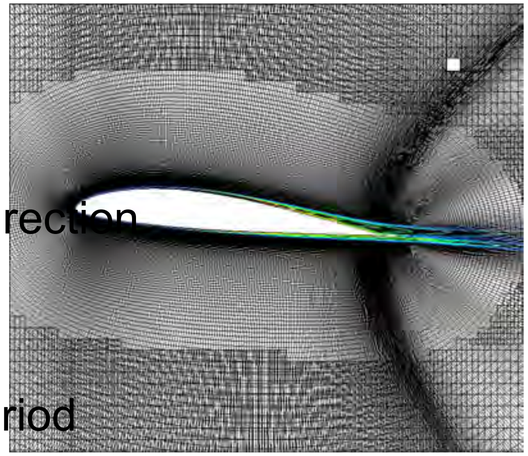


UH-60A Rotor



2-D dynamic stall CFD studies

- The 2-D dynamic stall problem has been extensively studied over three decades
- Limited numerical resolution in the early studies caused the results to be more sensitive to numerical resolution than turbulence modeling (RANS, DES, LES)
- Basic limitations with 2-D modeling of an inherently 3-D phenomena
- Research over the last decade has established the numerical resolution requirements
  - M. Costes et al. (2005)
    - NACA0015 grid refinement study
    - ~2000 points around the airfoil, ~200 points in the normal direction
  - K. Richter et al., (2011)
    - OA209, grid refinement study, effect of turbulence models
    - ~1000 points around the airfoil, 18000 steps per pitching period
  - N. Liggett et al., (2012)
    - VR12 and NACA0012, spatial and temporal refinement study
    - 811 points around the airfoil, 18000 steps per pitching period
  - US Army/ONERA performed grid sensitivity study on 2-D wing under the US/France Project Agreement; identified the importance of temporal and spatial convergence, and fully turbulent versus transition modeling



2-D wing stall experimental datasets

- 2-D
  - McCroskey data (several airfoils), Piziali data (NACA 0015) (**US**)
  - The Ohio State University data, University of Wyoming data (**US universities**)
  - Visbal et al. data (**US Air Force**)
  - OA209 and DSA-9A airfoil (**DLR**)
  - OA209 airfoil (**ONERA**)
  - University of Glasgow (range of NACA, SSC-A09, RAE9645) (**UK**)
  - Many others…

3-D Wing, finite-span wing dynamic stall studies

- 3-D computational requirements 1-2 orders of magnitude more than 2-D

- Earlier 3-D studies used relatively coarse spatial/temporal resolution
  - J. Ekaterinaris (1994) – 3-D, finite-span, NACA0015 wing
  - A. Spentzos (2007) – 3-D, finite-span wing
  - Many others

- Finer spatial/temporal resolutions in recent studies
  - F. Richez et al. (2015) – OA209 finite-span, static stall, zonal DES
  - K. Kaufmann et al. (2015) – OA209 finite-span wing, URANS, fully turbulent
  - M. Costes et al. (2015) (OA209 finite-span wing, URANS, fully turbulent)
  - R. Jain et al., (2016) (OA209 finite-span wing, structured and unstructured grids, URANS and DDES, transitional and fully turbulent)
  - K. Kaufmann et al. (2017) Merz finite-span wing (swept tip, DSA-9A airfoil)

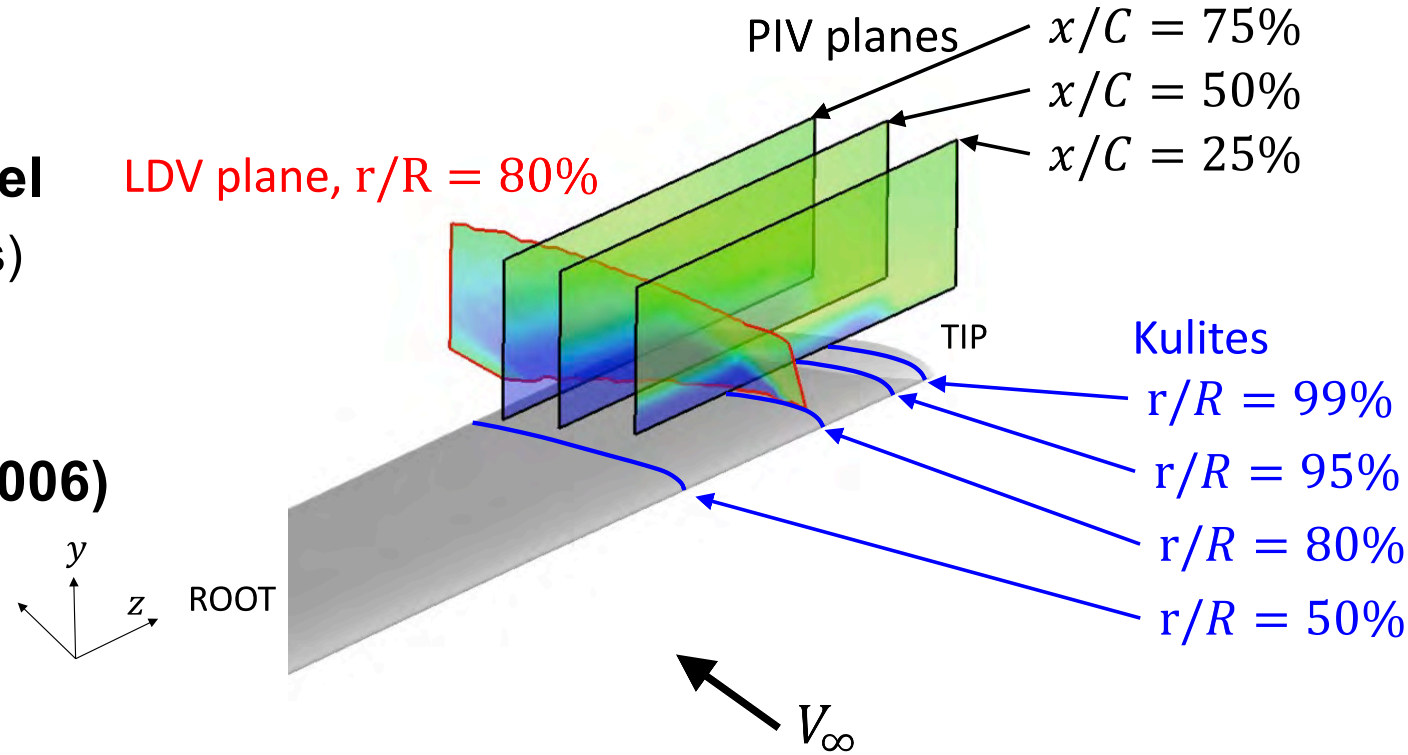
➢ **All these studies showed satisfactory agreement with the test data**

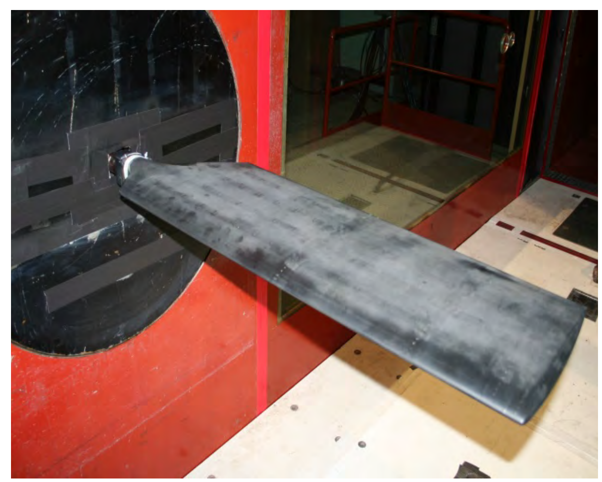
3-D wing stall experimental datasets

- 3D Wing
  - Piziali data finite wing (NACA 0015), Lorber finite wing (SSC-A09) (**US**)
  - Merz finite wing, Möwe double-swept transonic wingtip (**DLR**)
  - OA209 finite wing (**ONERA**)
  - University of Glasgow (RAE9645) (**UK**)

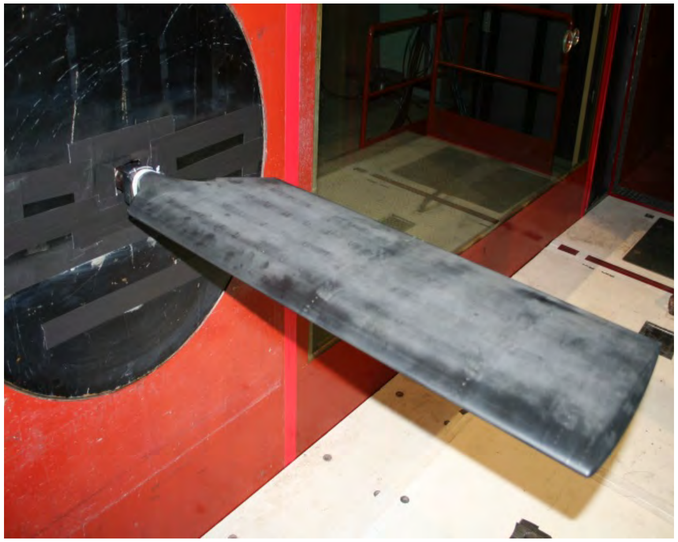
ONERA 3-D OA209 wing wind-tunnel tests

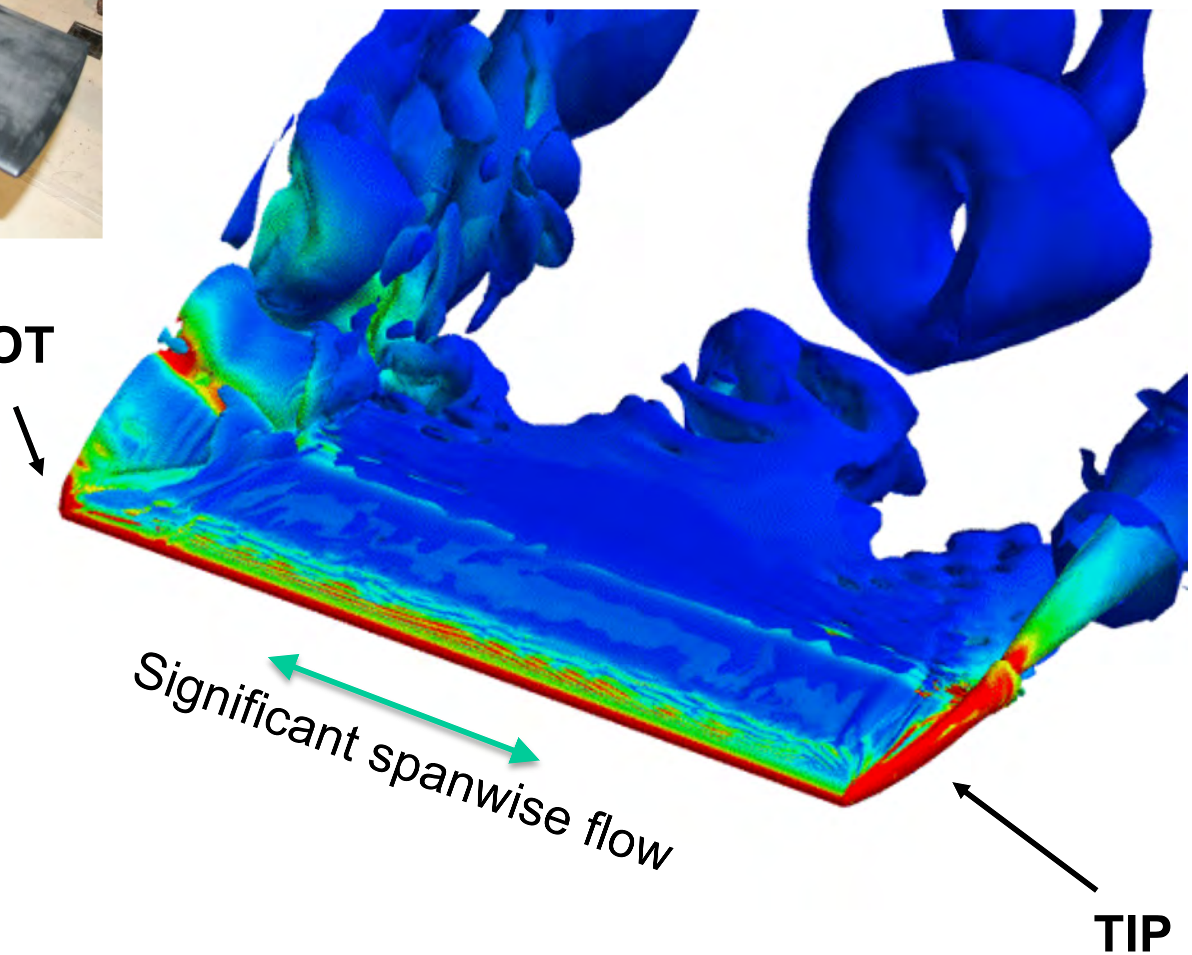
- **ONERA F2 wind-tunnel**
  - Low speed (< 100 m/s)
  - Full optical access
  - In-site LDV system
- **OA209 wing model (2006)**
  - Chord = 0.3 m
  - Aspect ratio ≈ 3
  - No sweep, no twist
  - Rounded tip cap
  - Light carbon fiber models
  - Fully instrumented
    - Kulites (50, 80, 95, and 99% R)
    - PIV and LDV
  - Pitching motion = 17 + 5sin(ωt),
  - M=0.16, Re=1 million



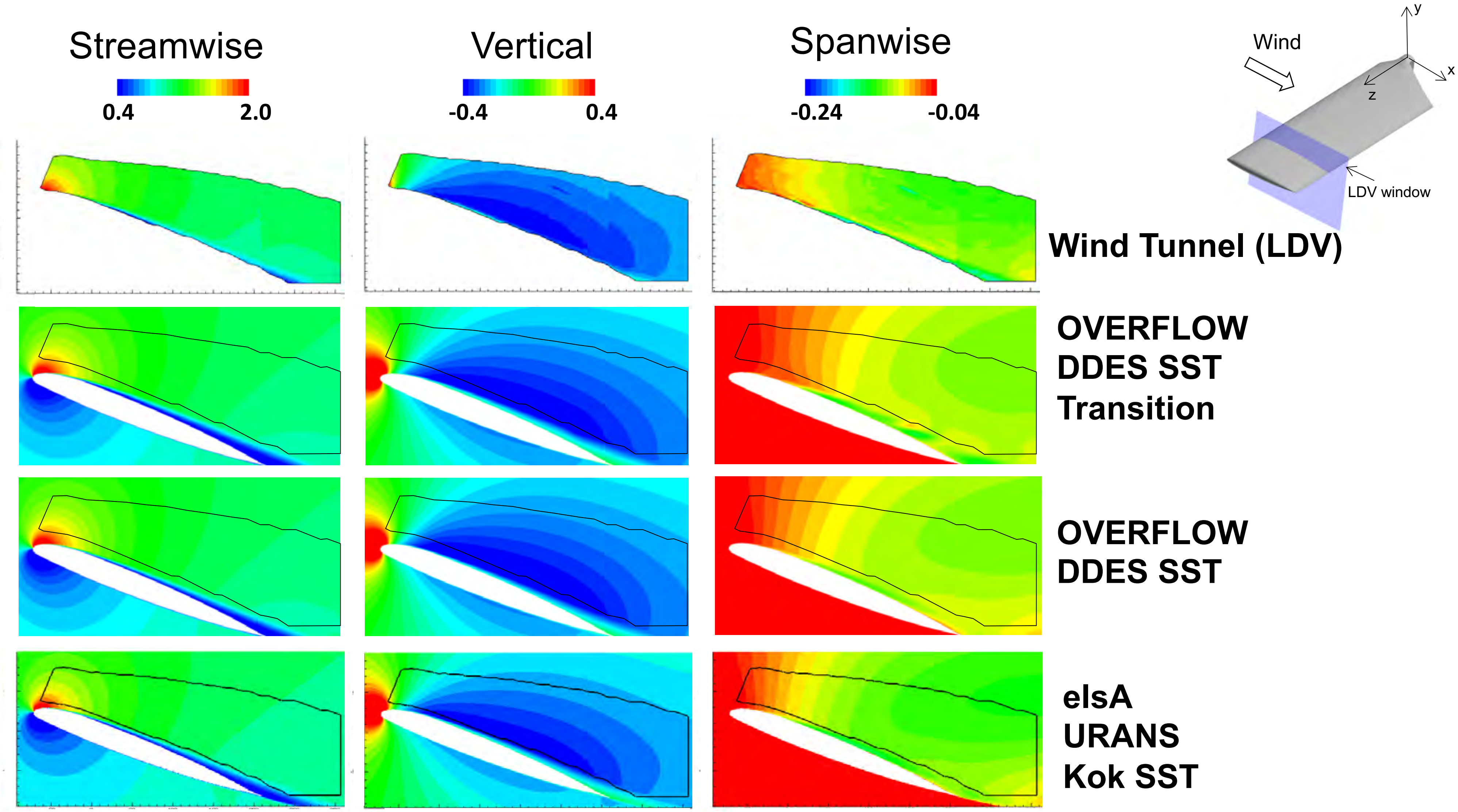


OA209 wing flow animation (CFD, Helios)



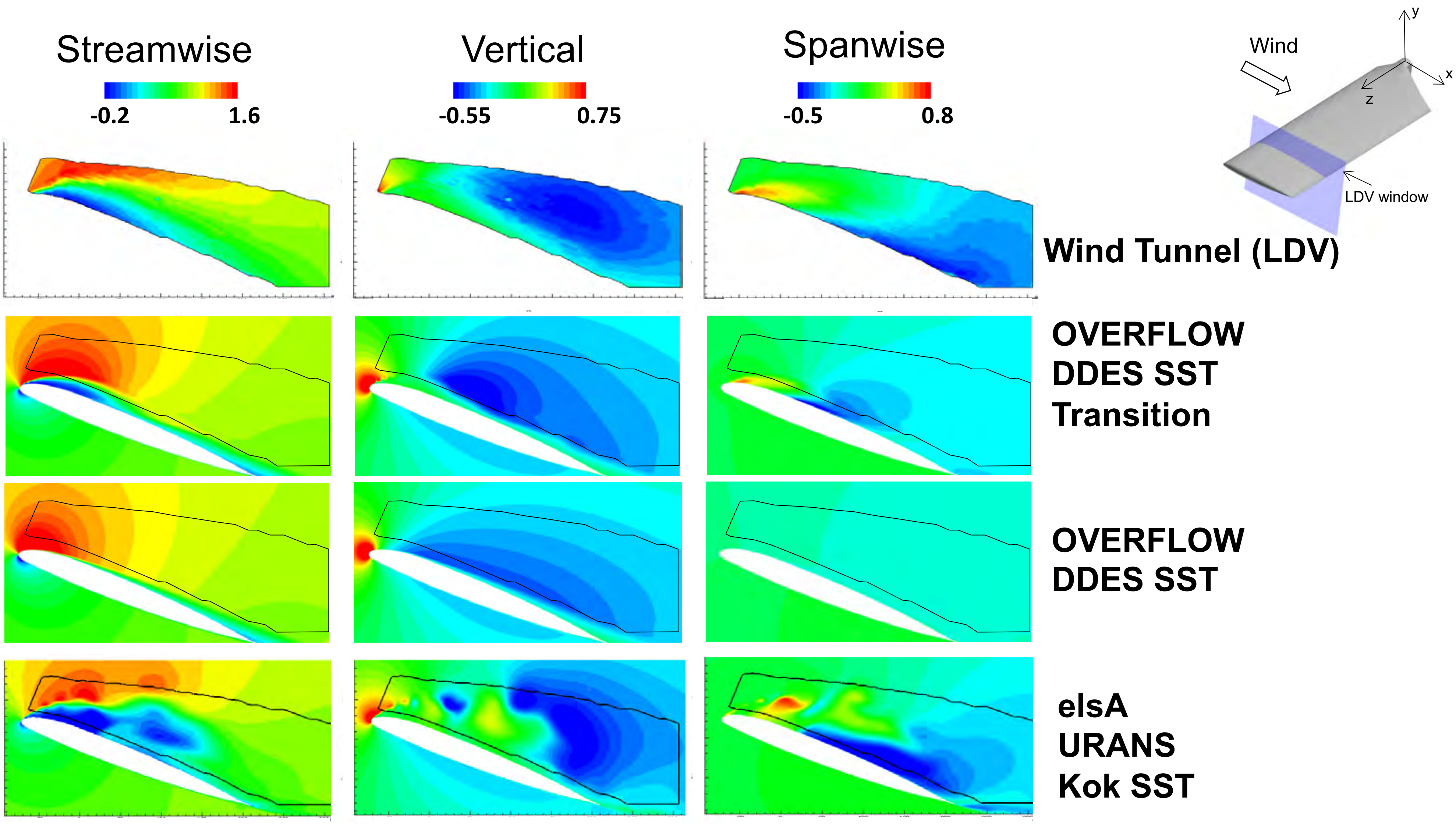


Flowfield at 80% R, θ=21.8° ↑ (pre stall)



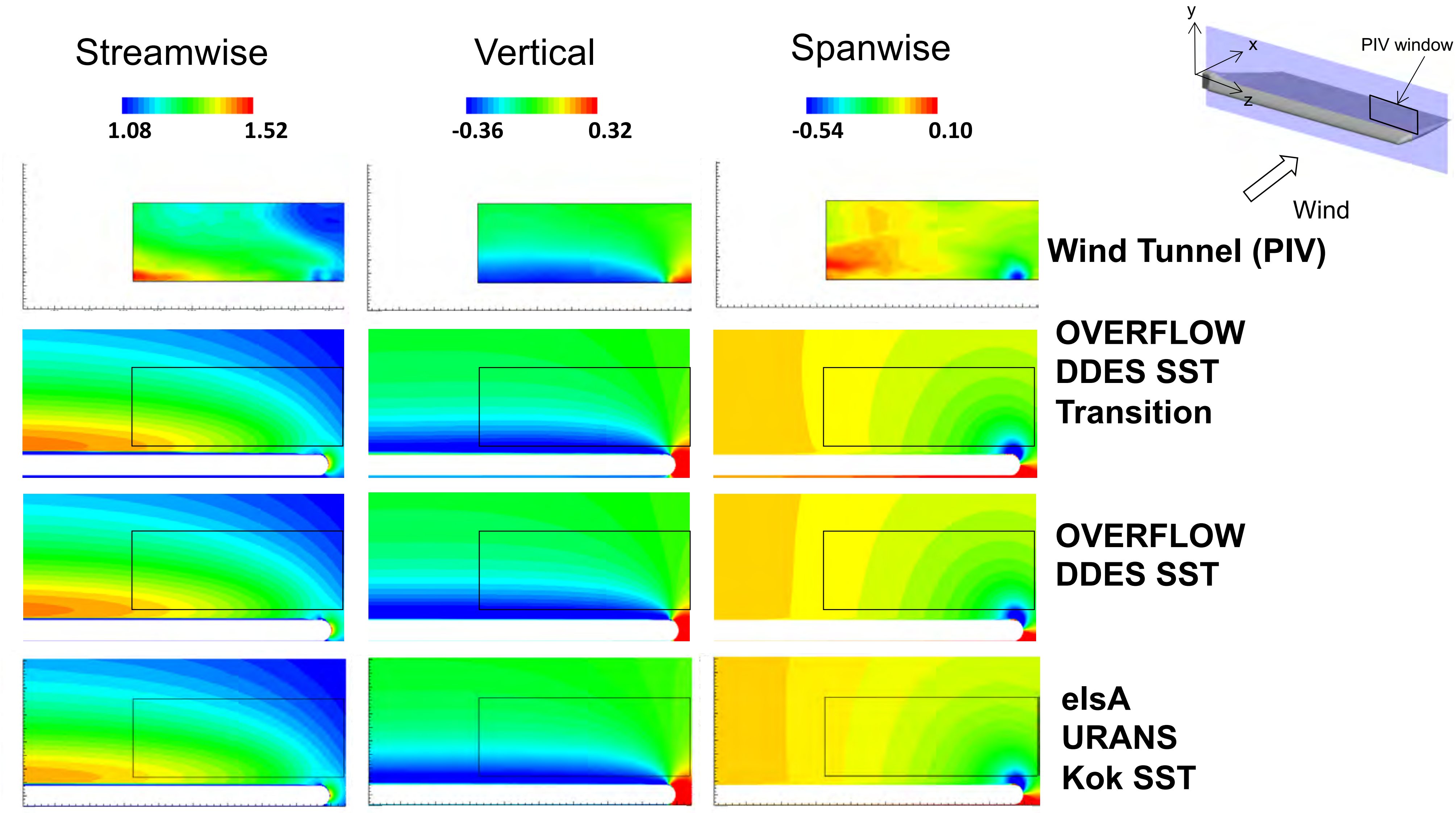
- Attached flow
- All predictions match

Flowfield at 80%R, θ=21.7° ↓ (post stall)



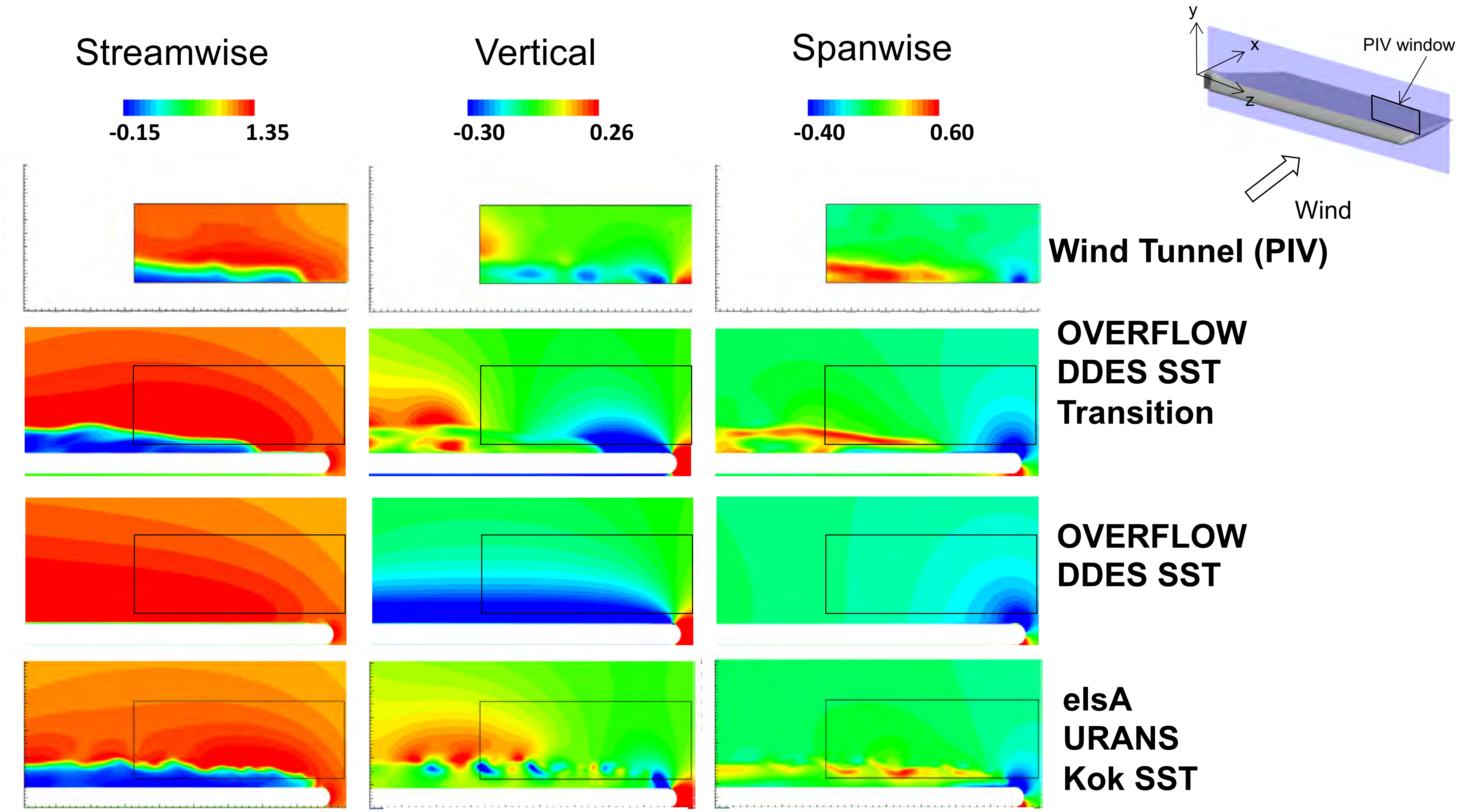
- Separation well captured by including transition
- Not captured by SST alone
- Overpredicted by Kok SST

Flowfield at 25% C, θ=21.2° ↑ (pre stall)



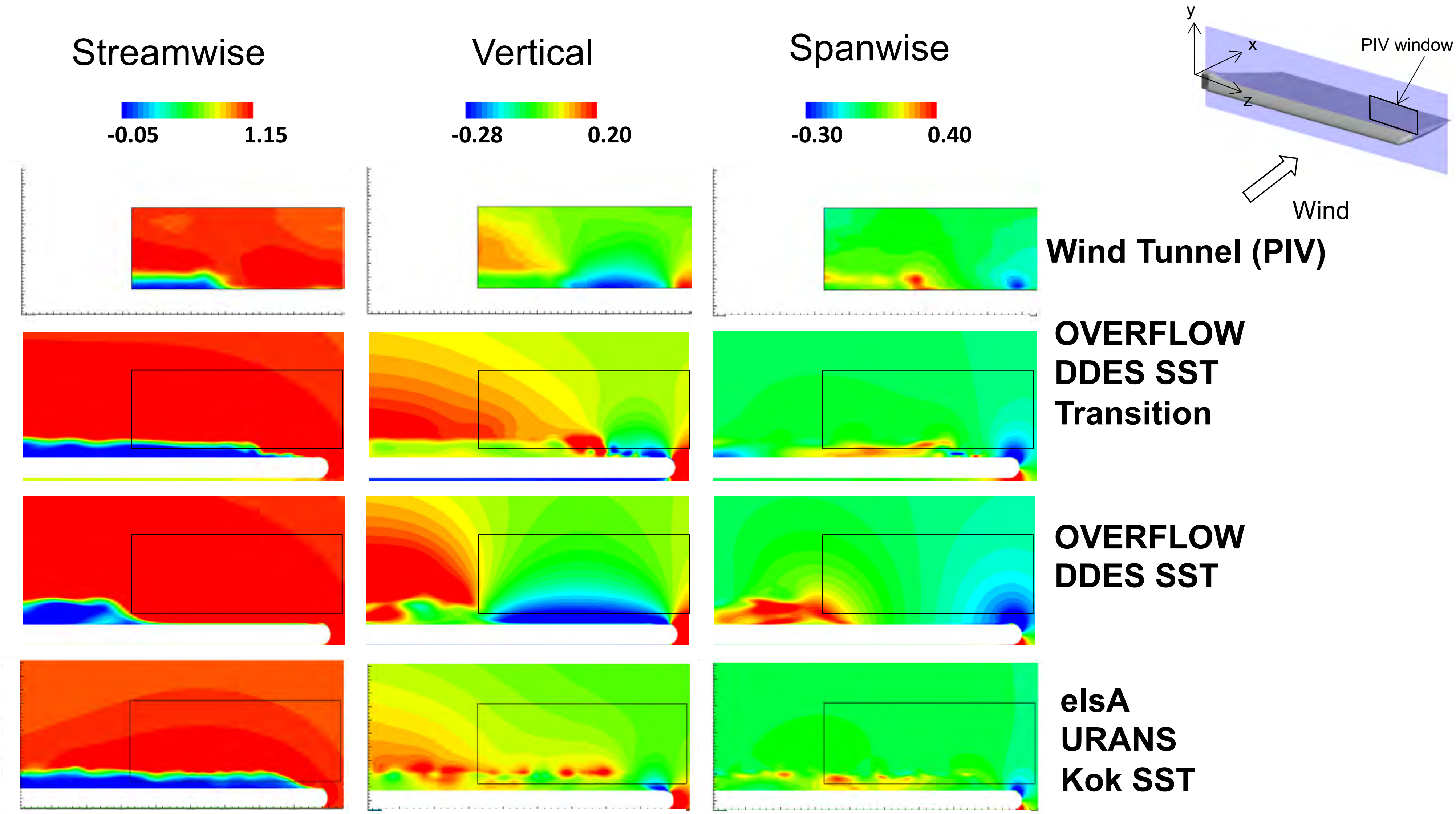
- Attached flow
- All predictions match

Flowfield at 25% C, θ=21.2° ↓ (post stall)



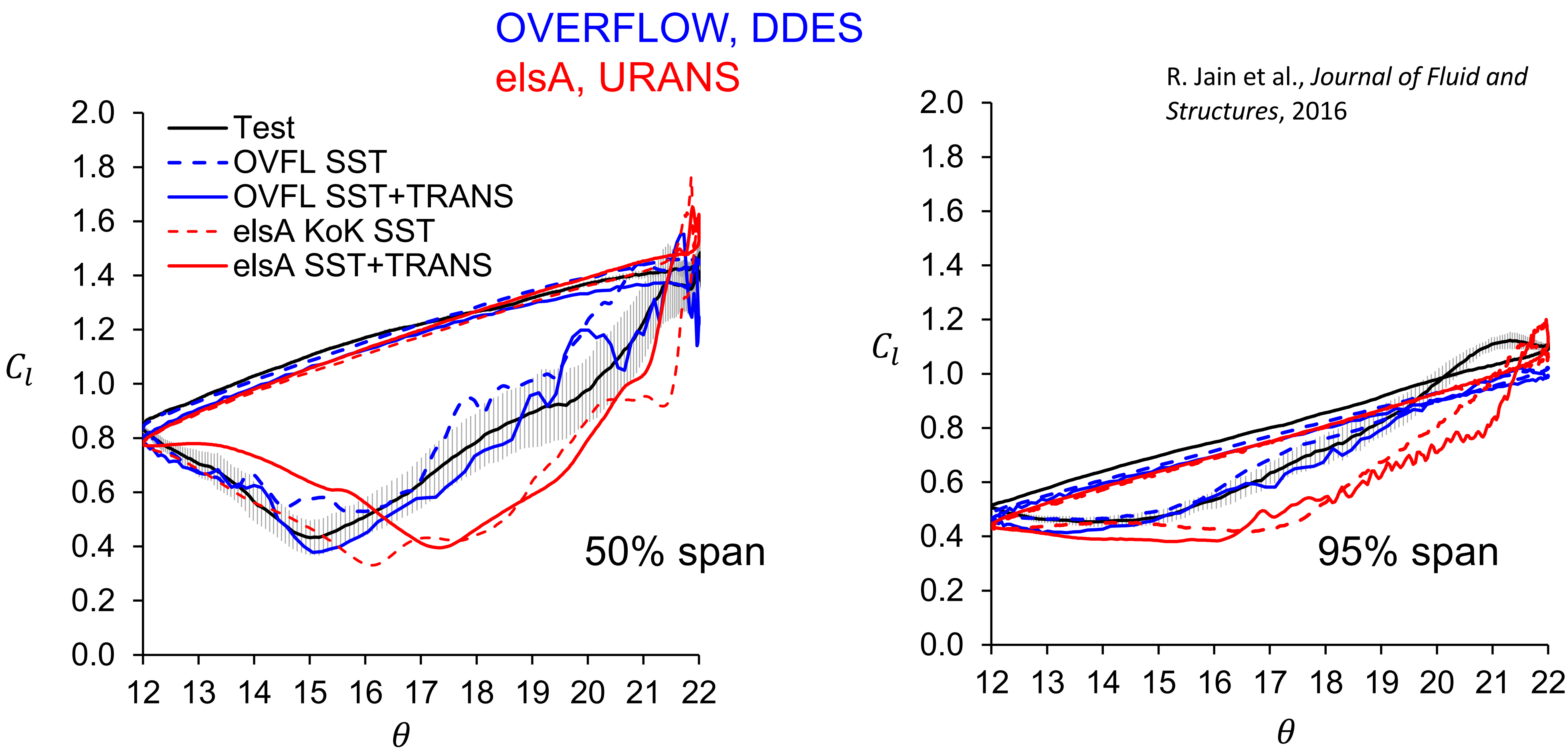
- Large spanwise flow
- Well captured by including transition
- Not captured by SST alone
- Separation outboard overpredicted by Kok SST

Flowfield at 25% C, θ=18° ↓ (post stall)



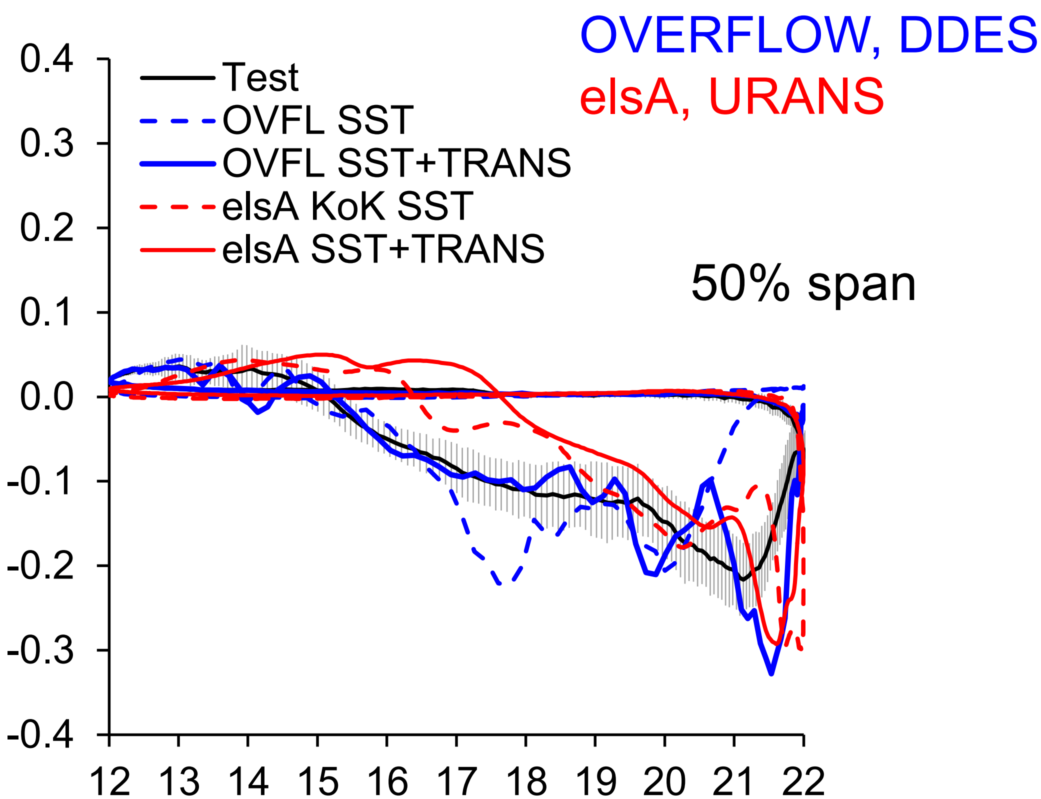
- Flow features well captured
- Outboard separation well captured by including transition
- Not captured by SST alone
- Separation outboard overpredicted by Kok SST

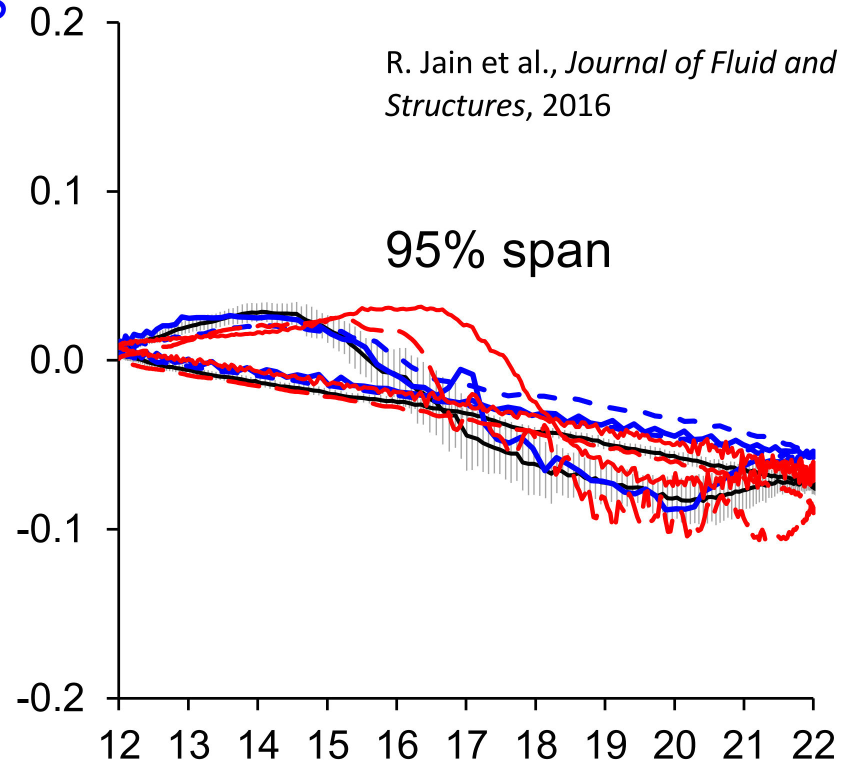
OA209 wing – section lift



- Good agreement with experiment
- URANS: overprediction of stall
- DDES: good lift hysteresis prediction
- DDES: some improvements when transition is included

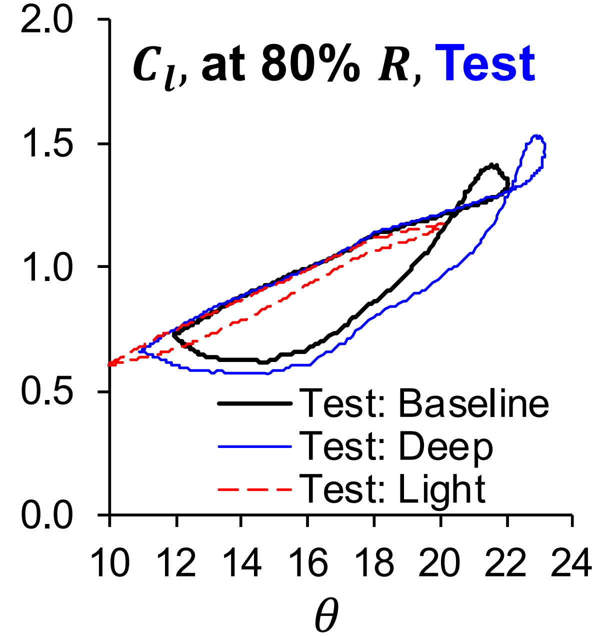
OA209 wing – section pitching moment

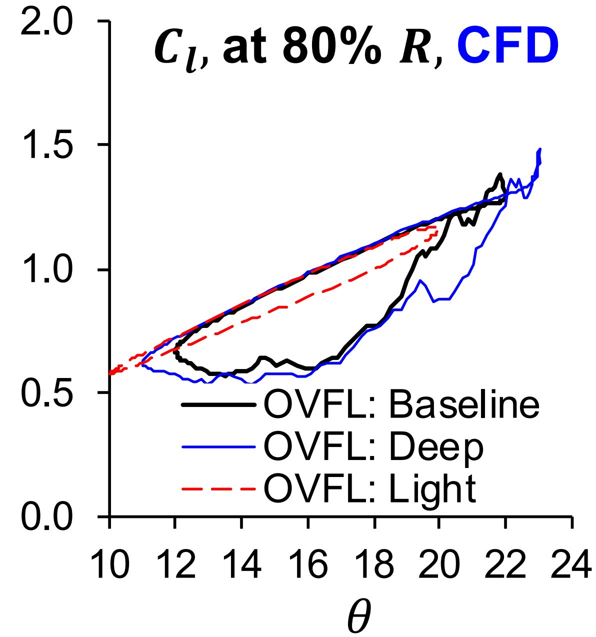




- Good agreement with experiment
- URANS: Overprediction of stall
- DDES: good lift hysteresis prediction
- DDES: Transition modeling improves the pitching moment prediction

Baseline, Deep, and Light Stall

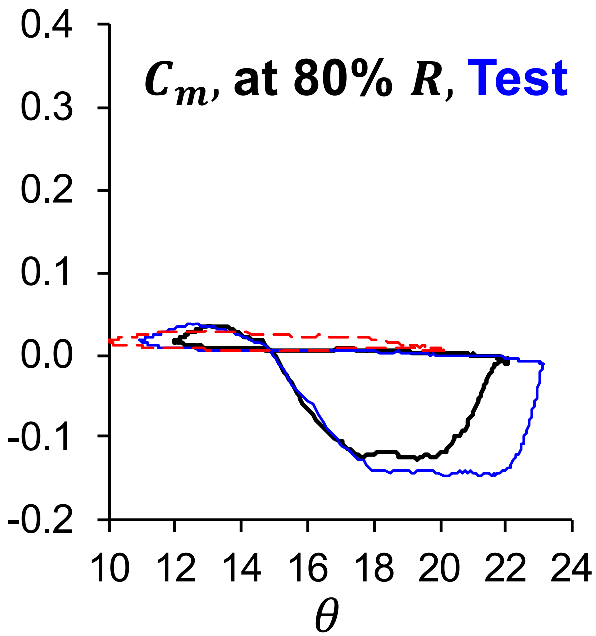


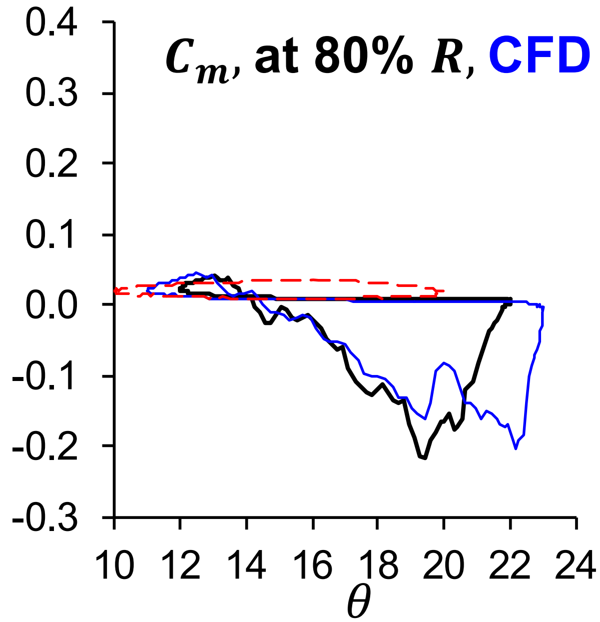


Baseline : $\theta(t) = 17 + 5\sin(\omega t)$

Deep : $\theta(t) = 17 + 6\sin(\omega t)$

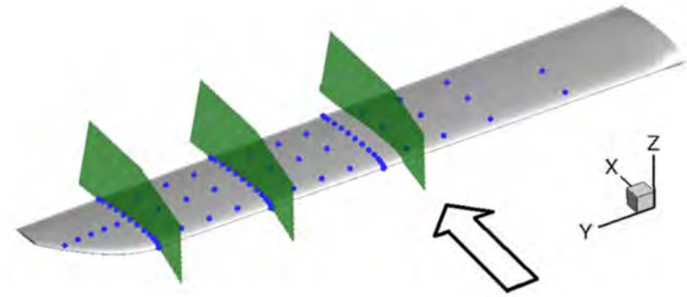
Light : $\theta(t) = 15 + 5\sin(\omega t)$





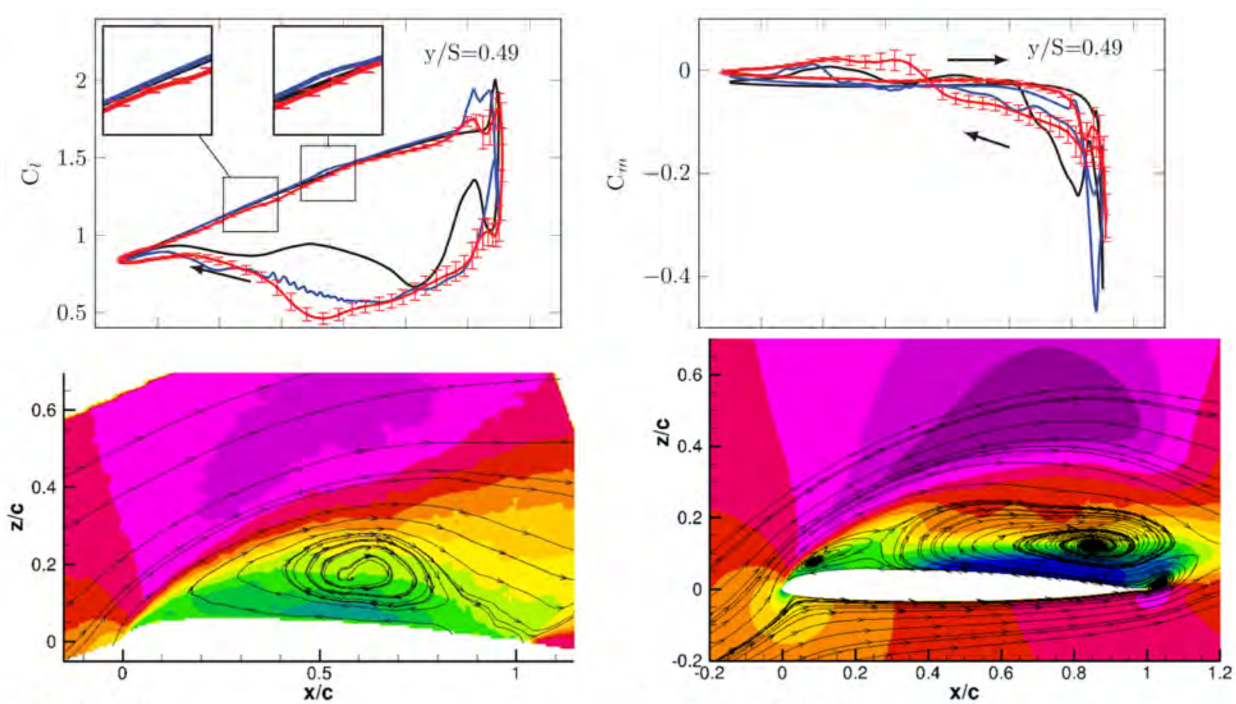
- Trends captured very well
- Agreement of the absolute values also very good (in the paper)

Test case: Merz finite wing



Follow-on to the ONERA OA209 wing:

- Reduced cycle-to-cycle variation
- Easier gridding
- Reduced wall installation effect
- Improved sensor placement, discretisation effect, pressure referencing
- High-speed PIV instead of LDV
- Comparability to DSA-9A airfoil data and computations; RTG Rotor experiments



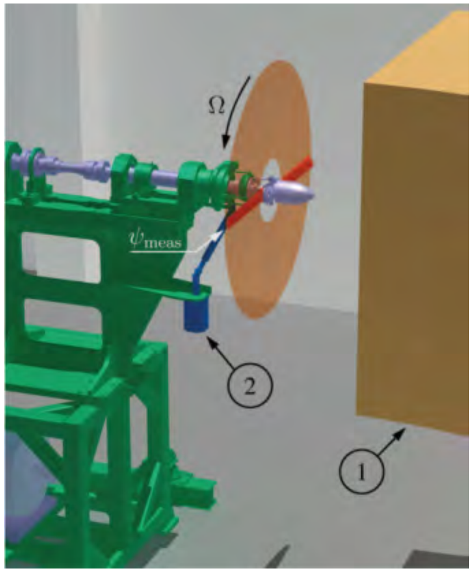
c) y/S=0.68 PIV

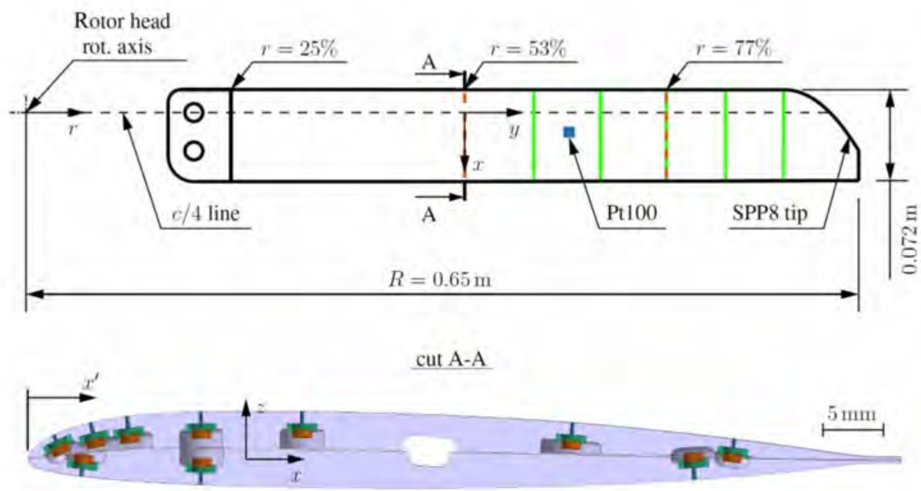
d) y/S=0.68 DLR-TAU

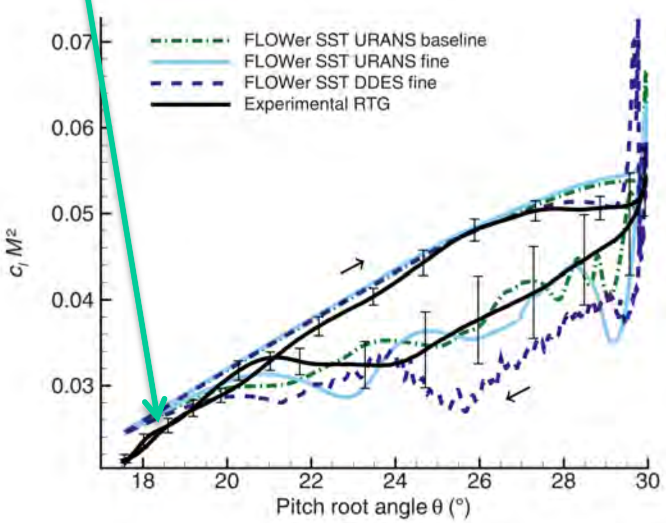
Test case: DSA-9A Rotor (RTG)

Follow-on to the Merz finite wing:

- Small-scale, rigid rotor
- High cyclic pitch with axial inflow
- Easy gridding, attached flow with rotor and farfield
- Computations DLR-TAU, IAG-FLOWer
- Small number of pressure sensors, root angle, forces
- High-speed PIV at 5 positions and 2048 azimuthal angles
- Comparability to DSA-9A airfoil data and computations; Merz finite wing
- Additionally: PSP, TSP (static cases)
- Also: DIT measurements and computations for pitching without stall
- Disadvantage: Rather low M_tip=0.23, Re_tip=4e5, BL Transition effect

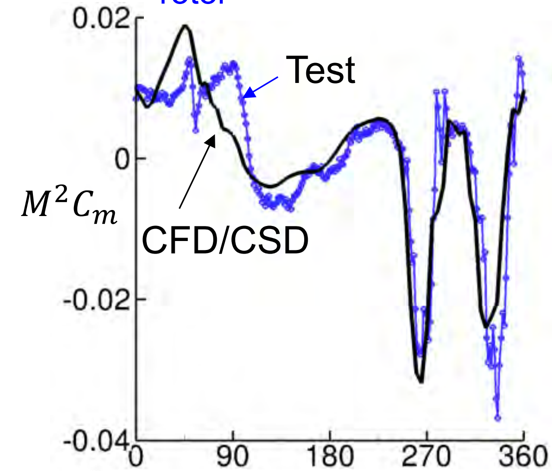






Rotor dynamic stall studies

Pitching moment at a stall condition for the UH-60A rotor



M. Potsdam et al., *AIAA Journal of Aircraft*, 2006

- Rotor computational are more expensive compared to 3-D wing
- Additional physics over non-rotating rigid wing
  - unsteady relative freestream
  - blade-vortex induced separation
  - torsion-dynamics induced stall
  - mix of leading-edge and trailing-edge stall
  - spanwise flow development
  - mixed reduced frequencies
  - Centrifugal/Coriolis forces
  - reversed flow stall
- Method requirements for rotor stall simulation
  - coupling between CFD and Comprehensive Analysis codes for trim and blade deformation
  - mesh deformation tool
  - overset techniques required, typically
  - accurate numerical method to capture blade vortices
  - good resolution in terms of spatial and temporal discretization
  - accurate RANS or hybrid RANS/LES models to capture flow separation
- Earlier high-fidelity coupled aero-elastic simulation carried out on the UH-60A rotor using the flight test data from NASA/Army UH-60A Airloads Program
  - M. Potsdam et al., AHS 60th Forum (2004) paper – rotor dynamic stall prediction using coupled aero-elastic methodology (CFD/CSD)
  - DARPA Helicopter Quieting Program participants (2004-2007)

Rotor stall experimental datasets

- Rotors
  - NACA0012 Rotor (Komerath et al.), UH-60A NFAC (**NASA/US Army**)
  - Bousman rotors (airloads) (**US**)
  - McHugh stall boundary test (CH-47B/C) (**US**)
  - RTG data (dynamic stall on rotor in axial flow) (**DLR**)
  - 7A, 7AD, ERATO rotors (**ONERA**)
  - GOAHEAD data (7AD rotor + NH90 fuselage + BO105 tail rotor) (**EU**)

7A rotor in S1MA wind tunnel

Bluecopter in flight

GOAHEAD in DNW-LLF wind tunnel

UH-60A in NFAC Wind tunnel And flight test

Recent prediction studies have focused on rotor stall

- Potsdam, M., Yeo, H., and Johnson, W., “Rotor Airloads Prediction Using Loose Aerodynamic/Structural Coupling”, Journal of Aircraft, Vol. 43, No. 3, May-June 2006, pp. 732-742
- Dietz, M. , Khier, W. , Knutzen, B., Wagner, S. and Krämer, E., “Numerical Simulation of a Full Helicopter Configuration Using Weak Fluid-Structure Coupling”, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 2008
- A.F. Antoniadis, D. Drikakis, B. Zhong, G. Barakos, R. Steijlb, M. Biavac, L. Vigevano, A. Brocklehurst, O. Boelense, M. Dietz, M., Embacher, W. Khierh, “Assessment of CFD methods against experimental flow measurements for
- helicopter flows”, Aerospace Science and Technology , Vol.19, pp. 86–100, 2012
- Yeo, H. and Romander, E., A., “Loads Correlation of a Full-Scale UH-60A Airloads Rotor in a Wind Tunnel, ”, Journal of the American Helicopter Society, Vol. 58, 022003, 2013
- Yeo, H., Potsdam, M., Ortun, B. and Van Truong, K., “High-Fidelity Structural Loads Analysis of the ONERA 7A Rotor”, Journal fo Aircraft, Vol. 54, No. 5, 2017
- Richez, F., and Ortun, B., “Numerical Investigation of the Flow Separation on a Helicopter Rotor in Dynamic Stall Configuration”, 42nd European Rotorcraft Forum, Lille, France, September 5-9, 2016
- Ortun, B., Potsdam, M., Yeo, H. and Truong, K., “Rotor Loads Prediction on the ONERA 7A Rotor using Loose Fluid/Structure Coupling”, Journal of the American Helicopter Society, Vol. 62, No. 3, July 2017
- Chaderjian N., “Navier-stokes simulation of UH-60A rotor wake interaction using adaptive mesh refinement,” in 73rd American Helicopter Society International Annual Forum and Technology Display, 2017
- Richez, F., “Numerical analysis of dynamic stall for different helicopter rotor flight conditions,” in 73rd American Helicopter Society Annual Forum, 2017
- Richez, F., “Analysis of dynamic stall mechanisms in helicopter rotor environment,” in Journal of the American Helicopter Society, vol. 63, 2018
- Grubb, A., C. Castells, C., Jain, R., Richez, F., and Smith, M., “High fidelity CFD analyses of dynamic stall on a four-bladed fully articulated rotor system,” 74th American Helicopter Society International Annual Forum and Technology Display, Arizona, USA, May 14-17, 2018, 2018
- Castells, C., Richez, F and Costes, M., “Numerical Analysis of RPM effect on Dynamic Stall Phenomena on Helicopter Rotor at High Thrust Forward Flight”, Vertical Flight Society 75th Annual Forum & Technology Display, Philadelphia, Pennsylvania, May 13–16, 2019.
- Letzgus, J., Keßler, M. and Kramer, E., “Simulation of Dynamic Stall on an Elastic Rotor in High-Speed Turn Flight”, Vertical Flight Society 75th Annual Forum & Technology Display, Philadelphia, Pennsylvania, May 13–16, 2019

Commonly used toolset in the numerical simulation of rotor dynamic

- Widespread use of CFD/CSD in the rotorcraft community
  - Coupled CFD-CSD (computational structural dynamics)
  - NASA: OVERFLOW-RCAS/CAMRAD II, FUN3D-RCAS
  - US Army: CREATE-AV Helios with RCAS and CAMRAD II
  - University of Maryland CFD and CSD codes, DYMORE, TURNS…
  - Georgia Tech codes : FUN3D-RCAS, OVERFLOW/CSD with CHARM
  - DLR : TAU-HOST and FLOWer-HOST
  - ONERA: elsA-HOST
  - IAG (University of Stuttgart): FLOWer-CII and FLOWer-HOST
  - UK (University of Glasgow): HMB solver

CFD/CSD studies performed

Rotor or H/C	Flight condition			Authors	Codes	Validation data			
	Maneuver	CT/σ	μ			Control angles	Airloads	Structure loads	Pitch link loads
UH60A rotor	Forward flight	0.129	0.24	Potsdam et al., 2006	CII/Overflow-D	x	x	x	x
EC145 complete H/C	Turn flight	0.14	~0.25	Dietz et al., 2008	CII/FLOWer	x		x	
GOAHEAD	Forward flight	?	0.31	Antoniadis et al., 2012	HOST/FLOWer HBM		x		
UH60A rotor	Forward flight	0,125 5	0.3	Yeo et al., 2013	CII/Overflow 2	x	x	x	x
7A rotor	Forward flight	0.1	0.36	Yeo et al., 2017 Ortun et al., 2017	HOST/elsA RCAS/Helios	x	x	x	
UH60A rotor	Forward flight	0.126	0.237	Chaderjian, 2018	CII/Overflow 2		x		
7A rotor	Forward flight	0.1	0.36	Richez, 2018	HOST/elsA	x	x	x	
		0.1	0.36	Grubb et al., 2019	RCAS/FUN3D RCAS/Helios HOST/elsA	x	x		
		0.095	0.42						
		0.09	0.288	Castells, 2019	HOST/elsA	x	x	x	
		0.1	0.3						
		0.11	0.315						
Bluecopter	Turn flight	0.145	0.35	Letzgus, 2019	CII/FLOWer	x			x
UH-60A	Maneuver			Bhagwat (2007) Sitaraman (2017)	OVERFLOW/RC AS Helios/RCAS	x	x	x	x

ONERA 7A rotor wind-tunnel tests

- 7A Rotor was tested in high speed and high thrust conditions
- Separated flows with various strengths triggered by various mechanisms
- Wind tunnel condition

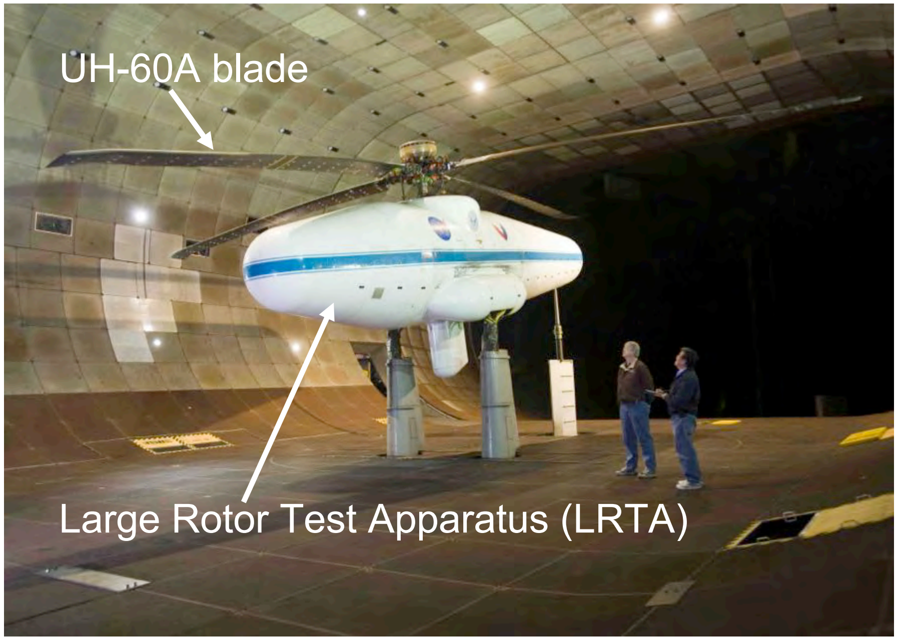
	Moderate DS (tp 293)
α_q	-6.7
θ_0	8.4
θ_{1C}	3.16
θ_{1S}	-3.51
M_{tip}	0.646
μ	0.3
C_L/σ	0.100
C_X/σ	0.0046
Flapping law	$\beta_{1S} = 0$ $\beta_{1C} + \theta_{1S} = 0$

7A ROTOR
ONERA S1MA WIND
TUNNEL
MODANE, FRANCE 1991

UH-60A airloads tests in the NFAC wind tunnel

- Test points
  - Speed sweep
  - High advance ratio
  - Thrust sweep
    - μ = 0.3
    - M_{tip} = 0.625
    - α = 0 deg
    - C_T/σ = 0.02 to 0.125 (θ_0 = 0.9 to 12.3 deg)
  - Measured data
    - Airloads at the nine stations
    - Rotor performance
    - Hub forces and moments
    - Structural loads at the nine measured stations
    - Blade deformations/displacements (for C_T/σ = 0.1 only) (PIV data not available for high-speed thrust sweep)

UH-60A Airloads Rotor Test in
USAF NFAC 40- by 80- Foot Wind Tunnel
Ames Research Center, USA, 2010

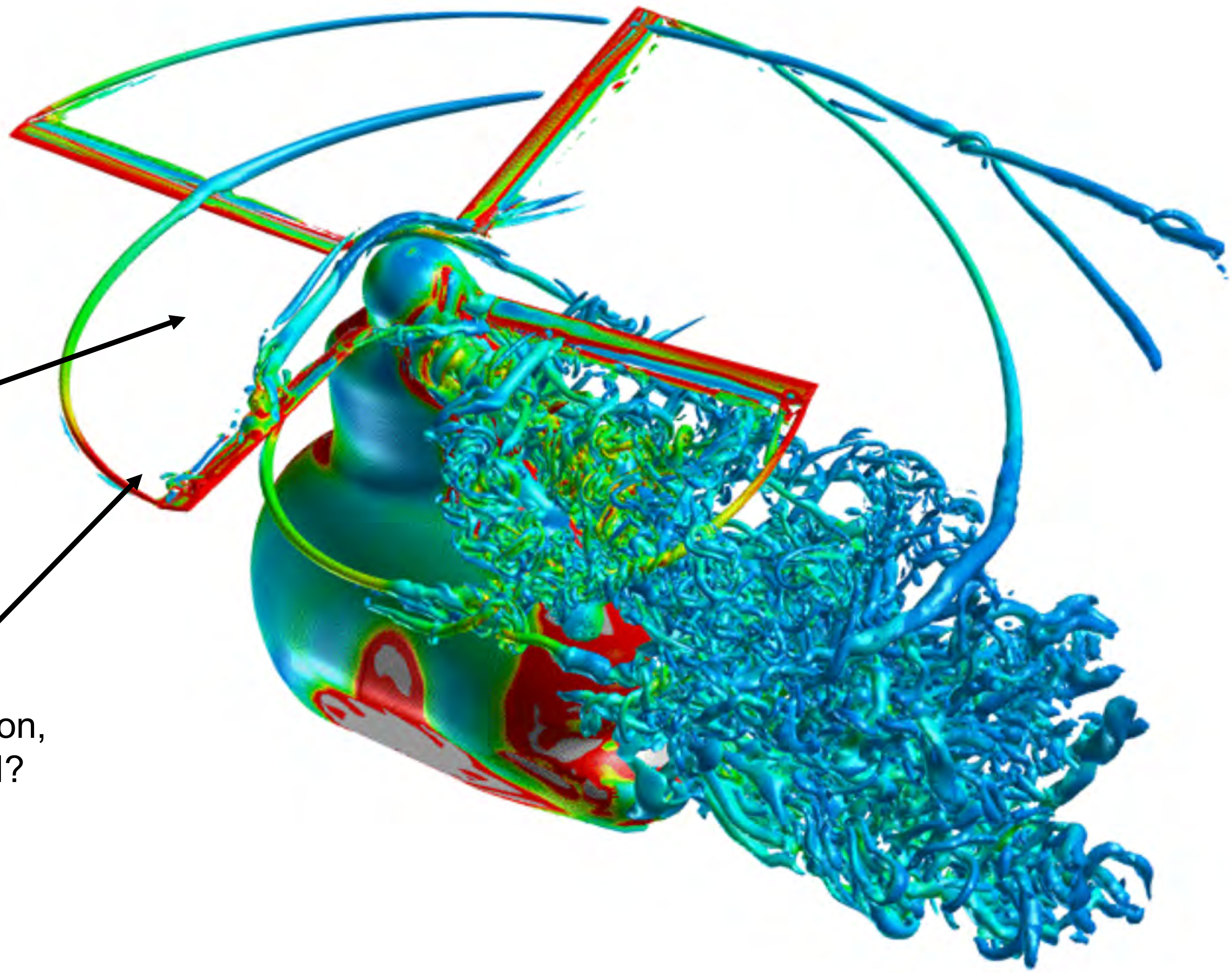


Reference: Tom Norman et al., “Full-Scale Wind Tunnel Test of the UH-60A Airloads Rotor,” 67th AHS Forum, 2011.

7A rotor flow animation (CFD, Helios)

C_T/σ **= 0.10**

wind

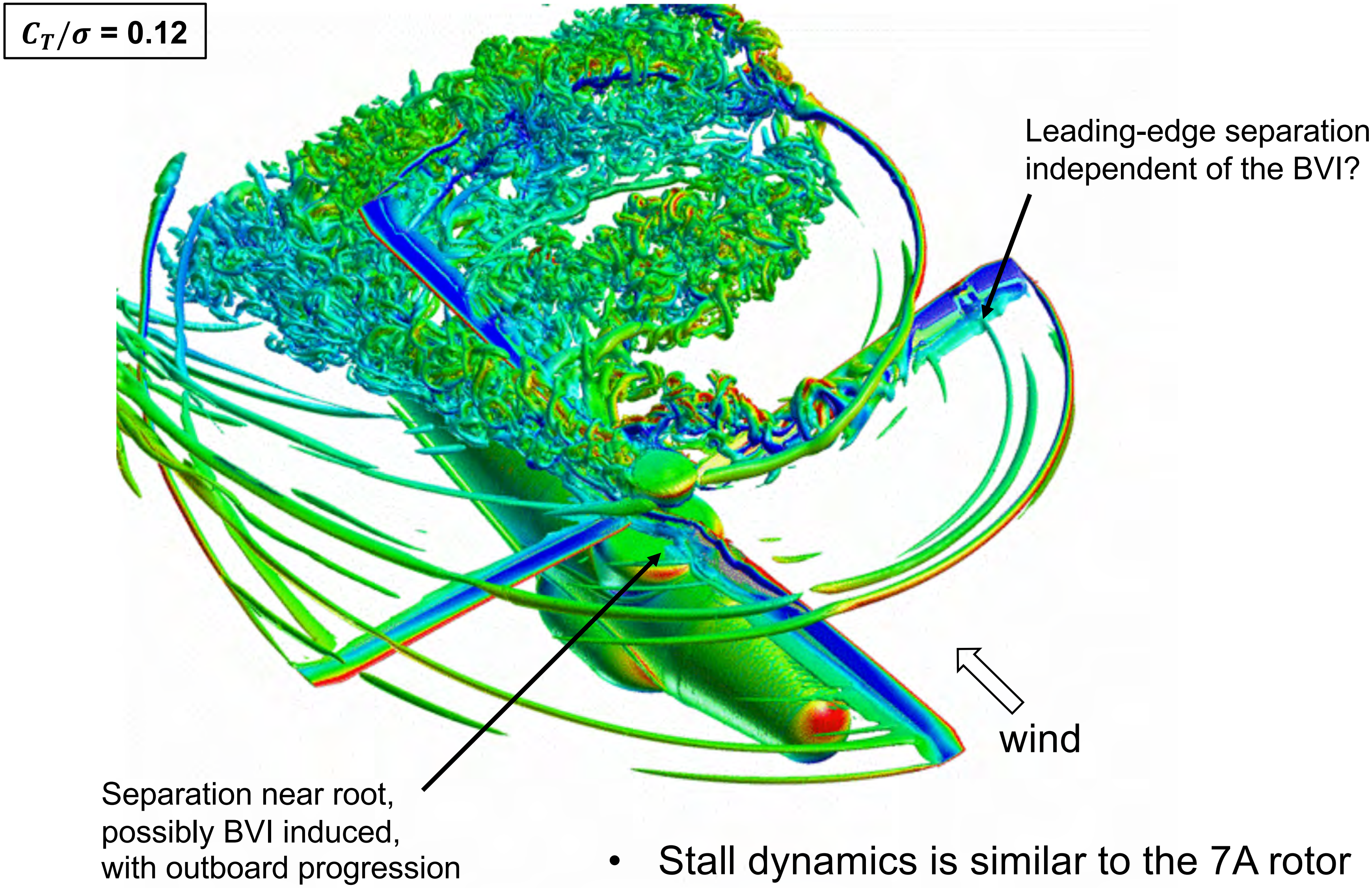


Separation at mid span, possibly BVI induced, with outboard progression

Leading-edge separation, independent of the BVI?

7A rotor wake animation by US Army (Helios)

UH-60A rotor flow animation (CFD, Helios)



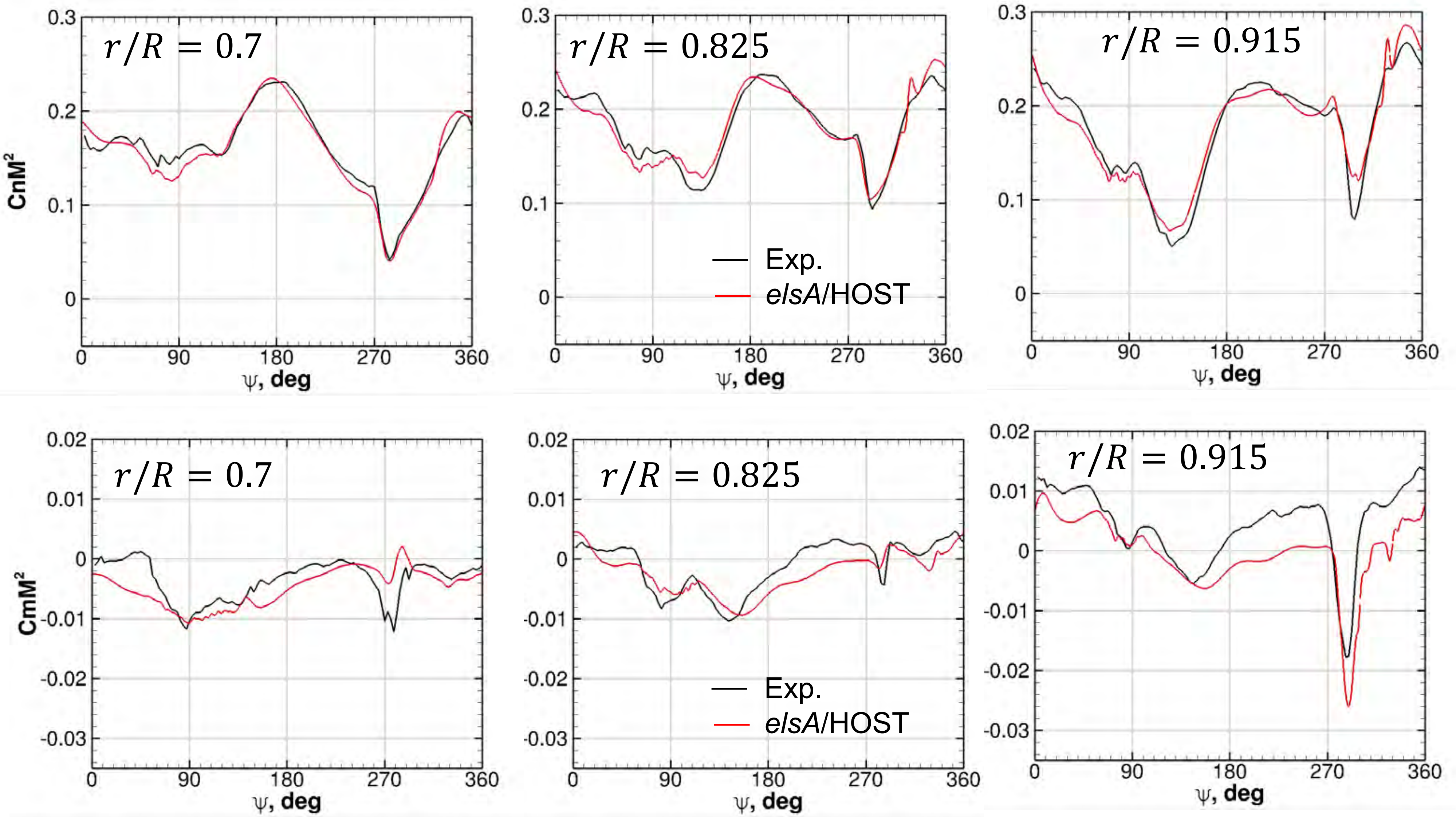
- Stall dynamics is similar to the 7A rotor

UH-60A rotor wake animation by US Army (Helios)

Numerical simulation of dynamic stall in rotor environment

- **Validation : airloads**

Richez, JAHS, 2018

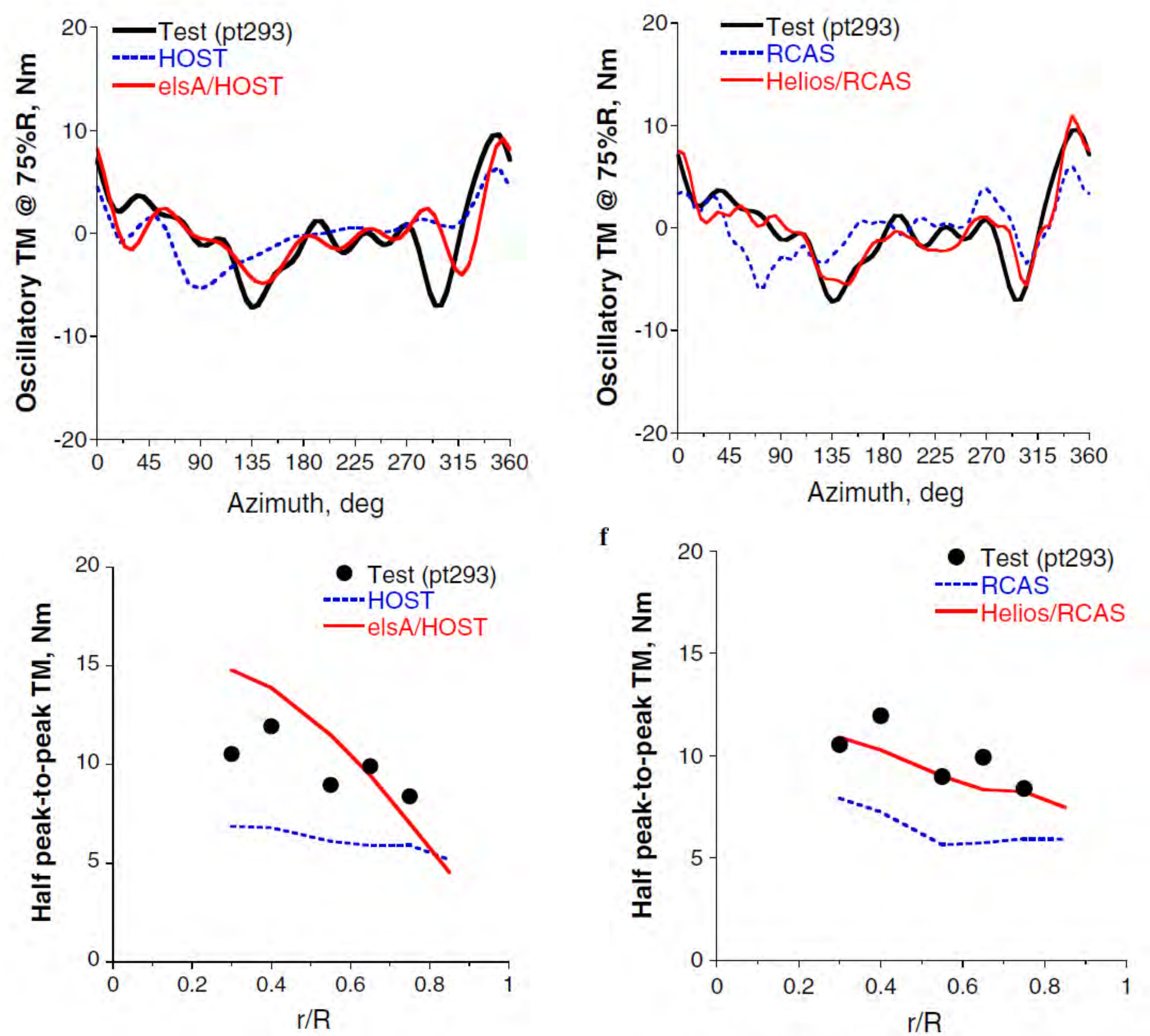


⇒ Good agreement for both lift and pitching moment coefficients

Numerical simulation of dynamic stall in rotor environment

Yeo et al., JoA, 2017

- **Validation : structural loads**



c) Torsion moment

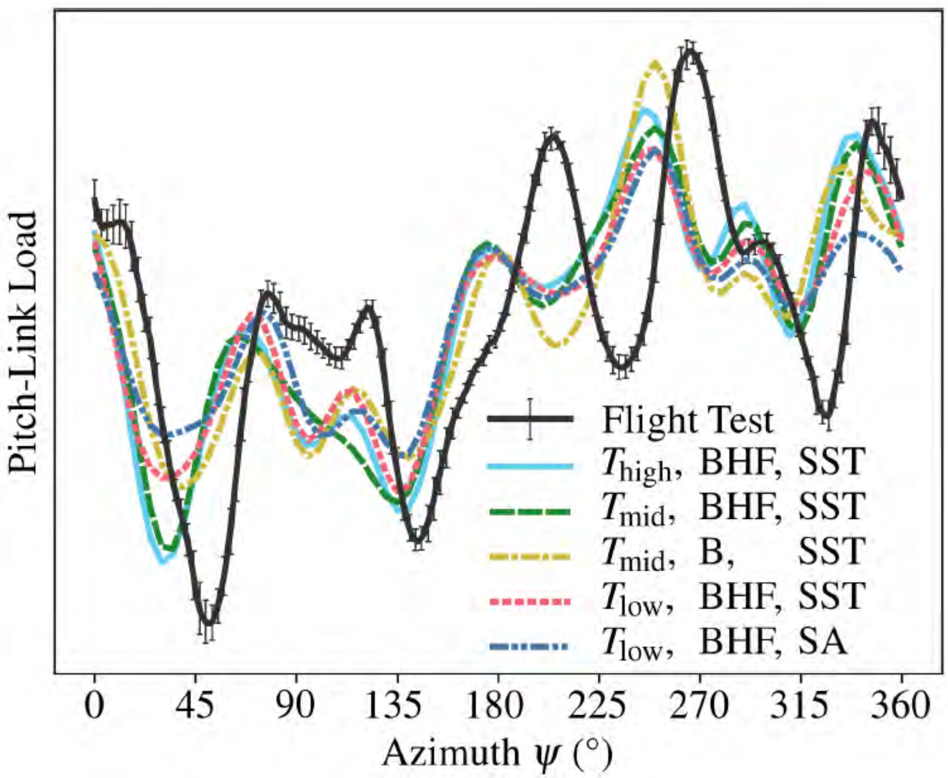
c) Torsion moment

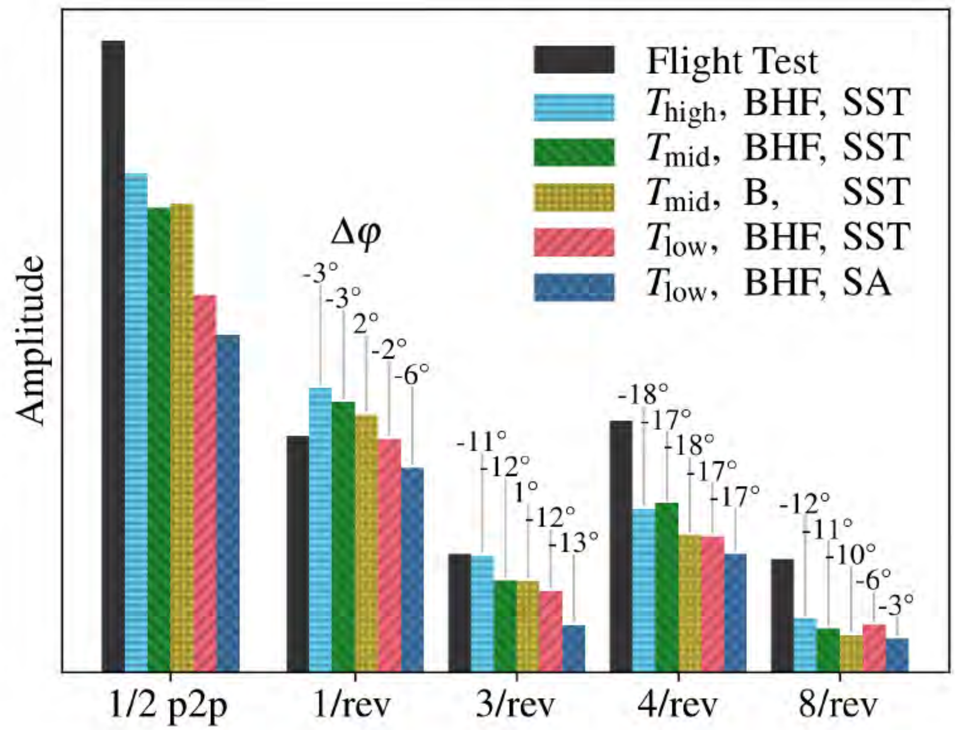
⇒ Clear improvement of structural loads with CFD compared to pure CA code

Numerical simulation of dynamic stall in rotor environment

- **Validation : pitch-link loads**

Letzgus et al., AHS, 2019





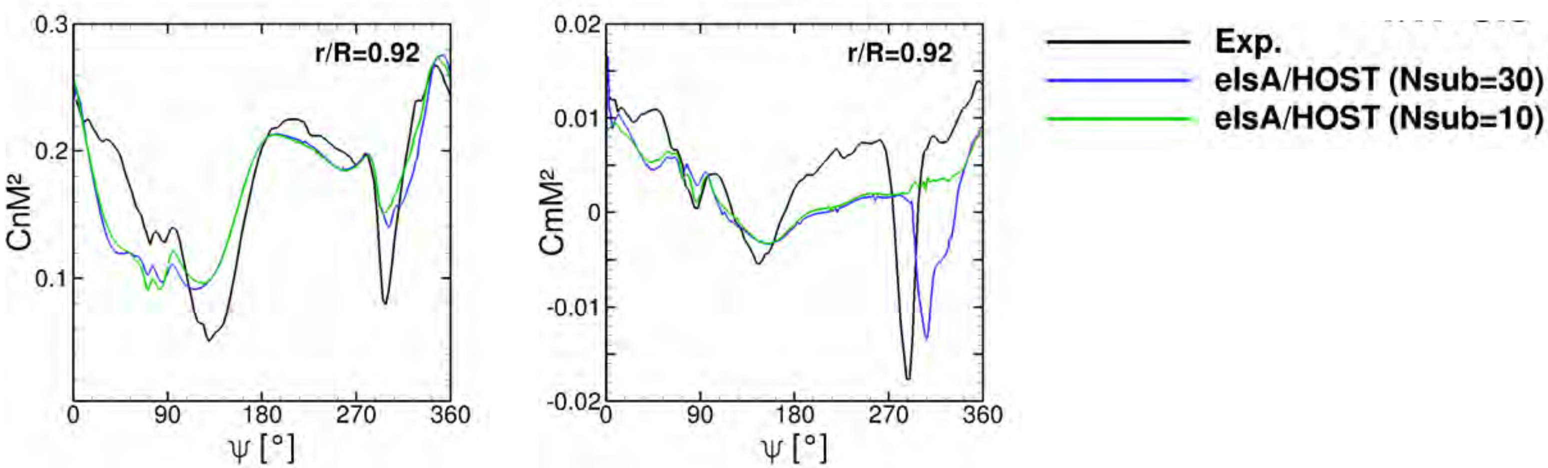
⇒ Satisfactory agreement on pitch link loads

⇒ but difficult to validate because to the structural model of the pitch-link or swashplate is often too simple and this has a strong impact on the prediction

Numerical simulation of dynamic stall in rotor environment

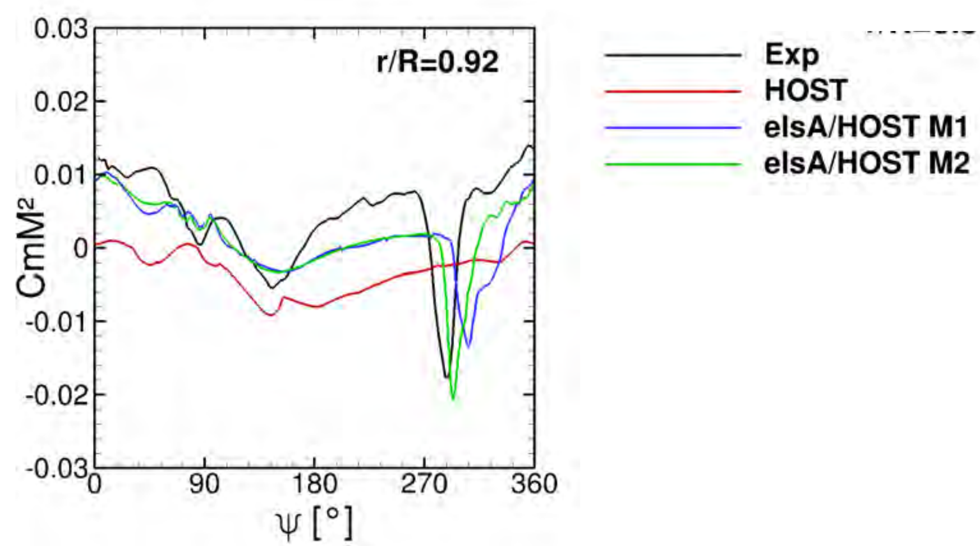
- **Sensitivity to the numerical methods**
  - Influence of the number of sub-iteration of the Newton process
    Gear second order time scheme with $\Delta\psi = 0.3°$

Richez et al., ERF, 2016



  - Influence of the blade grid refinement

	7A rotor M1	7A rotor M2
Number of points per blade grid	3.1 M	5.7 M
Total number of points	22.6 M	43.6 M
N around airfoil	217	313
N over the blade span	141	155
$\Delta x/c$ at leading edge	0.23%	0.11%
$\Delta x/c$ at mid chord	2.6%	1.6%
$\Delta z/c$	13%	5.6%
$\max(\Delta y^+)$	1.5	0.4
N in the boundary layer at mid chord	30	35

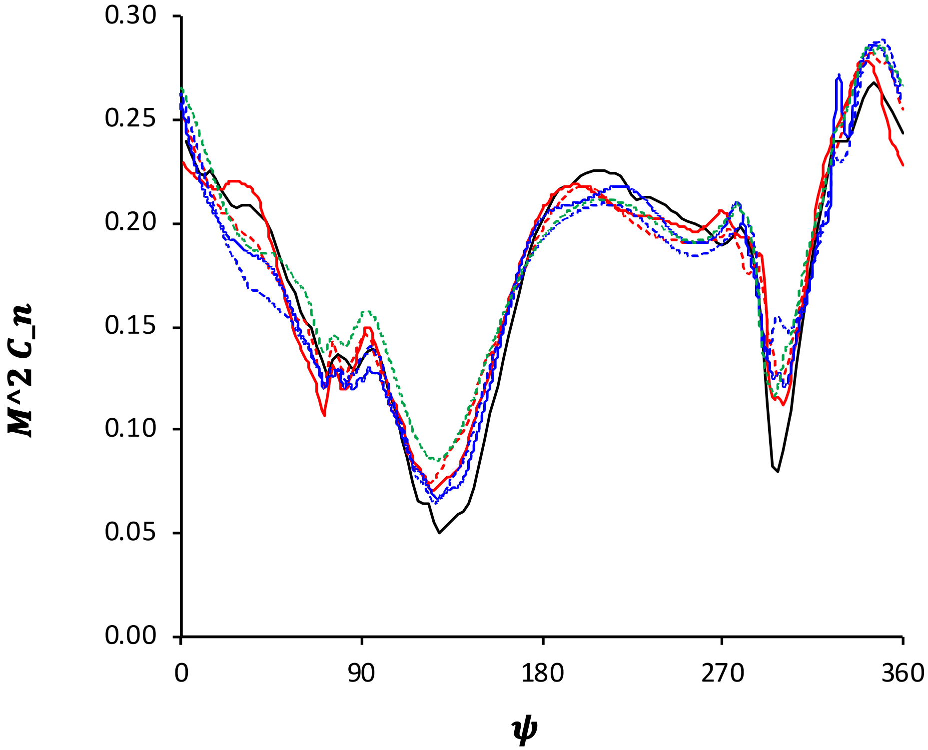


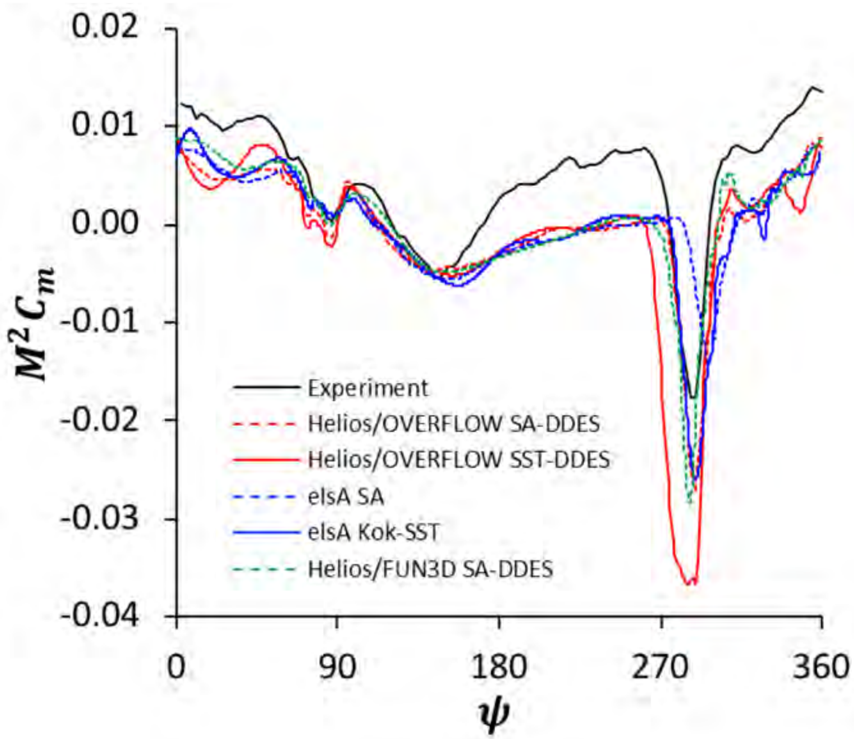
$\Rightarrow$ High sensitivity of the solution

Numerical simulation of dynamic stall in rotor environment

Grubb et al., AHS, 2018

- **Code-to-code comparison**

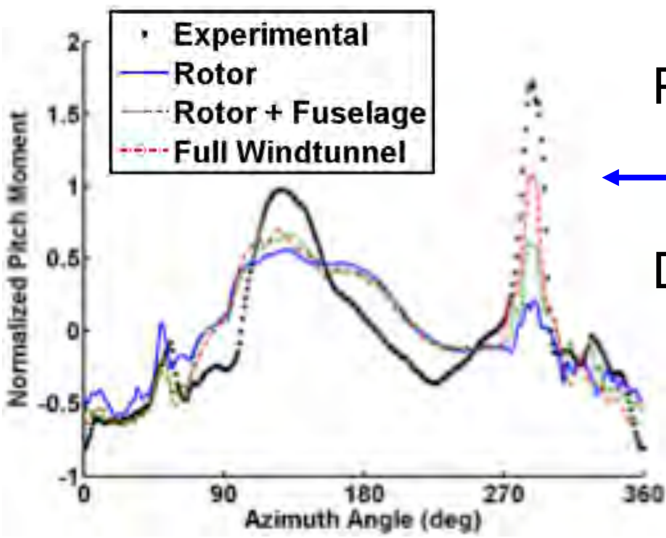




- Good overall agreement between codes
- Main differences due to RANS vs. DDES
- Good correlation obtain when experimental pressure integration was used and test stand was included

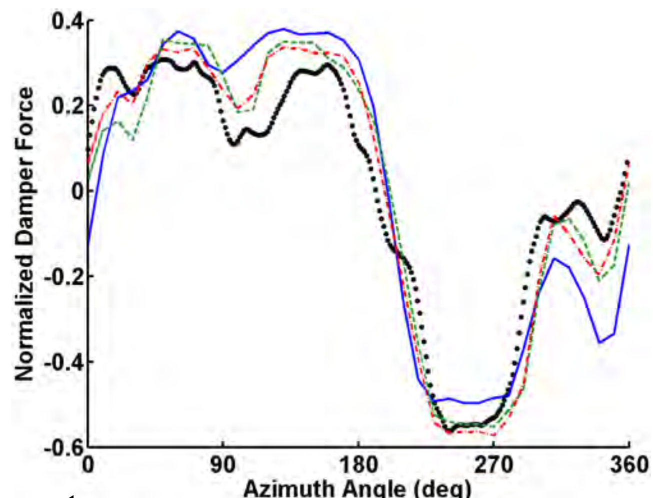
Dual-Solver Hybrid Approaches

- OVERFLOW/CSD+CHARM can provide results within 4% of full CFD/CSD at 30%-50% of cost for full rotor
- Comparable accuracy for normal force, pitching moments, bending moments (3 directions), and hub loads unlike earlier generation hybrid approaches
- Wake interactions appear to be more accurately captured with CHARM wake
- Modeling the wind-tunnel and fuselage can impact dynamic stall behavior
- Integration of data at pressure ports and use of damper model used in experiments needed to capture dynamic stall behavior correctly



Pitching Moment

Damper Force



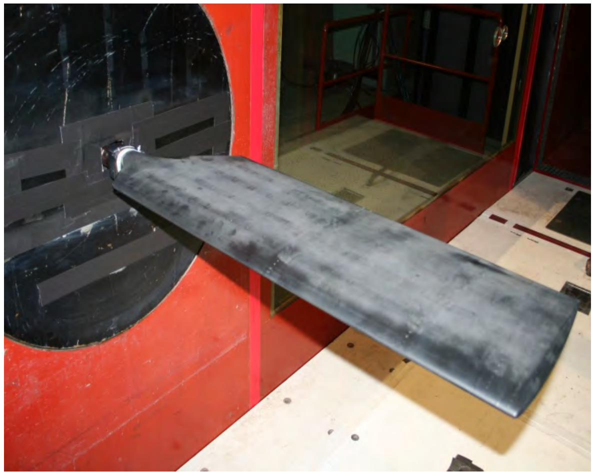
tp 4540 – high thrust

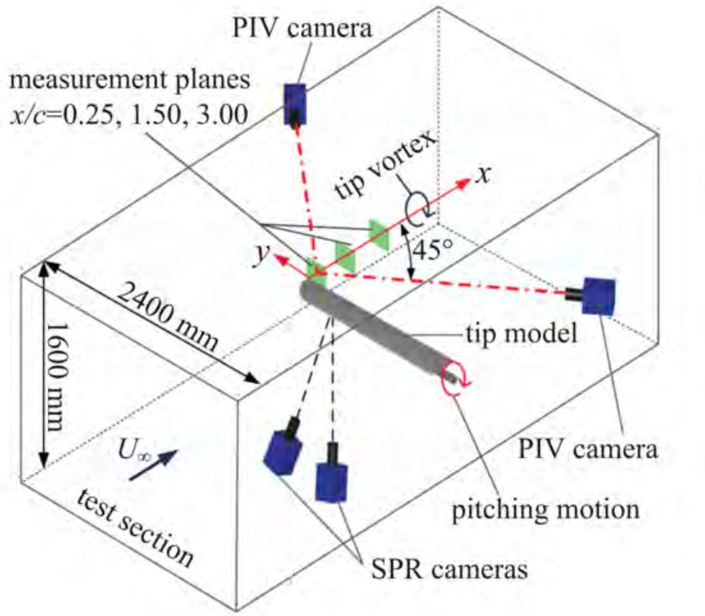
Ref: B-Y Min et al., "Toward Improved UH-60A Blade Structural Loads," 74th AHS Forum, 2018.
Wilbur et al., "UH-60A Rotor Analysis with an Accurate Dual-Formulation Hybrid Aeroelastic Methodology," Journal of Aircraft, revisions submitted.

LESSONS LEARNED

CFD design of experiments

- It was noted during the work on the ONERA finite wing that the wall connection was a source of difficulty.
- This resulted in the development of the DLR finite wing
  - Smooth wall connection
  - Positive twist
  - Extensive FEM analysis leading to a stiffer model
  - Better sensor placement (using CFD)
  - Wing tip with easier to grid geometry
- DLR noted that the CFD effort to grid and compute the DLR wing to a similar level of accuracy is much smaller than for the ONERA wing, showing a significant improvement in experimental design through CFD





Lessons learned from CFD of stall in rotor environment

- **2-D dynamic stall modeling is not representative of the inherent 3-D stall phenomena**

- **Requirements in terms of turbulence modeling**
  - Some sensitivity with respect to turbulence model
  - URANS k-ω model is preferred compared to Spalart-Allmaras
  - URANS or DDES or hybrid RANS/LES? No clear answer today
  - Transition does not seem to have a significant impact, at least with current transition models

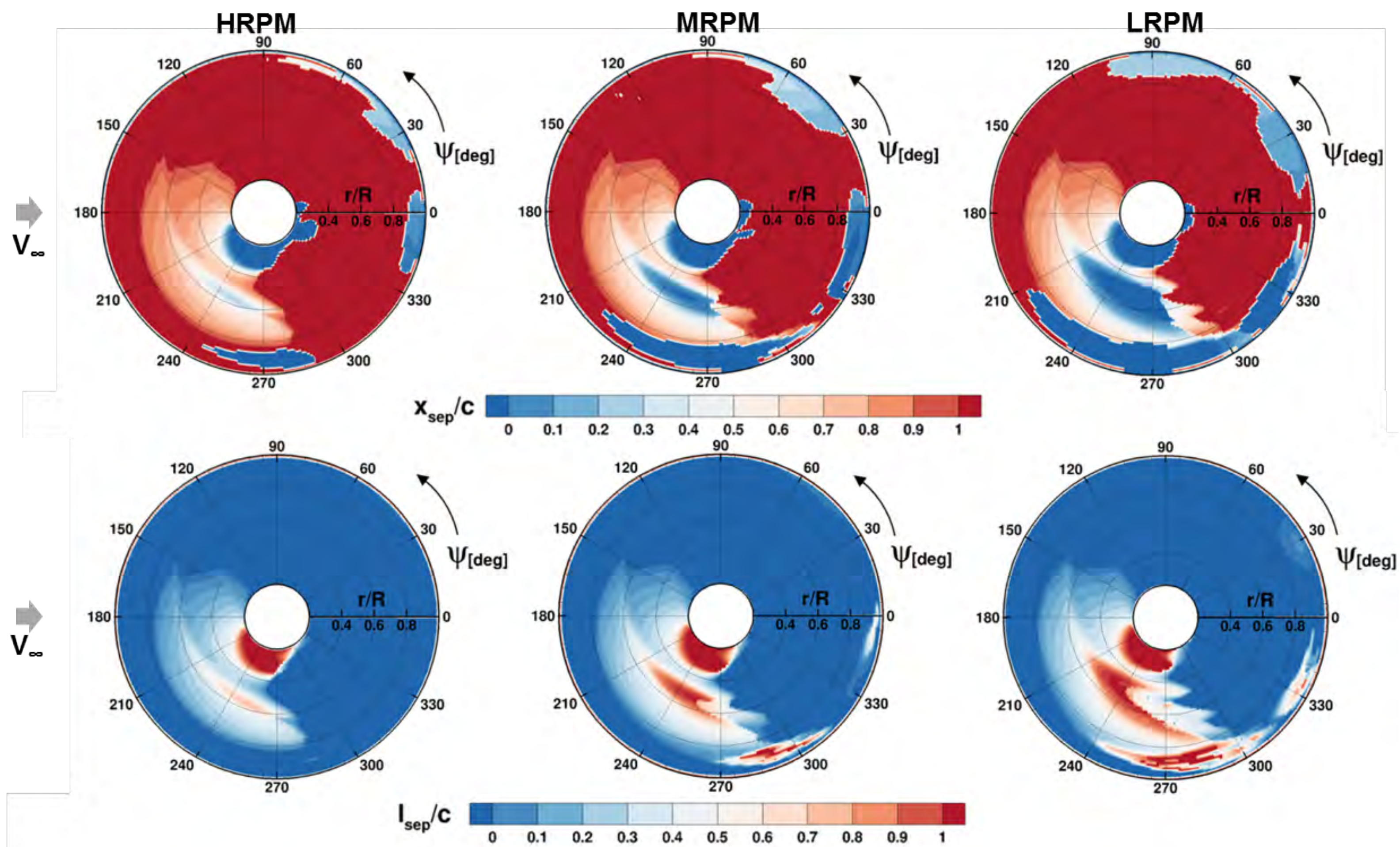
- **Requirements in terms of numerical methods**
  - Strong dependency of the solution with respect to time resolution and space resolution of the blade grid
  - Grid resolution of $\Delta x/c = 10\%$ in the Cartesian grid seems sufficient

- **Maturity of CFD to predict rotor stall**
  - For $\mu \sim 0.3$ and $C_T/\sigma \sim 0.1$
    - CFD provides very satisfactory results in terms of airloads on outboard blade sections
    - The inboard stall is not that well captured (lower Mach number and Reynolds number)
  - For higher advance ratio and higher thrust:
    - Section pitching moment peaks can be overestimated or be phase-shifted
  - CFD is not validated to predict the stall boundary (more difficult to predict airloads when stall is moderate, easier when stall is deep)
  - The capability to predict rotor dynamic loads in dynamic stall condition can also be limited by inadequate structural modeling of the pitch-link and swashplate

Lessons learned from CFD of stall in rotor environment

- **Physics of dynamic stall in rotor environment**
  - CFD has provided non-intrusive measurements that help our understanding of stall phenomenon in rotor environment
  - Rotor map of flow separation position and flow separation length

Castells et al., AHS, 2019

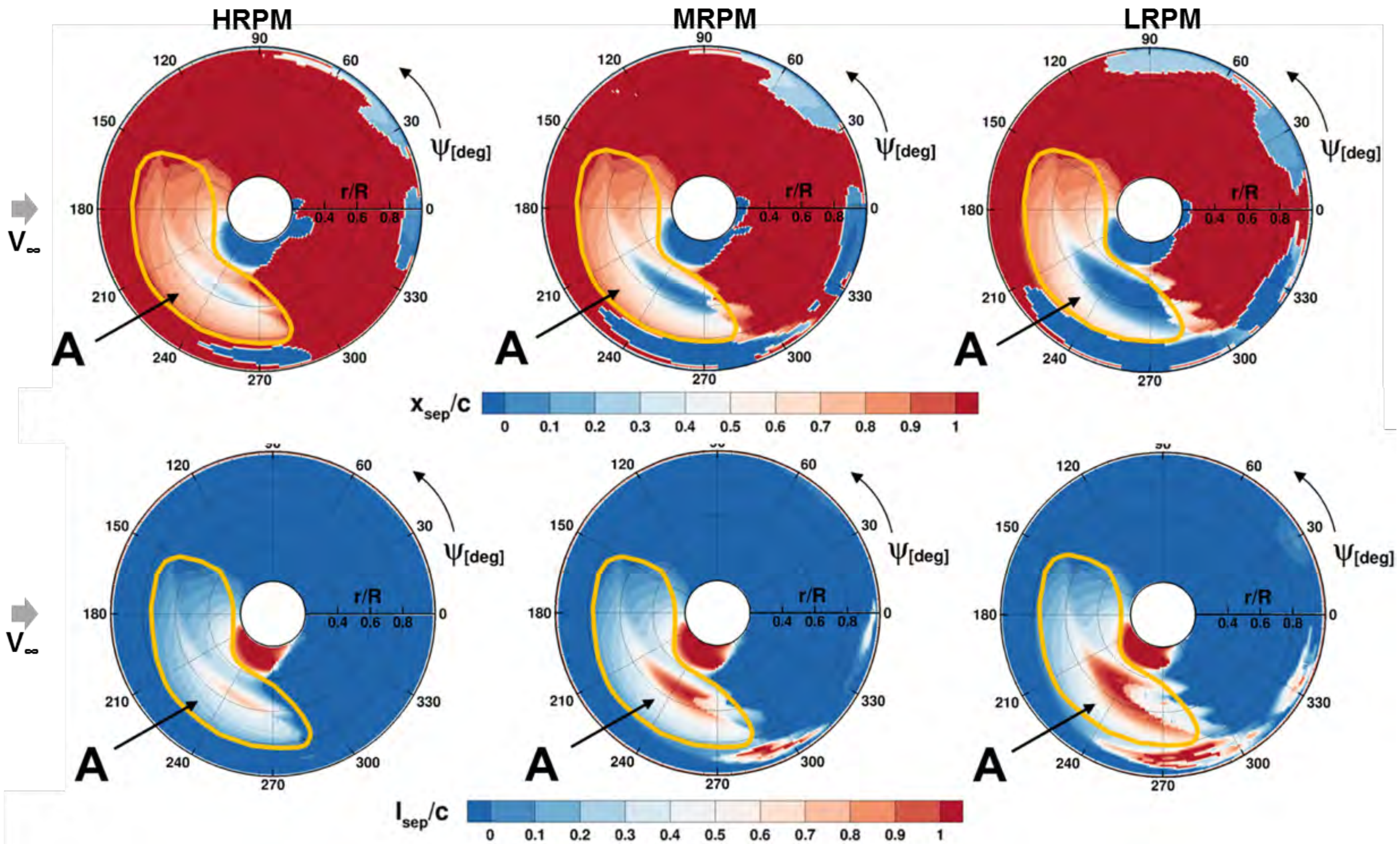


⇒ Several flow separation regions and several stall regions

Lessons learned from CFD of stall in rotor environment

- **Physics of dynamic stall in rotor environment**
  - CFD has provided non-intrusive measurements that help our understanding of stall phenomenon in rotor environment
  - Rotor map of flow separation position an d flow separation length

Castells et al., AHS, 2019

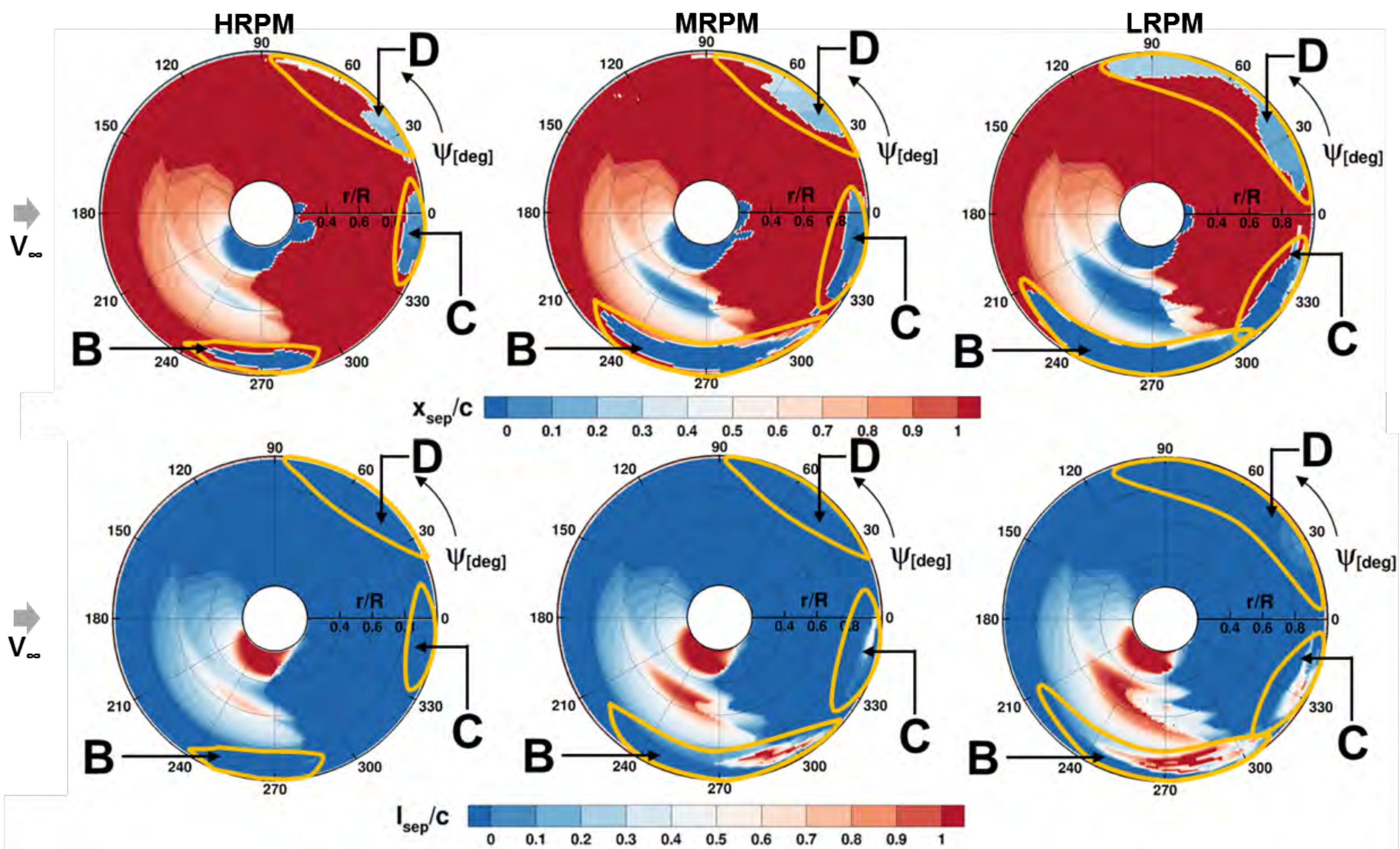


⇒ One stall event on the inboard sections

Lessons learned from CFD of stall in rotor environment

- **Physics of dynamic stall in rotor environment**
  - CFD has provided non-intrusive measurements that help our understanding of stall phenomenon in rotor environment
  - Rotor map of flow separation position an reattachment

Castells et al., AHS, 2019

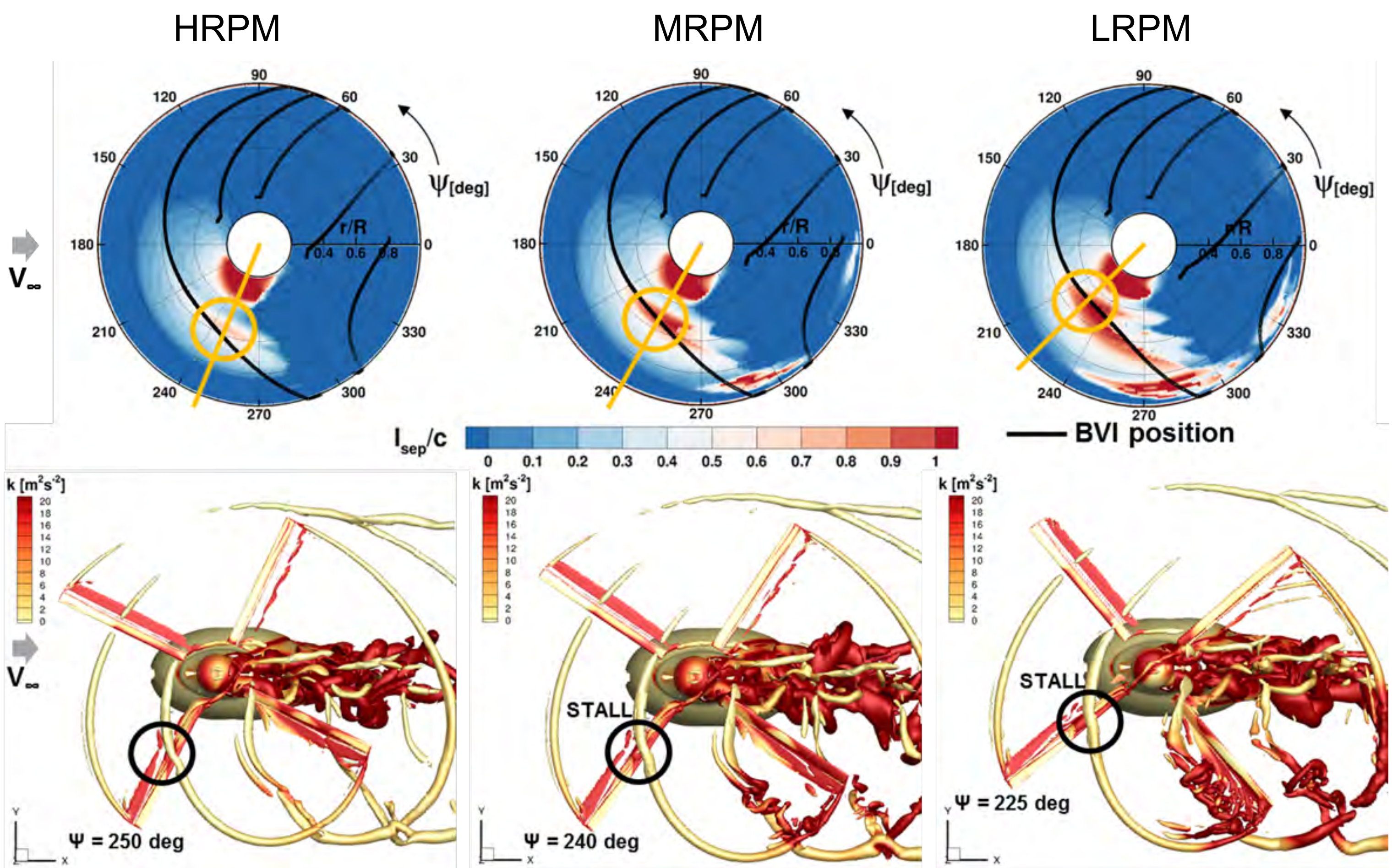


⇒ Several separated flow regions on the outboard sections (with possible several stall events)

Lessons learned from CFD of stall in rotor environment

- **Physics of dynamic stall in rotor environment**
  - CFD has provided non-intrusive measurements that help our understanding of stall phenomenon in rotor environment
  - Link between blade vortex interaction and stall onset

Castells et al., AHS, 2019

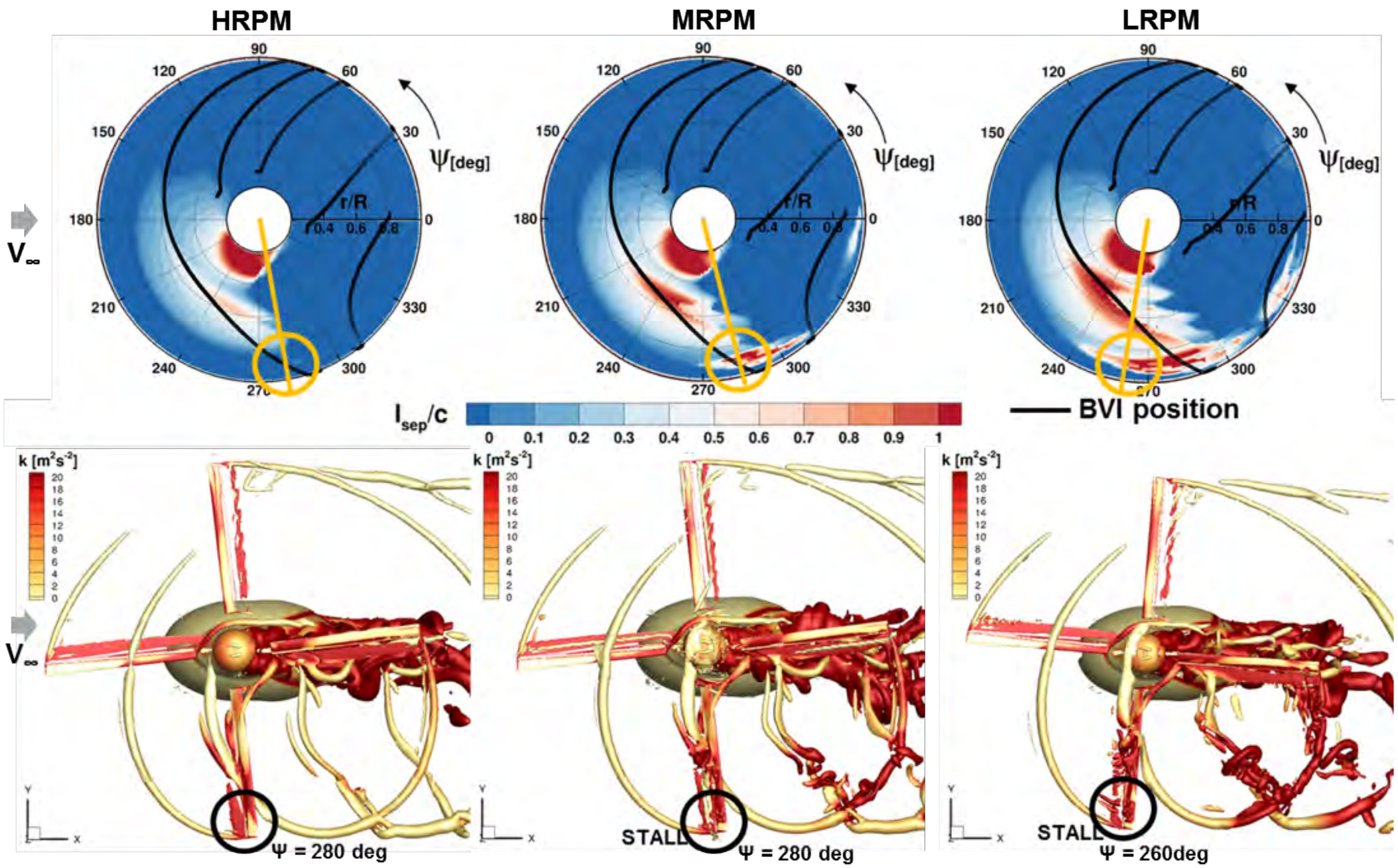


⇒ Blade vortex interaction triggers stall on the inboard sections

Lessons learned from CFD of stall in rotor environment

- **Physics of dynamic stall in rotor environment**
  - CFD has provided non-intrusive measurements that help our understanding of stall phenomenon in rotor environment
  - Link between blade vortex interaction and stall onset

Castells et al., AHS, 2019



⇒ Blade vortex interaction may trigger stall on the outboard sections… or not?

DISCUSSION

What do we need now for rotor stall simulation?

- **More validations**
  - Low speed and higher speed case
  - Prediction of the stall edge
- **Method improvement**
  - Lack of accuracy of flow separation on the inboard sections
  - Influence of laminar-turbulent transition?
  - Is tight CFD/CA coupling necessary or is loose coupling sufficient?
  - Is RANS enough or do we need RANS/LES?
- **Other stall conditions**
  - High μ with strong reverse flow stall
  - Few validation on turn flight cases
  - Dynamic stall for small rotor (UAV)?
- **Physics understanding**
  - Has BVI always a critical effect on dynamic stall?
  - Is flow separation just an excitation of blade torsion or is it an coupled aeroelastic global instability?

Future directions

1. Are there test cases which we can agree on as reference data for a particular effect?
    - Can we avoid duplication of effort or dissipation due to use of many similar but not identical test cases?
    - Examples:
        - 7A Rotor for vortex induced stall
        - Stiff rotor?
        - Finite wing dataset?
        - Flow control and measurement technique development testbed?
        - A-B comparison pairs for tool industrialisation?
2. Can we identify test cases as desirable, which have not yet been performed (or need higher effort/quality or open data availability or no experiments exist as yet)?
    - Vacuum tests for structural models in the rotating system?
    - Are there propeller data sets which would be useful?
    - Is there a need for rotor data sets which are trimmed to collective angle rather than trimmed to thrust?
    - Is there a need for data sets at M>0.5?
    - What describing numbers do we need:
        - From Pressure/Force: CLmax, CMmin, Averages, Integrals
        - From PIV: Circulation (bound/unbound), Separation point, bounding streamline
        - Other: Vortex minimum pressure?

Future directions

3. Can we identify any test case types as superfluous for the future?
    - Is the pitching airfoil now dead?
    - Are pitching wing and rotor measurements without root angle and deformation measurements useful?
    - Are rotor measurements without root angles and a validated structural model useful?

End goals of dynamic stall modeling & predictions

- Improved prediction capability for unsteady flow separation, in general
  - Rotors, hub, fuselage, propellers and their interactions
  - An important question in this regard is – employing best practices in the realm of hybrid RANS/LES modeling what is confidence level in predicting the rotor stall map of a "new" untested rotor design?
  - What are the considerations that should be given in future to increase the confidence level in predictions?
  - What are the modeling as well as physical uncertainties to be considered in predictions?
  - Does modeling practices developed for isolated rotor carry forward to the analyses of full vehicles in terms of accuracy and simulation cost affordability? Including aero-elastics is important.
- Accurate prediction on rotor stall boundary in hover and forward flight
  - Improved Hover out-of-ground-effect (HOGE)
  - Better cruise efficiency
  - Lower drag
  - Higher speed
  - Better lift capability

End goals of dynamic stall modeling & predictions

- Transition of the tools/expertise to the industry
  - DLR tests have shown that correct A-B comparisons for (Which of two potential designs is better) result from a factor 10 fewer cells, factor 10 coarser timestep and are reliable across solvers and turbulence models
  - Should we be investing more effort into low-fidelity tools, for example combining CAMRAD with 2D unsteady CFD instead of BEM

Questions?

On the use of high order FE methods for 3D dynamic stall simulation over rotating blades

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ERAU

GT-ARO Dynamic Stall Workshop, Atlanta GA, Sept. 10– 11, 2019

Question 1: What progress has been made?

1. The current state of the art in understanding dynamic stall and its control through computations is use implicit LES or high fidelity simulations with LES-like resolution of relatively low aspect ratio pitching and oscillating wings at low Reynolds numbers where transitional flow effects are important

2. These computational investigations have been pioneered and are carried out at at AFRL by Visbal and his collaborators for dynamic stall over wing sections or for low aspect ratio oscillating or rapidly pitching fixed wing using high order accurate (6^{th} – order) finite-difference numerical methods and explicit filtering

3. The AFRL computational studies have demonstrated that at least for low aspect ratio wings three dimensional effects are important both for flow separation and dynamic stall flow structure. As a result at this point 2D URANS simulations cannot offer much in further understanding dynamic stall of high aspect ratio wings or sections rotating blades that has been investigated in simulations and experiments.

Question 2: How does your current research fit in?

- Computational investigation of dynamic stall over rotating blades is important because it encompasses features significant to helicopter rotor that are not present in dynamic stall over oscillating rigid or flexible wings

Synopsis and outlook of high order FE methods for the investigation 3D DS

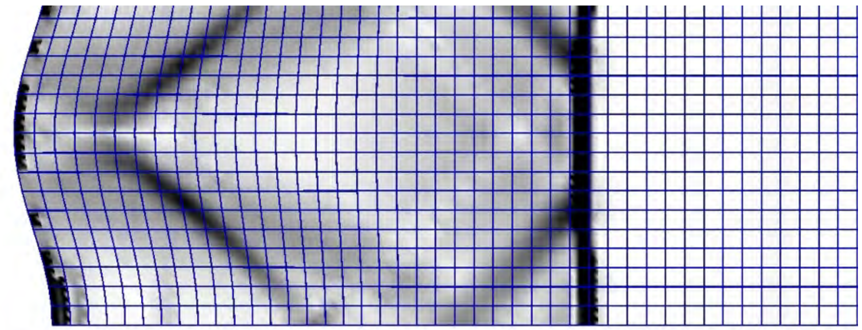
- Use of FE methods with subgrid models or implicit LES and AMR based on density or entropy variations of coherent smooth flow features present in dynamic stall is a key element for reducing computational cost of simulations.

- Combined dynamic h/p refinement can be applied for problems with embedded smooth but complex flow features of dynamic stall to increase the efficiency and effectiveness of FE discretizations without compromising numerical accuracy in order to reduce computational cost for very large scale computations required for large scale simulations of 3D dynamic stall and its control

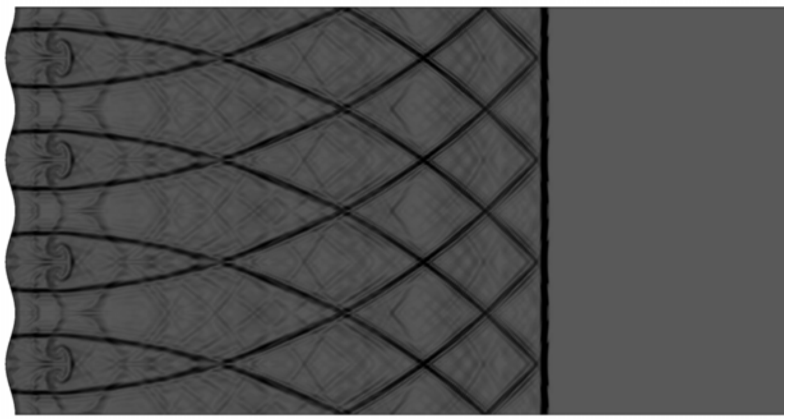
- Furthered enhancements are expected from the application of isogeometric approach and its implementation to 3D dynamic stall including fluid structure interaction

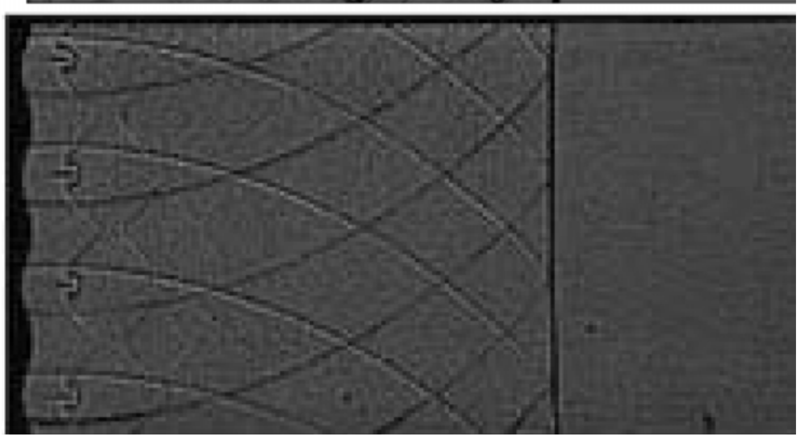
- Detailed experimental measurements of 3D dynamic stall of oscillating and rotating rigid and flexible blades or complete rotors are necessary to support findings of simulations

Reflection of a M=2 shock from a wavy wall



Computed density gradient numerical schlieren using a P9 (10^{th} order) numerical solution on a rather coarse mesh

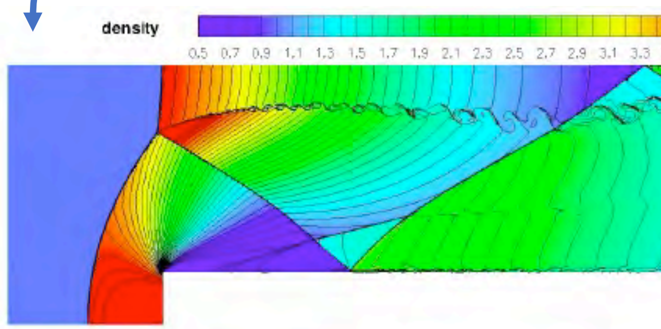


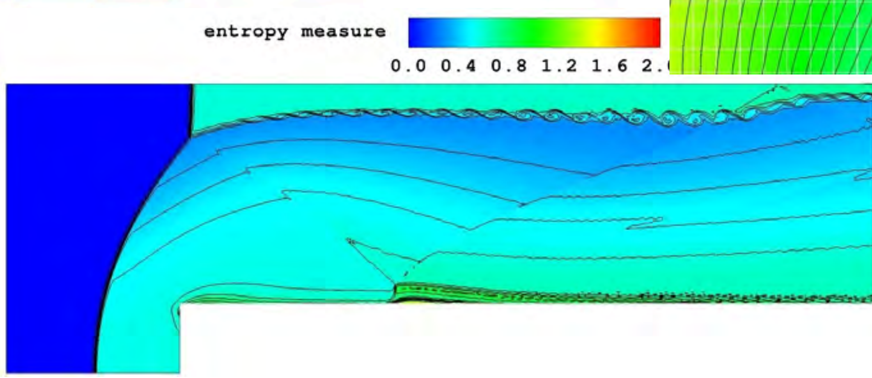


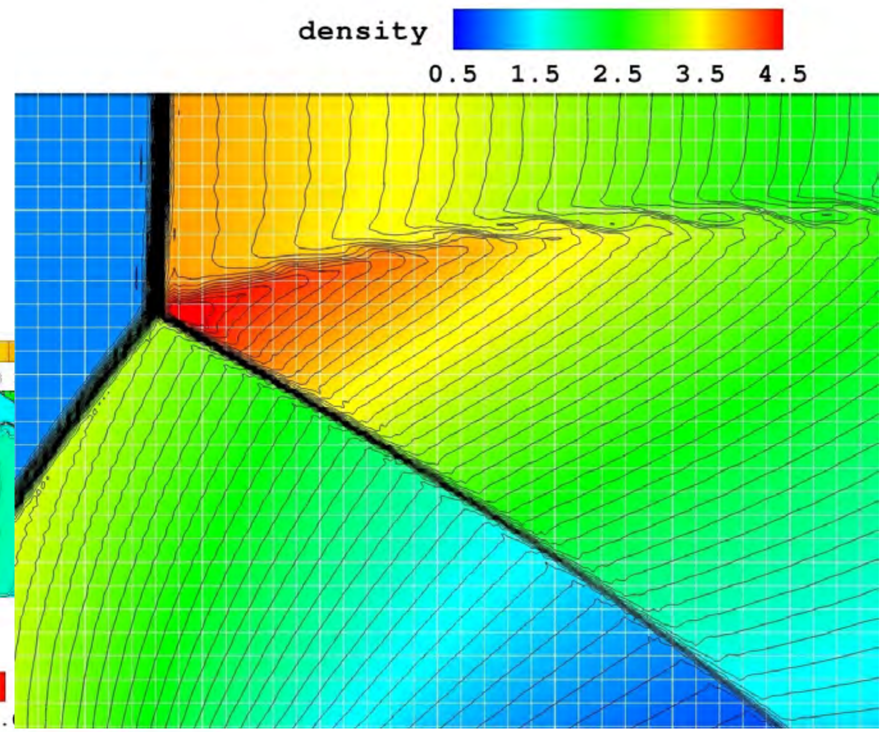
Experimental sclieren

Flow at M = 3 in a tunnel with a step

P1 adaptive
h = 1/ 640
at shocks and slip lines







P5 h = 1/ 50

Question 3: What is Next?

- What physics are still needed to be understood ?
  - The development of 3D separation including effects of transition and the flow field structure over rotating blades

- What research still needs to be done?
  - Synergetic investigations including detailed experimental measurements that can support high fidelity numerical simulations of dynamic stall over rotating blades

- What roadblocks do you see preventing us from eliminating or controlling Dynamic Stall?
  - For dynamic stall over blades at relatively low Reynolds numbers the control authority available in existing flow control concepts, such synthetic jets and DBD, can help control of dynamic stall. The energetic flow character of dynamic stall at high Reynolds numbers over rotating blades presents serious challenges for controlling dynamic stall over rotors of full scale helicopter.

High-fidelity simulation and flow control of an airfoil under dynamic stall condition

Renato Miotto[1,2]

Brener Ramos[1]

Hugo Lui[1]

William Wolf[1]

Datta Gaitonde[2]

Miguel Visbal[3]

University of Campinas[1]

The Ohio State University[2]

Air Force Research Laboratory[3]

Objectives

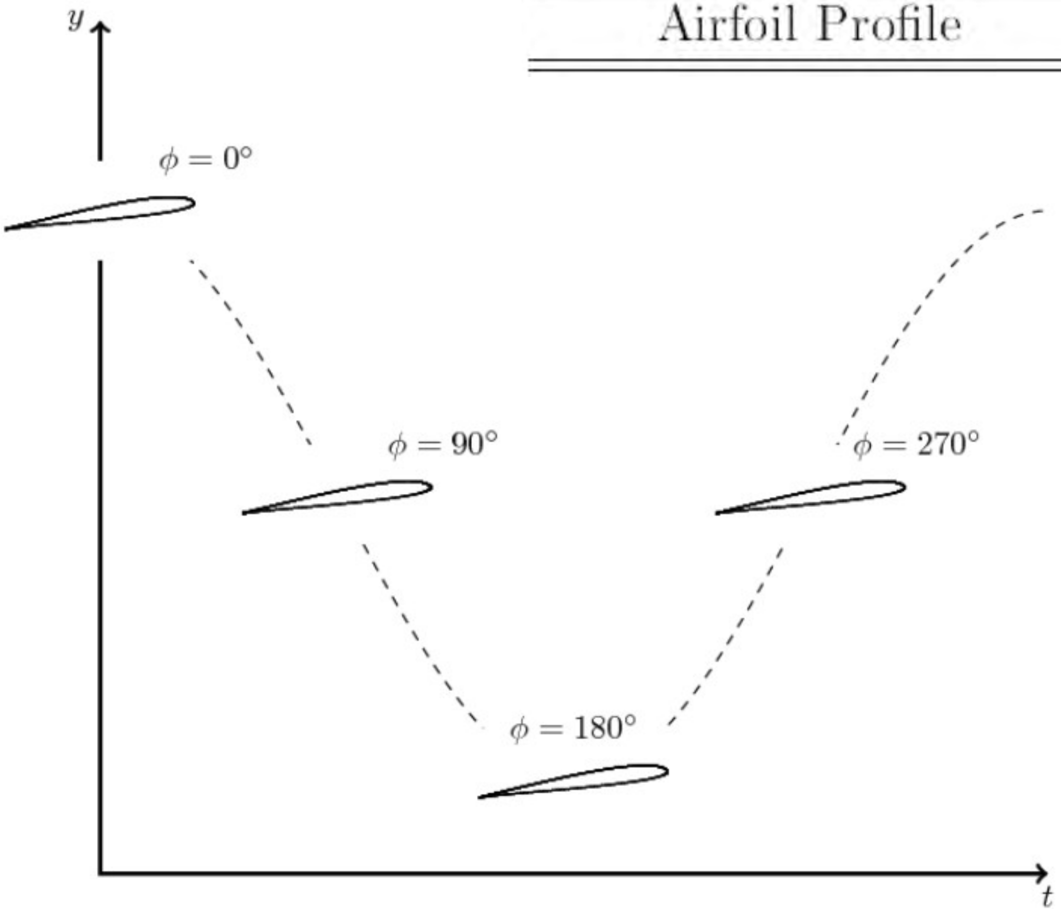
- Understand flow physics involving unsteady separation from dynamic stall
- Due to broad range of parameters (Mach, Reynolds, kinematics, geometry) we will start with simple plunging wing section
- Assessment of different flow actuation setups for mitigation of leading-edge vortex
- Develop novel reduced-order modeling strategies for prediction of flows involving dynamic stall

Numerical simulation

- Compressible Navier-Stokes equations in general curvilinear form
- Equations solved in non-inertial frame
- Implicit large-eddy simulation (ILES)
- High-order/high-resolution compact finite difference approach for staggered grid
- Compact filtering for damping high-frequency errors
- Hybrid implicit-explicit time marching method
- Sponges + characteristic BCs on far-field; periodic BC on span

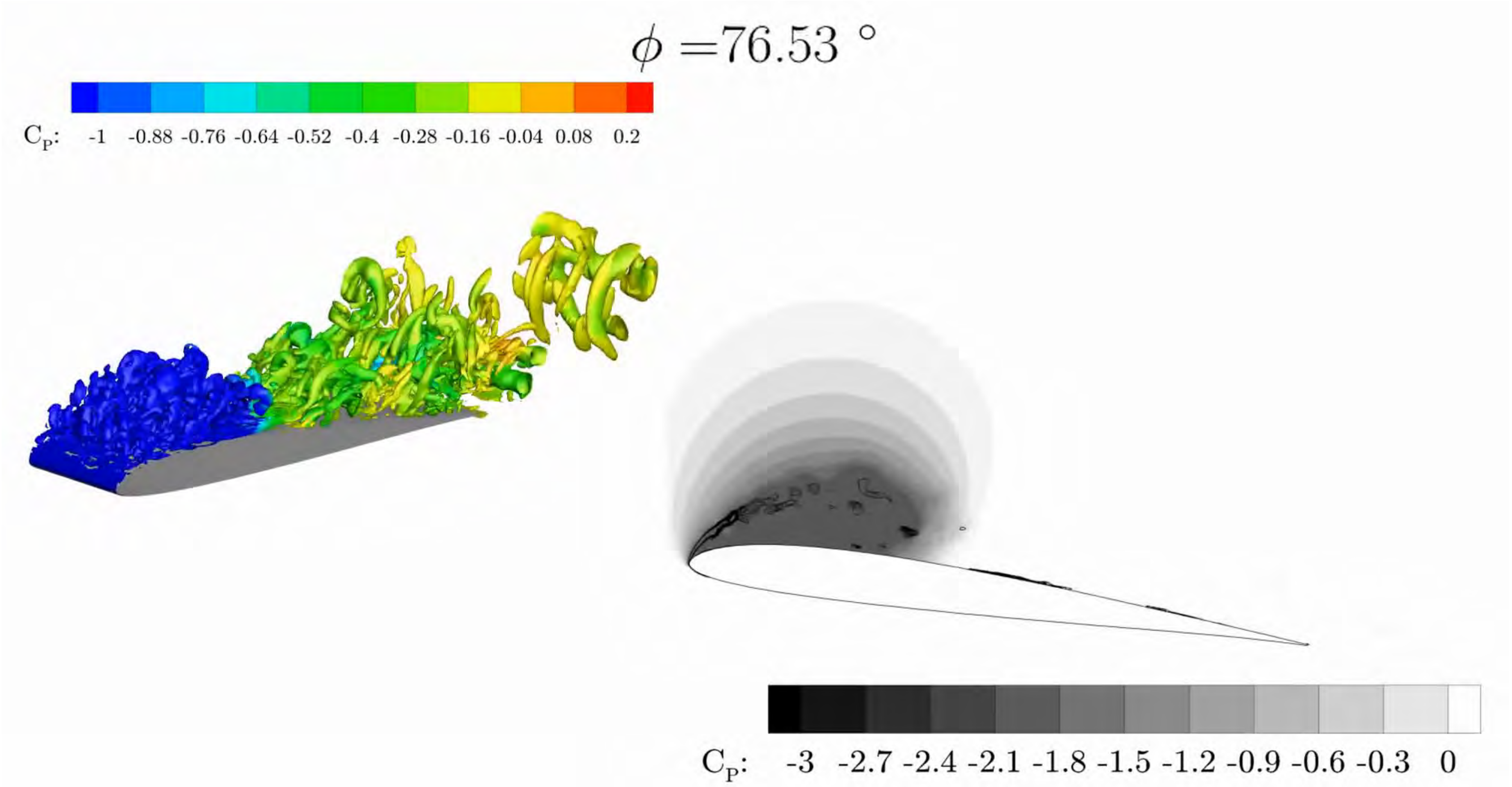
Numerical simulation

Re	60,000
Ma	0.1
Plunge Motion	$y = 0.5\sin(0.5t)$
Static Angle of Attack	$\alpha = 8^\circ$
Span	0.4
Airfoil Profile	SD7003

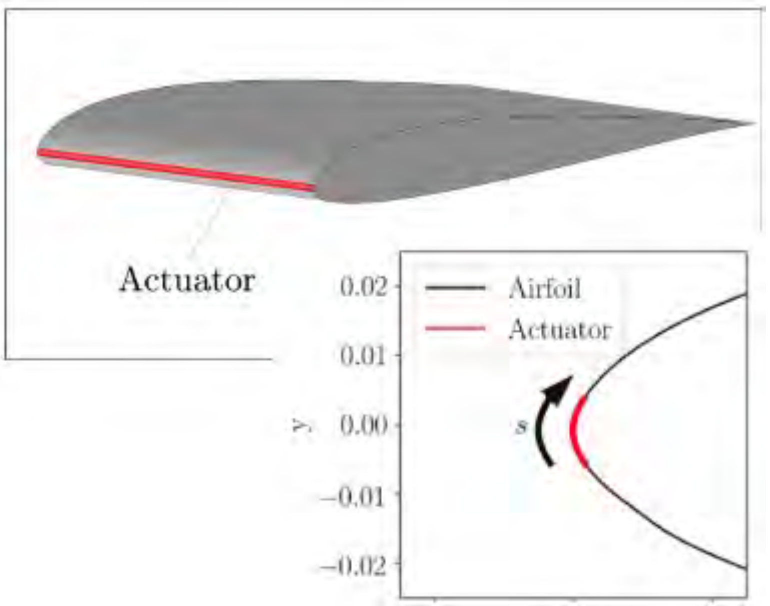


Flow features

Q-criterion colored by pressure (left) and pressure coefficient (right)



Active flow actuation

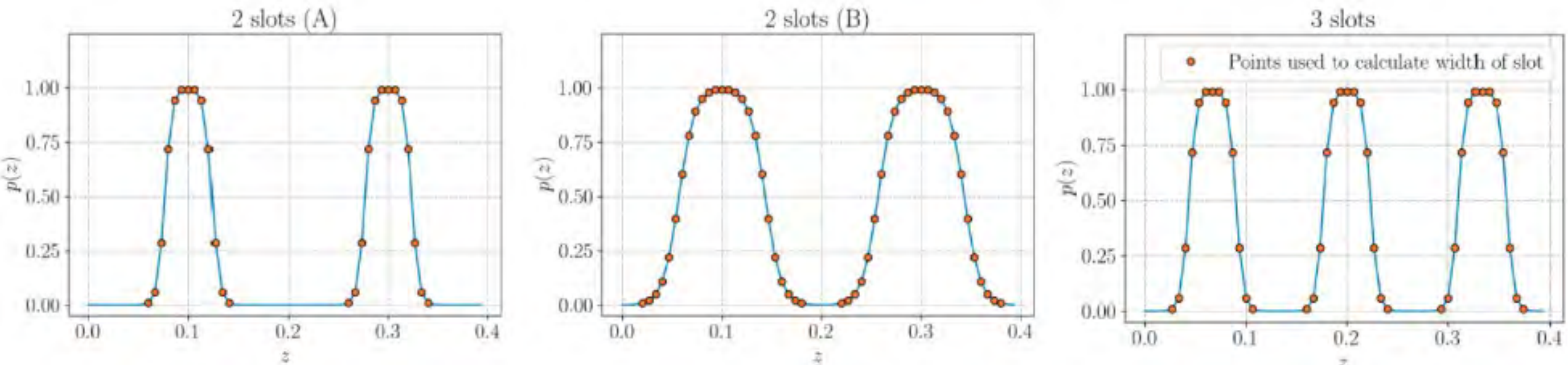


- Open loop flow actuation applied along the leading-edge
- Unsteady suction and blowing with controlled frequency

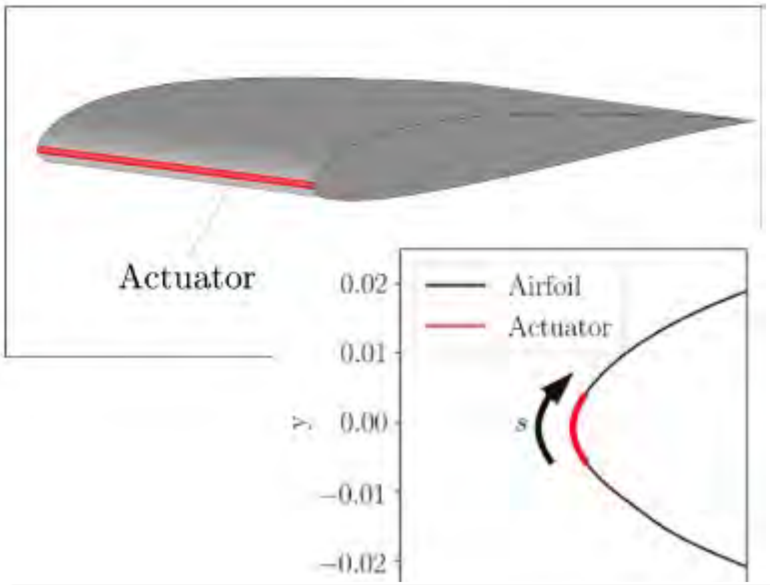
$$\frac{U_{jet}}{U_\infty} = \frac{U_{jet\ max}}{U_\infty} F(s)\, G(t)\, P(z)$$

F(s) is a Gaussian profile

G(t) is a sinusoidal function



Active flow actuation



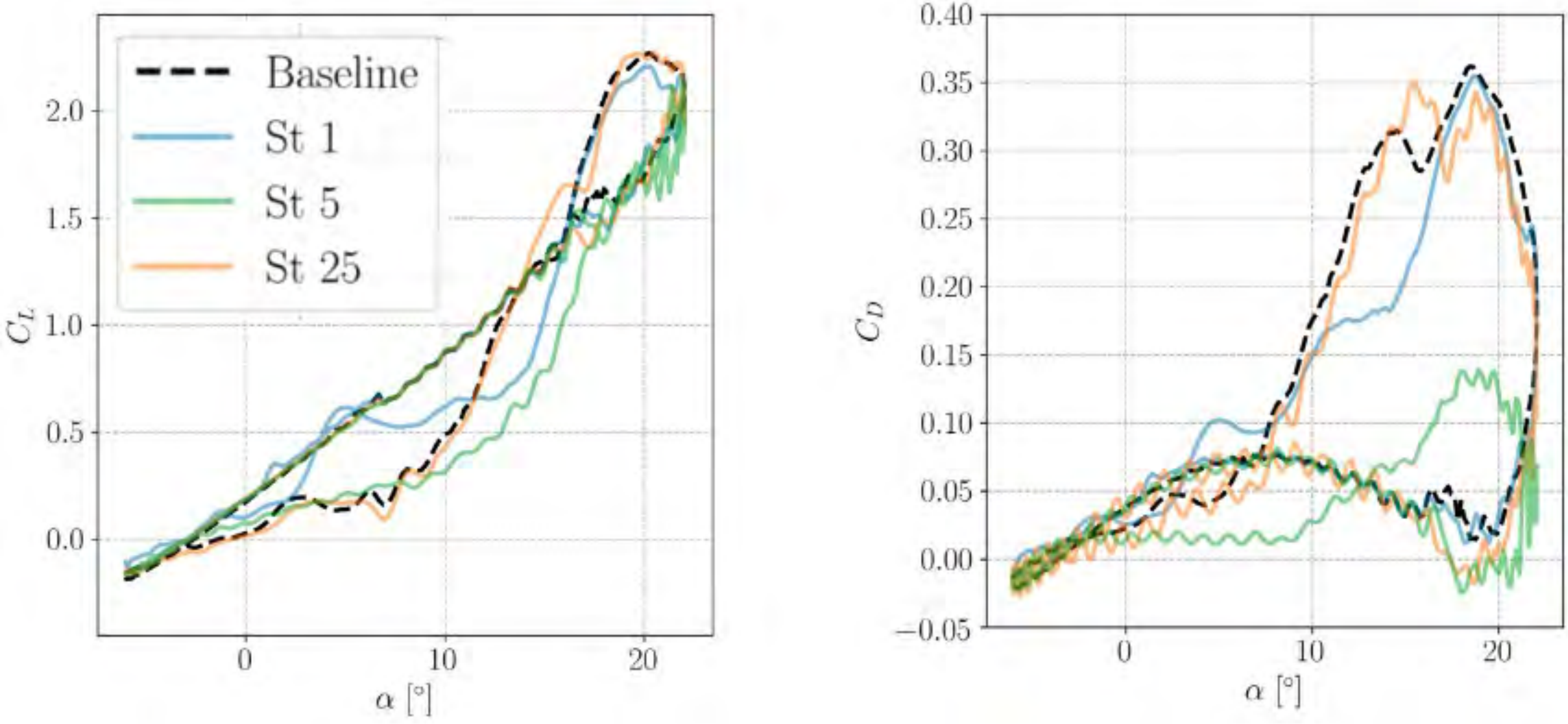
- Open loop flow actuation applied along the leading-edge
- Unsteady suction and blowing with controlled frequency

$$\frac{U_{jet}}{U_\infty} = \frac{U_{jet\ max}}{U_\infty} F(s)\,G(t)\,P(z)$$

Case	C_μ	$\frac{U_{jet\ max}}{U_\infty}$ 2D Act.	2 slots (A)	2 slots (B)	3 slots
1	1.78e−01%	0.8	-	-	-
2	4.46e−02%	0.4	0.90	0.67	0.74
3	1.12e−02%	0.2	-	-	-

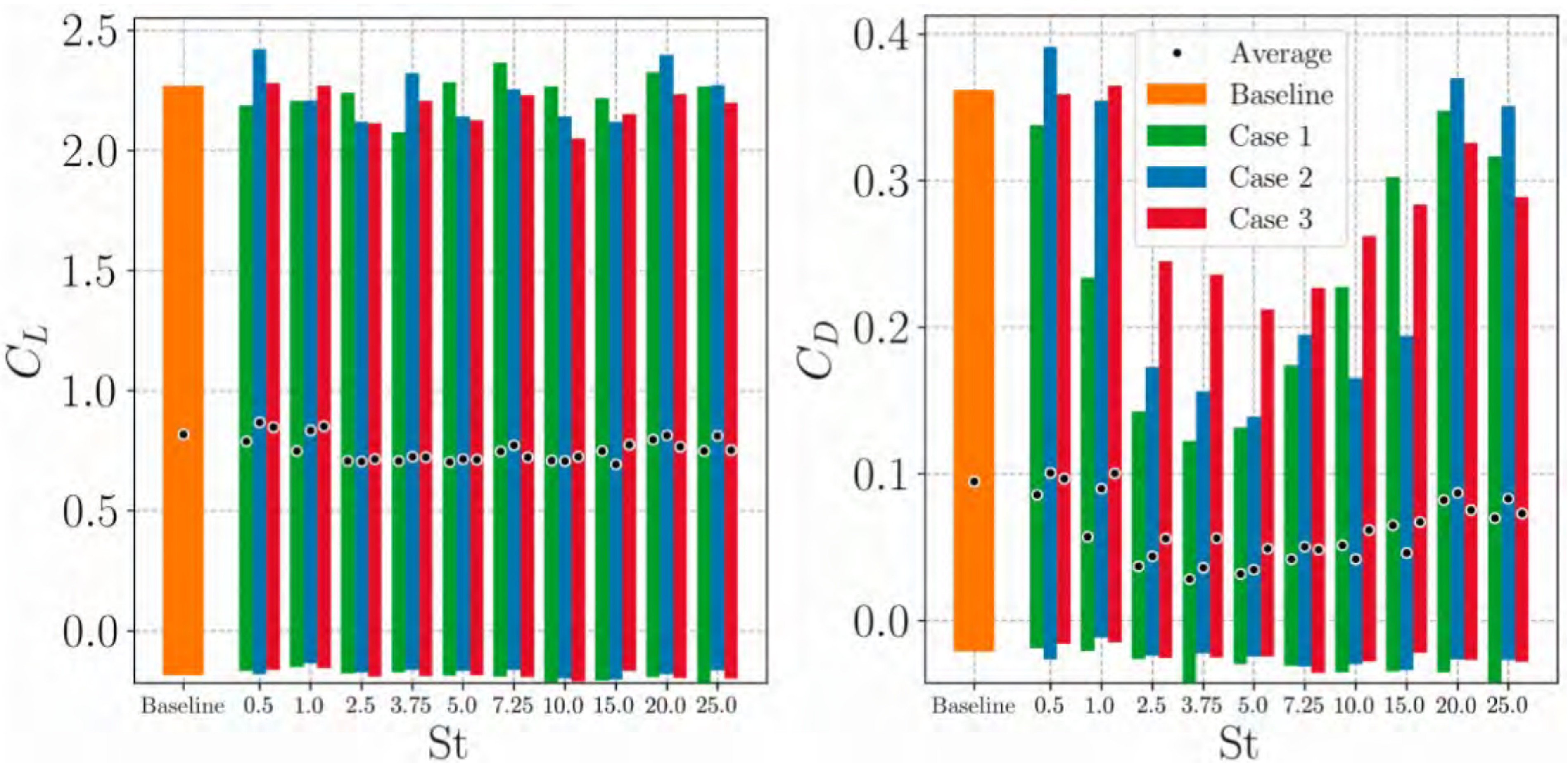
Active flow actuation

2D actuation

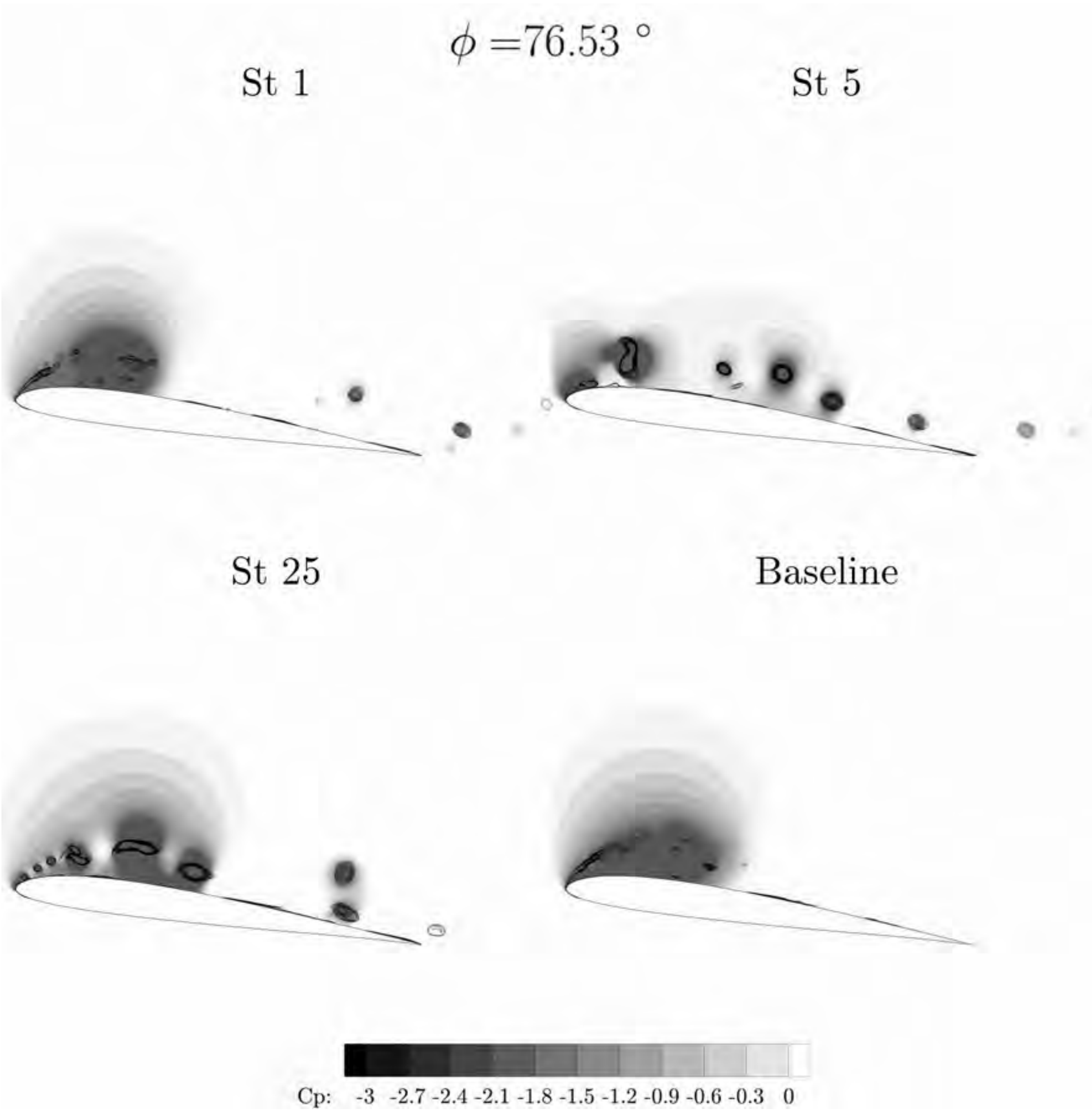


Active flow actuation

2D actuation

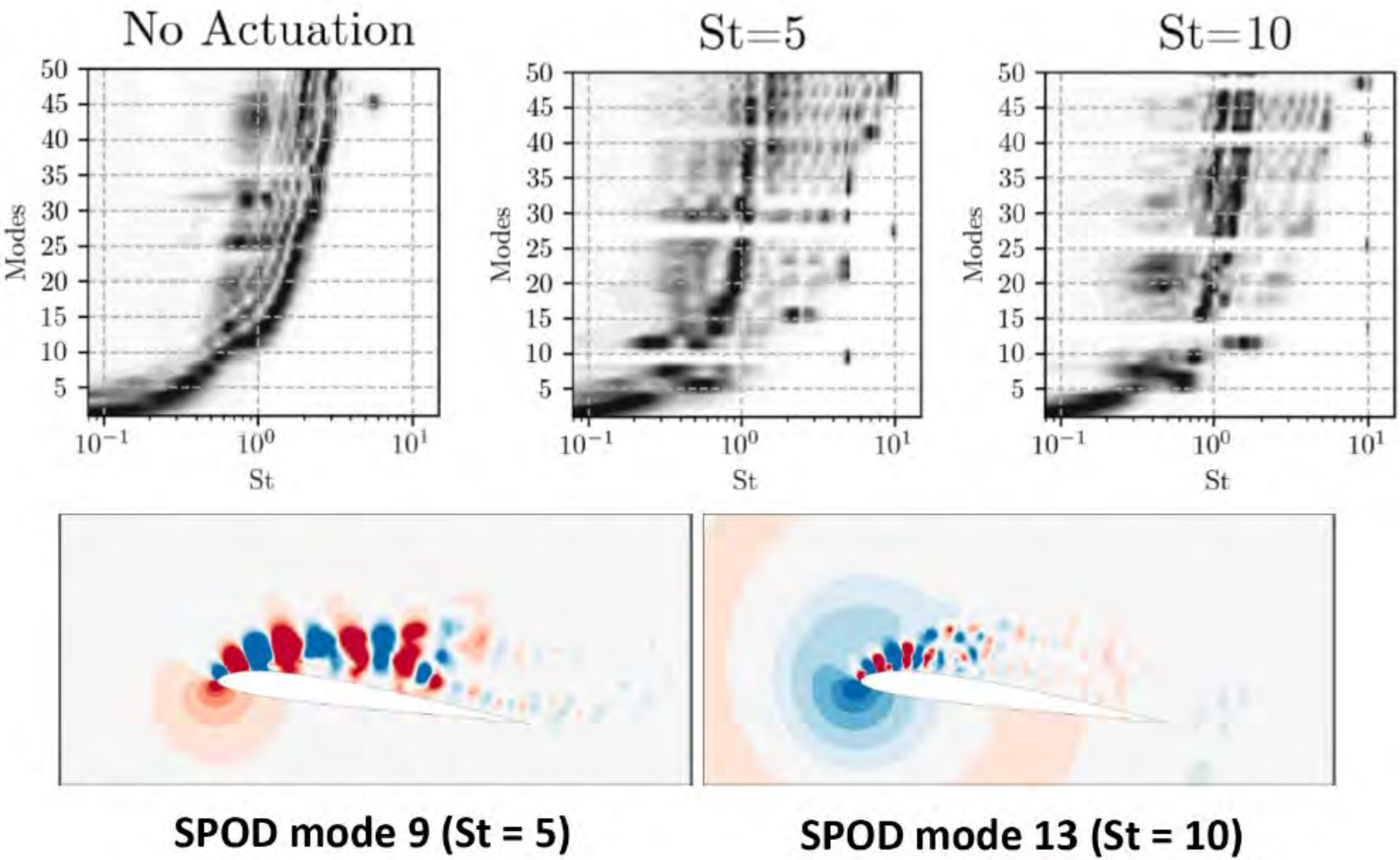


Active flow actuation



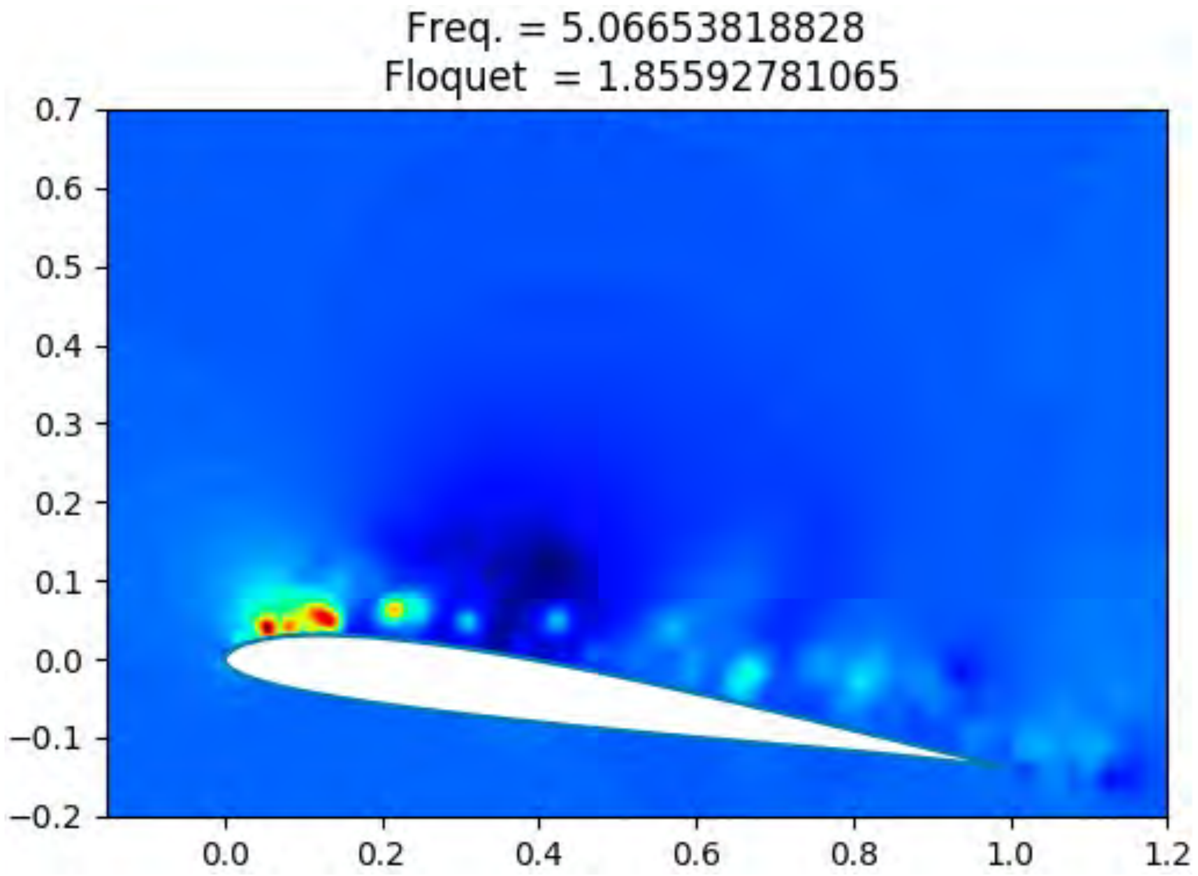
- For St = 5, actuation is able to disrupt the formation of leading-edge vortex
- Smaller coherent structures are formed and pressure reduction is not as intense

Modal decomposition

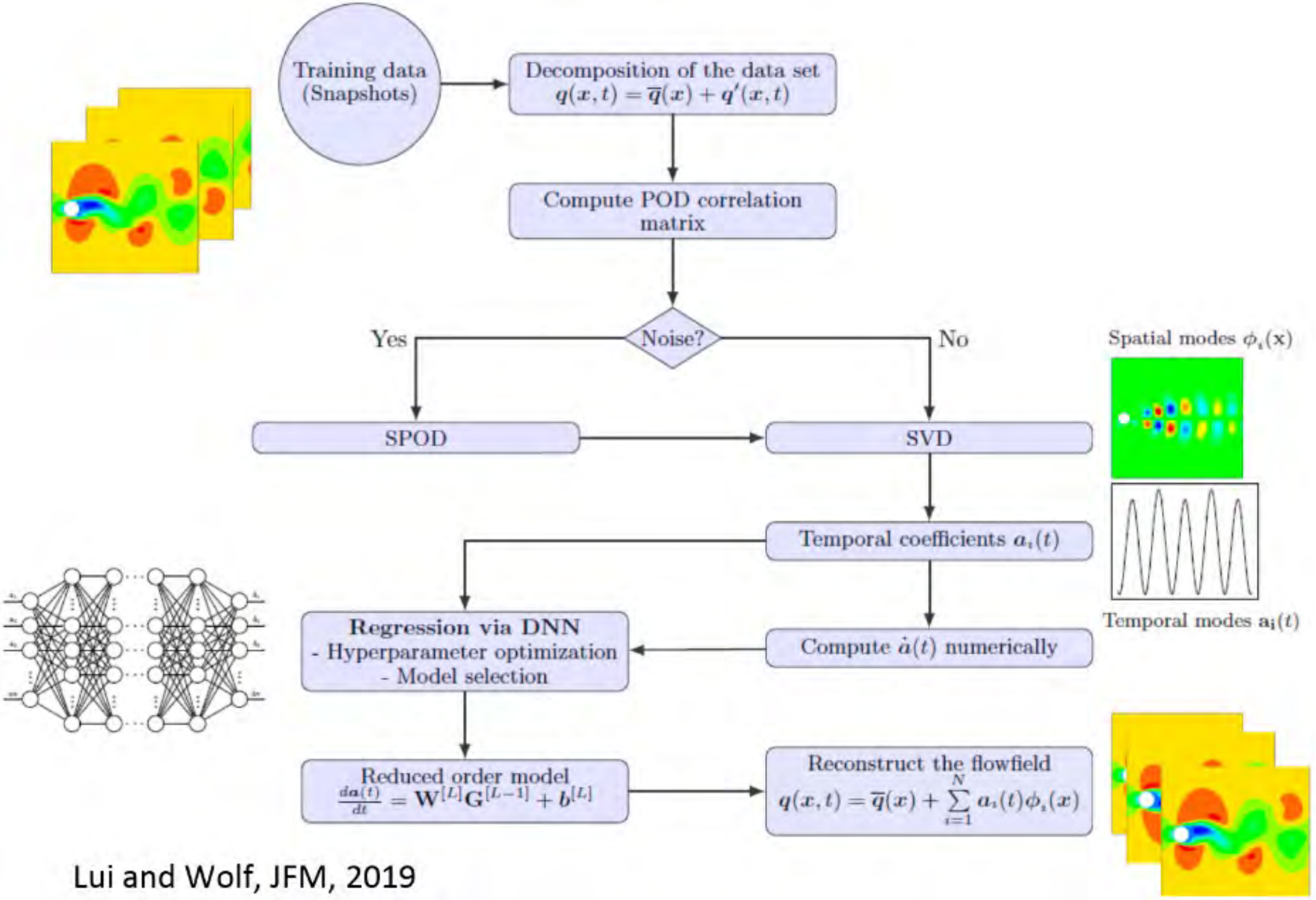


Modal decomposition

Dynamic mode decomposition

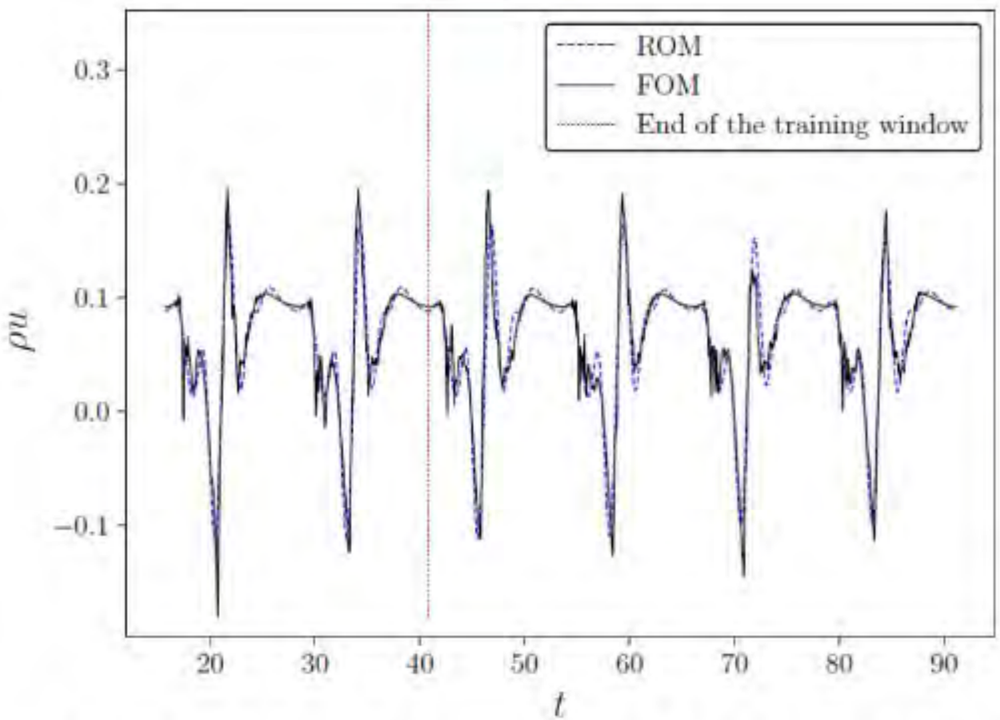


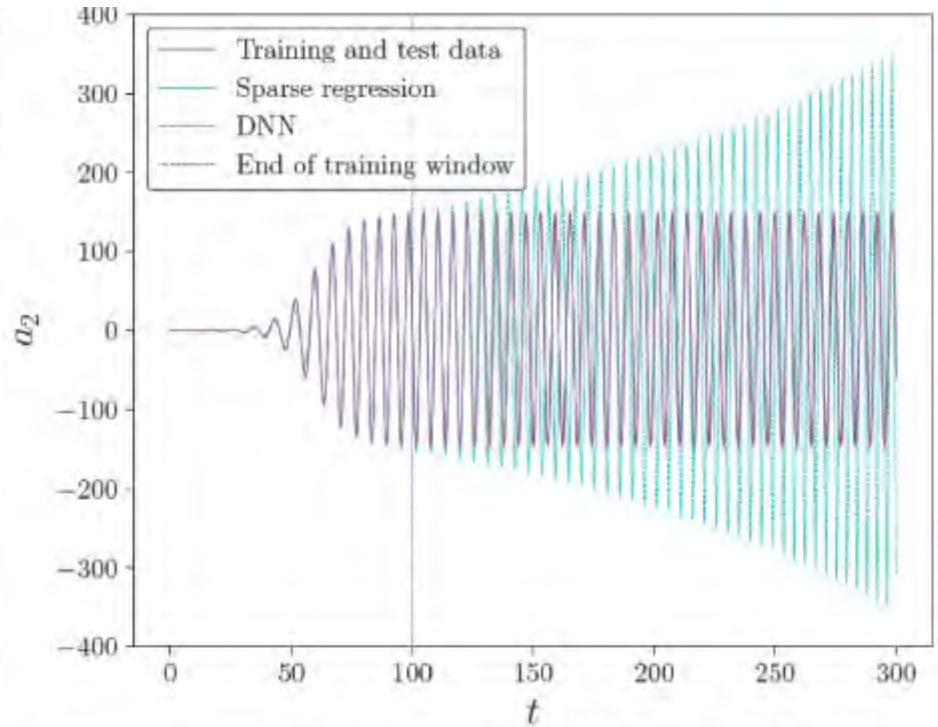
Reduced-order models



Lui and Wolf, JFM, 2019

Reduced-order models





(Left): complex flow features of dynamic stall can be learned with a small percentage of flow information

(Right): DNNs can learn transient features of a cylinder flow; method is stable and accurate for long-term predictions (beyond the training window)

Conclusions, perspectives & challenges

- LES provide good results for dynamic stall
- Understand the role of other parameters: compressibility, Reynolds, motion, geometry
- Look for more robust flow analysis (POD, DMD, mean flow perturbation, resolvent analysis) and control strategies:
- Our group is opened to collaboration with other groups (both experimental and numerical)
- Open data policy

Aknowledgements

References

- Lui, H., & Wolf, W. (2019). Construction of reduced-order models for fluid flows using deep feedforward neural networks. Journal of Fluid Mechanics, 872, 963-994. doi:10.1017/jfm.2019.358

- Brener L. O. Ramos, William R. Wolf, Chi-An Yeh, and Kunihiko Taira (2019). Active flow control for drag reduction of a plunging airfoil under deep dynamic stall. Phys. Rev. Fluids 4, 074603. doi:https://doi.org/10.1103/PhysRevFluids.4.074603

Contribution on Numerical Simulation of Dynamic Stall

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University of Glasgow

VIA VERITAS VITA

LABORATORY

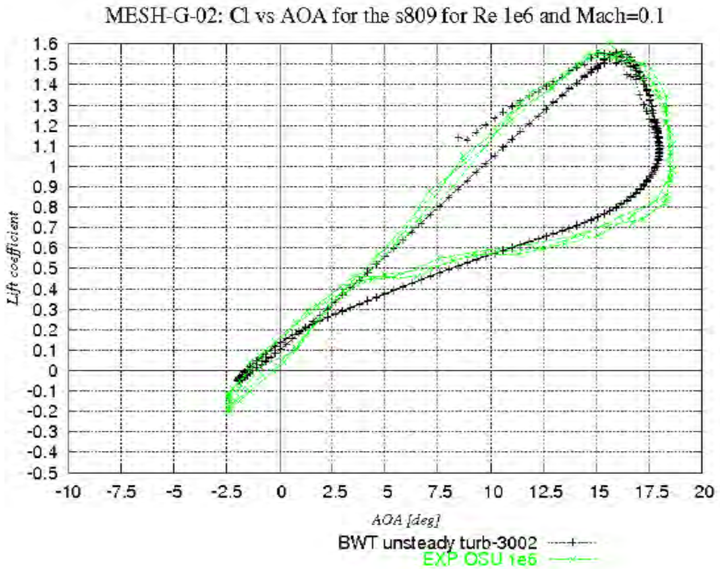
Progress to date on DS predictions with CFD

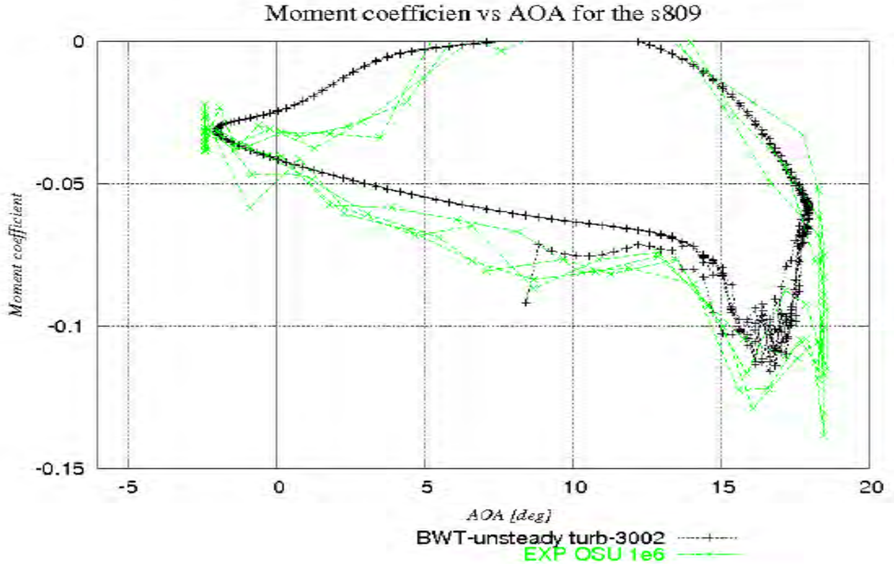
- The main physics of DS is broadly understood within the rotorcraft domain.
- There is good appreciation of DS implications on blade loads and some understanding of how to avoid DS occurring. DS control is well-demonstrated at low Re and wing/2D configurations.
- Accurate numerical predictions for rotors in DS are not yet evident in the open literature.
- The concept of using DS to enhance rotor-blade lift is not taken forward and DS is still seen as a problem rather than an opportunity.
- The 2D DS, and 3D DS of a wing are within reach and can be resolved with CFD and experiments adequately, given time and resources.
- 3D DS is measured and simulated for flows over wings and there are good sets of data from wind tunnels (e.g. Glasgow, Marseille, NASA) for validation of predictive tools and calibration of models.
- There is very little on 3D DS on rotors and this is the current state-of-the-art in predicting, measuring and controlling DS.

Current Status of research

- Current 2D DS simulations are mainly driven by wind energy applications and the need for coefficients and parameters of simpler DS models used with BEM (slide 3). There is some interest in Neural Networks and models of DS via deep learning.
- Current research on 3D DS on wings is almost stagnant since there is less interest from the military fixed-wing community for fast-moving canards and whole-moving control surfaces (slides 4-6).
- Attempts to measure and simulate 3D DS on rotors as part of the F6 GOAHEAD project produced some limited results (slide 9). Nevertheless, 3D DS is still a good objective and requires CFD refinements and developments.
- 3D DS on a rotor is of interest and there is now good evidence that this is somehow related to wake/blade interactions especially for rotors at high speeds (slide 7).

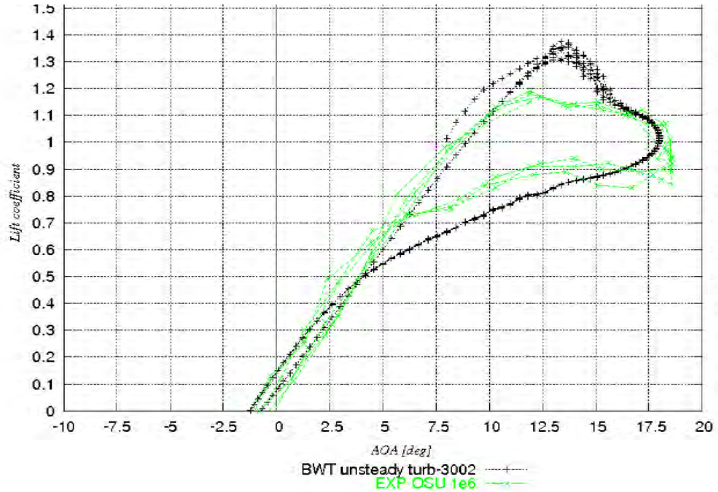
2D Dynamic Stall Blind Comparisons for WT sections

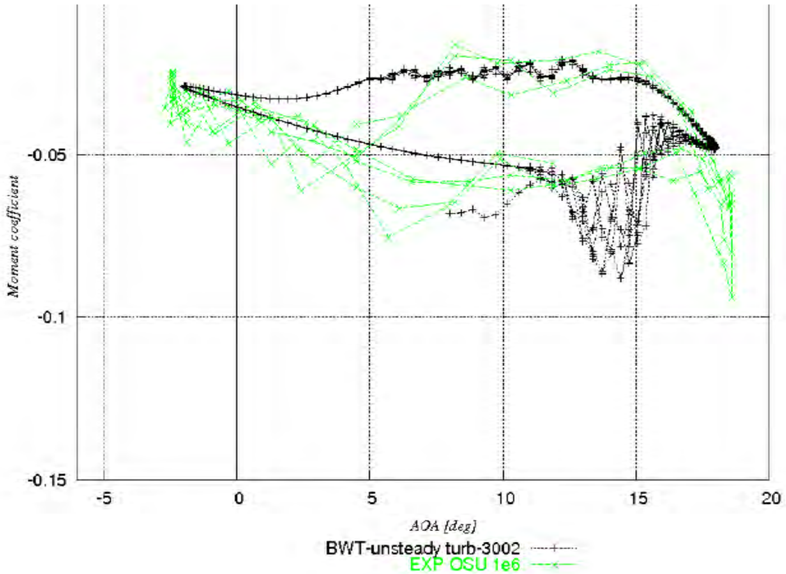


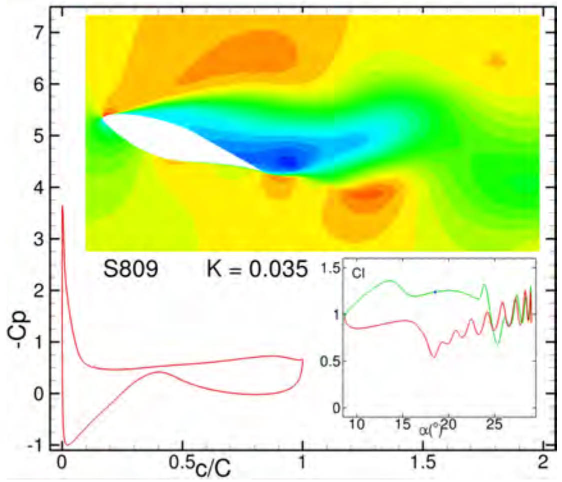


Oscillating S809 section
Tripped case simulated as 2D using URANS models

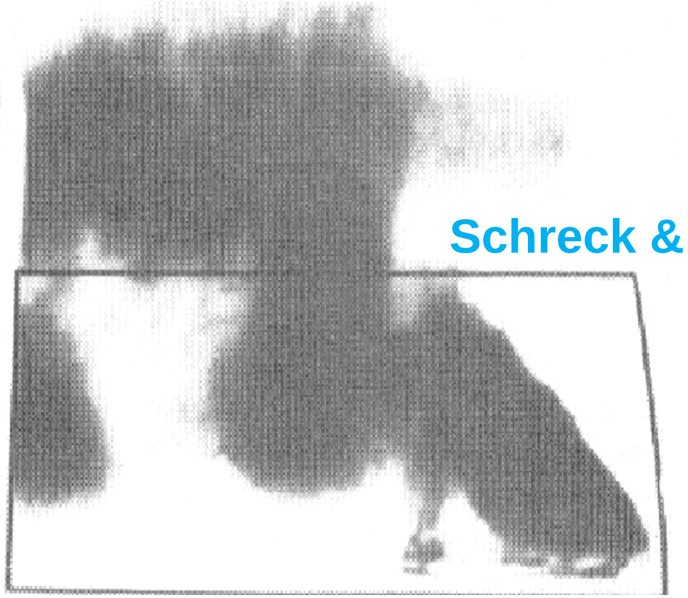
There are tests data from several oscillations showing cycle to cycle variability



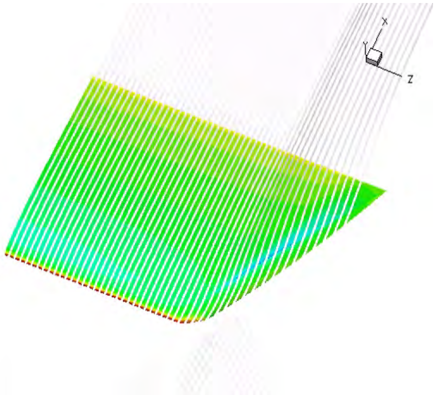


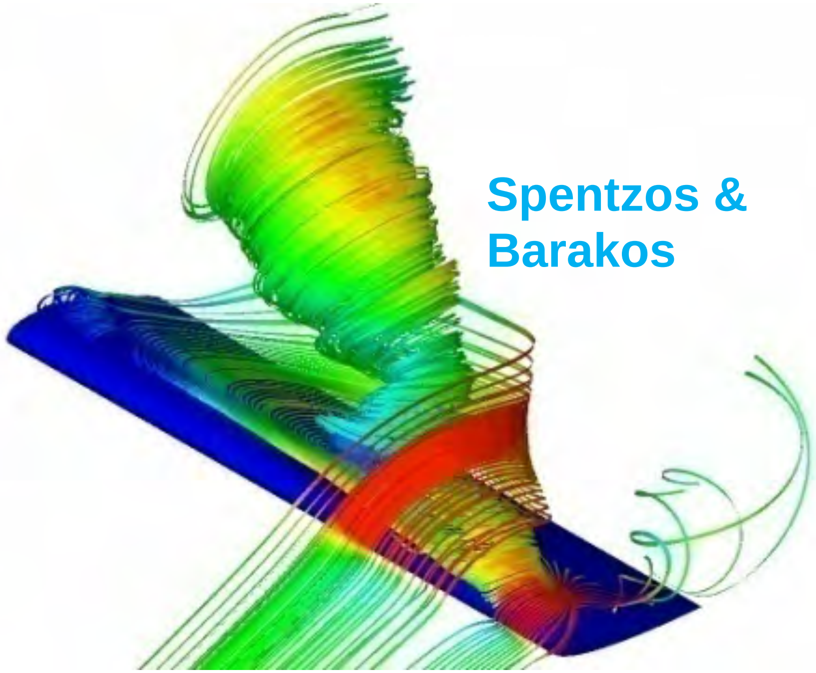


3D DS on Wing - Flow Topology



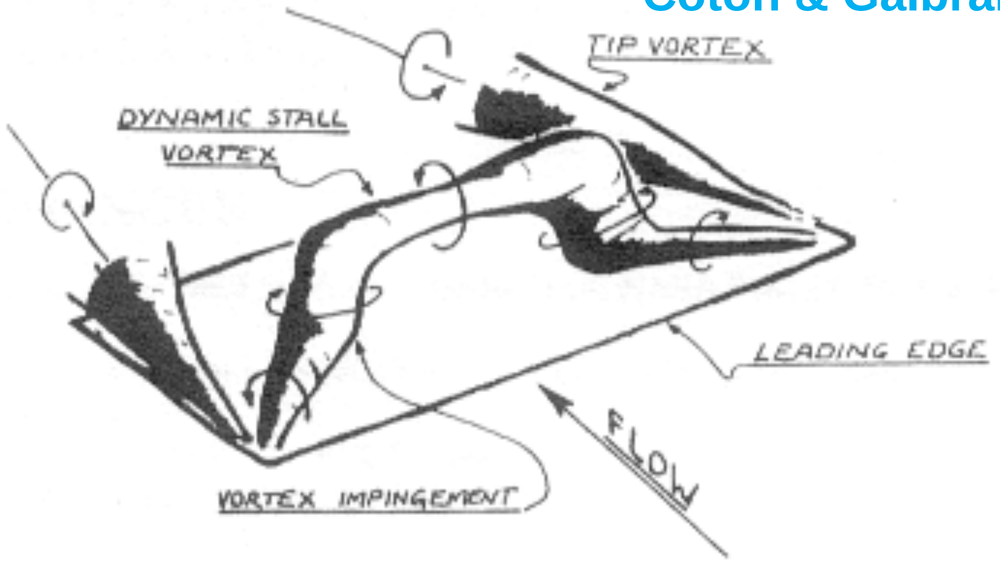
Schreck & Helin





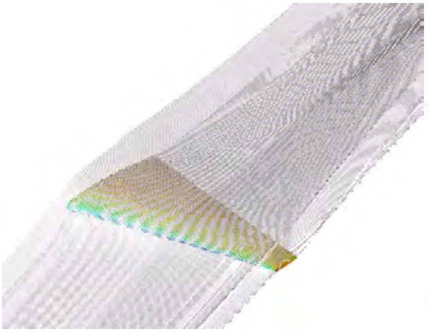
Spentzos & Barakos

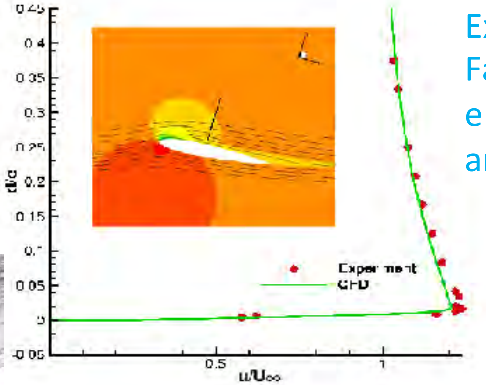
Moir & Coton



Coton & Galbraith

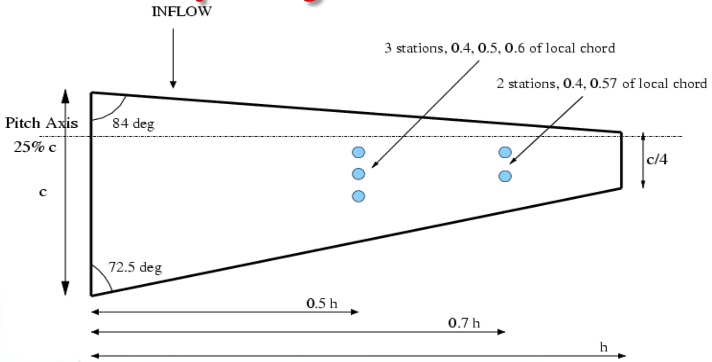
3D DS on Wing (Canard)
Flow Topology- Result with HMB from the UNSI F5 EU project





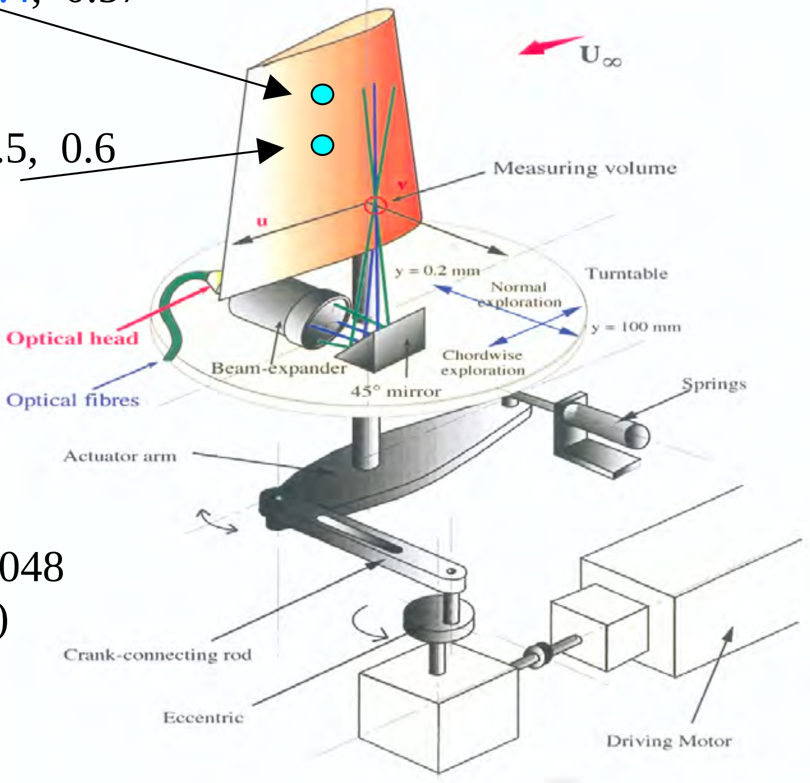
AoA = 12 deg upstroke

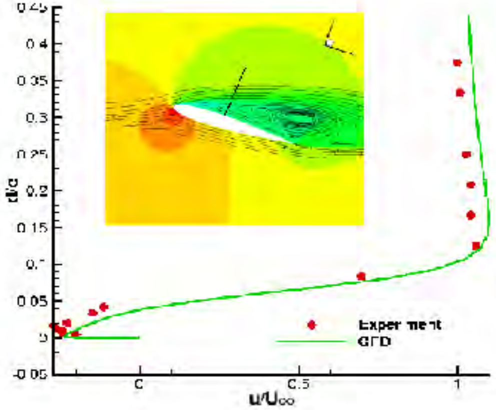
Experiments by Berton E., Allain C., Favier D. and Maresca C, using embedded LDA and CFD by Spentzos A. and Barakos G.



z/c = 0.7 > x/c = 0.4, 0.57

z/c = 0.5 > x/c = 0.4, 0.5, 0.6

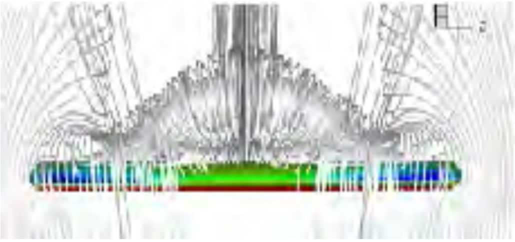




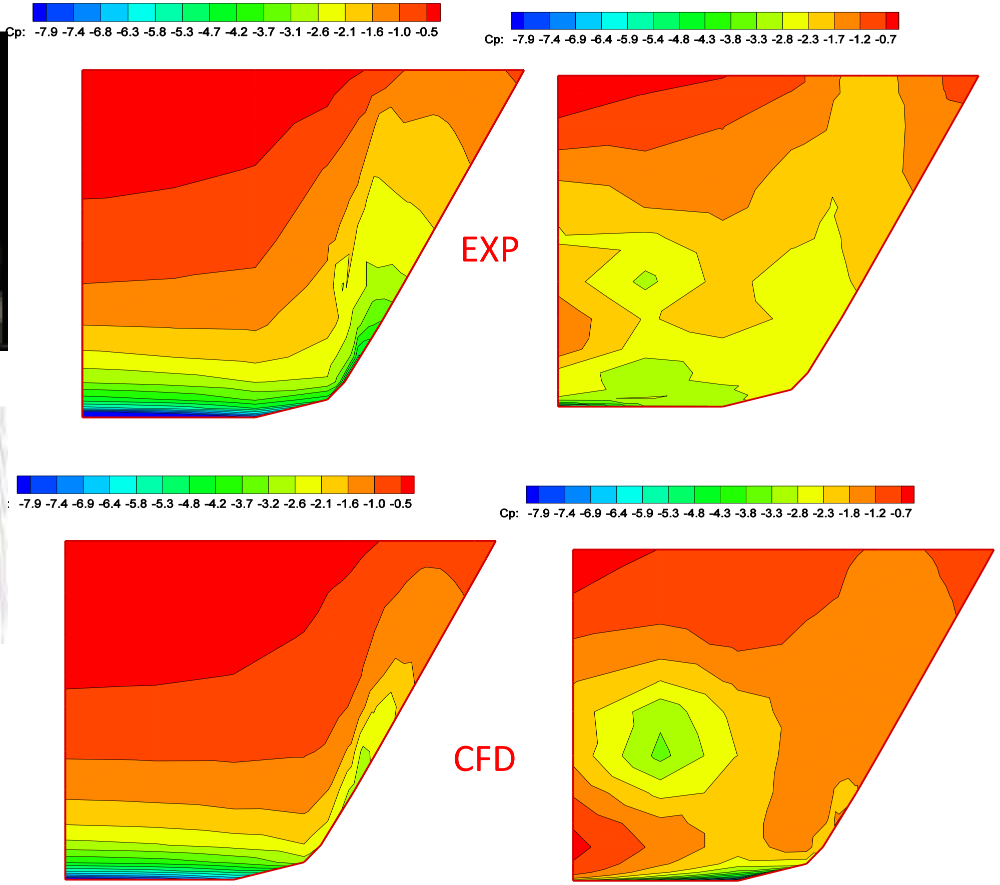
AoA = 18 deg downstroke

Pitching motion, k = 0.048
AoA=18 + 6 sin(wt)
x/c = 0.4
z/c =0.5

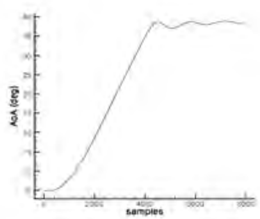
3D DS on Wing
Experiments by Coton & Galbraith and Moir & Cotton at Glasgow compared with CFD



Leading edge view, 40 degrees of incidence



25deg 35 deg



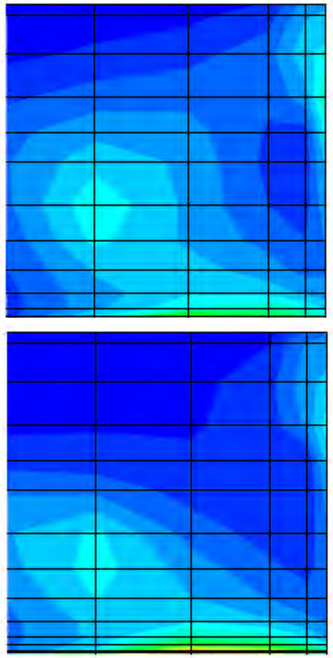
Ramping motion

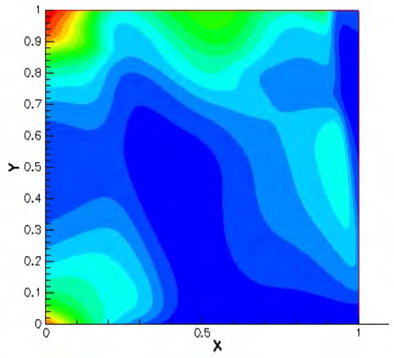
$a^+ = 0.027$

$-5^o \rightarrow 40^o$

$Re=1.45x10^6$

M=0.16

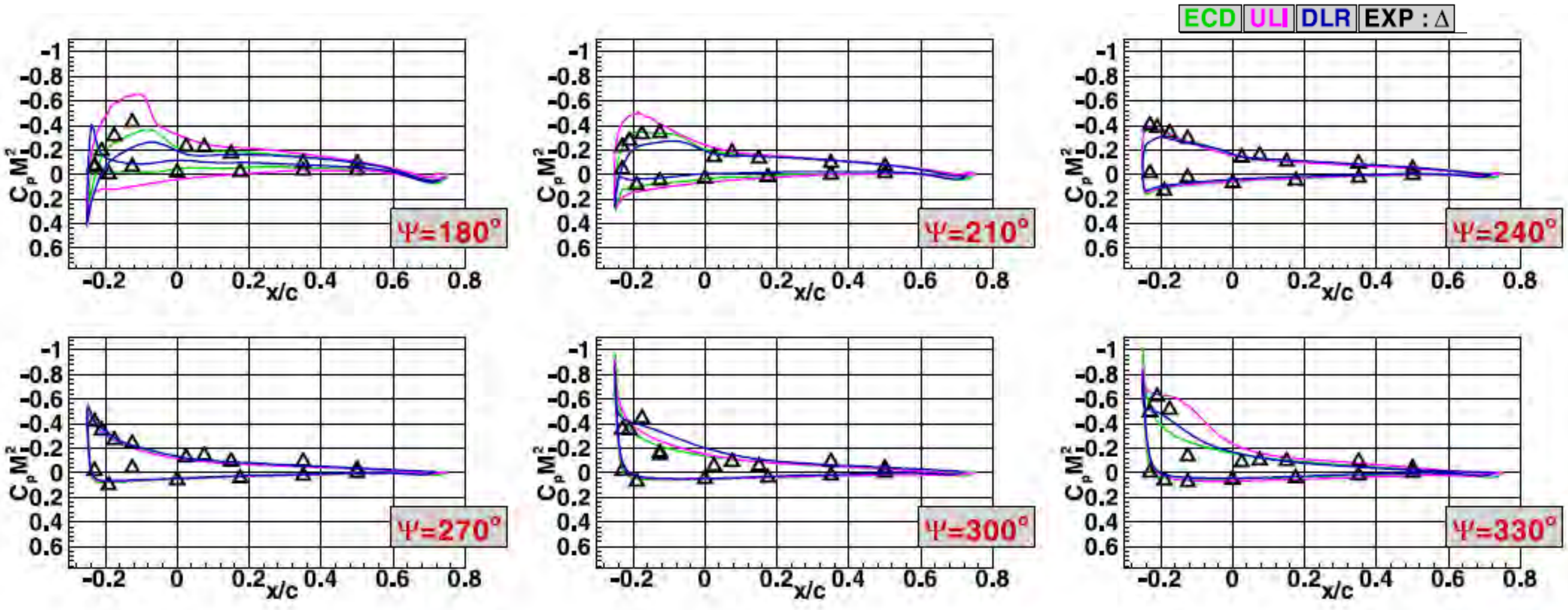




NN training with CFD

3D DS on Rotor - GOAHEAD F6 EU Project

Limited evidence of stall from 300 to 330 degrees of azimuth, r/R=0.98 but not necessarily DS
One test case attempted during wind tunnel tests at DNW (Test Case 5)
Data set restricted to GOAHEAD partners.



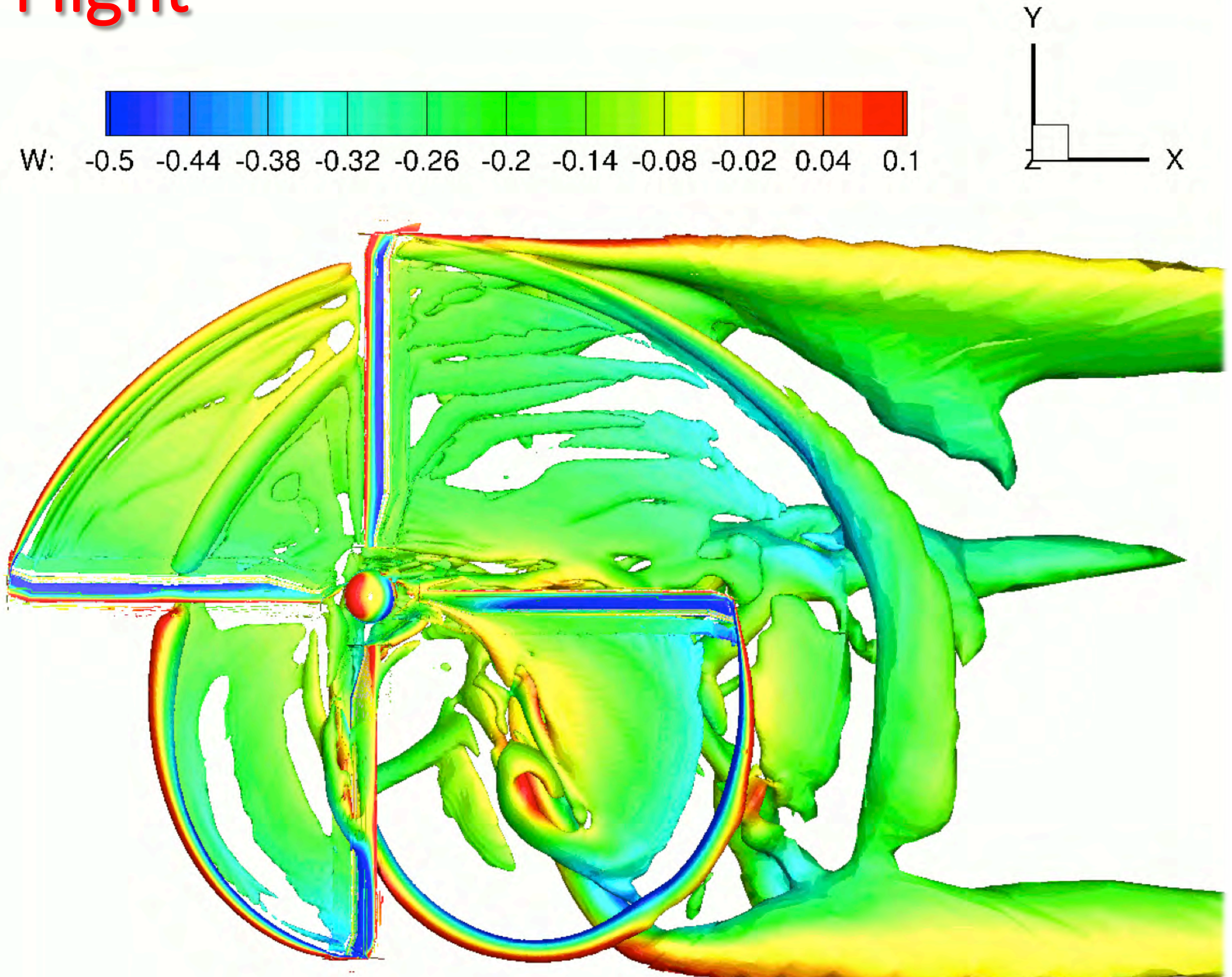
3D on rotor - AH-64A in High Speed Forward Flight

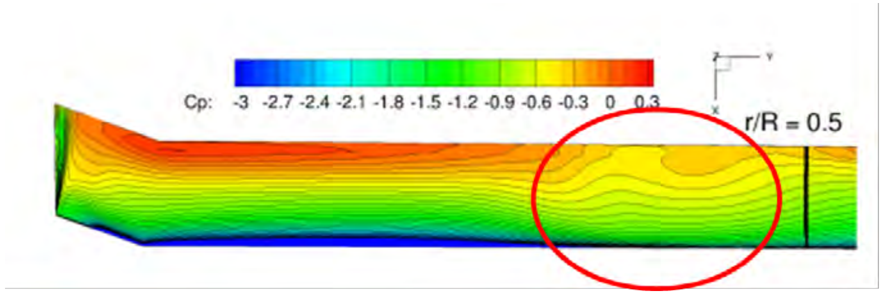
Parameter	Value in degrees
Shaft angle, α_s	-5.431
Collective angle, θ_0	10.413
Lateral cyclic, θ_{1s}	7.421
Longitudinal cyclic, θ_{1c}	-3.072
Coning angle, β_0	3.5
Lateral flapping angle, β_{1s}	0.0
Longitudinal flapping angle, β_{1c}	0.0

C_T = 0.00903, μ = 0.3

Wake animation using Q-criterion (value of 0.002) coloured by vertical velocity shows 3D DS on the retreating side initiated by wake/blade interaction at 200 degrees of azimuth

No test data available for this case





Retreating blade side

ERF 2019 paper on AH64A rotor

Future Steps

- The 3D DS on a rotor is still not understood, measured, or numerically simulated with fidelity.
  - Model-scale rotors are difficult to use near stall and there is no detailed data for comparisons with CFD
  - Surface pressure showing clearly DS, flow visualization, blade loads, long, well-sampled signals to be analyzed alongside modern DES-based CFD results.
  - CFD studies are possible but due to cost these may be under-resolved, and most of the times without aeroelastic effects.
- There is no sufficient momentum in 3D DS rotor research
  - Cost issues, related to CFD studies and CFD
  - Practical issues related to model and full-scale measurements.
- Perhaps an integrated effort to measure and simulate 3D DS on a rotor is one of the challenges the rotorcraft research community could put forward.

University of Stuttgart
Institute of Aerodynamics and Gas Dynamics (IAG)

CFD Simulations of Dynamic Stall on Helicopter Rotors

Johannes Letzgus,
Manuel Keßler, Ewald Krämer

ARO Dynamic Stall Workshop
Georgia Tech, Atlanta, GA
September 10-11 2019

CFD Simulations of Dynamic Stall on Helicopter Rotors

- Helicopters & aeroacoustics group

University of Stuttgart
Germany

IAG

Ewald Krämer	Manuel Keßler	Johannes Letzgus
Head of Institute	Senior Scientist	Research Assistant
		

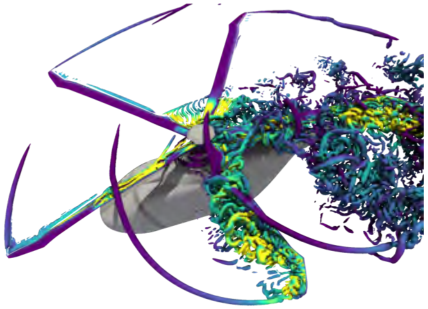
- Current dynamic-stall collaborations

DLR	AIRBUS
Göttingen, Germany	Donauwörth, Germany

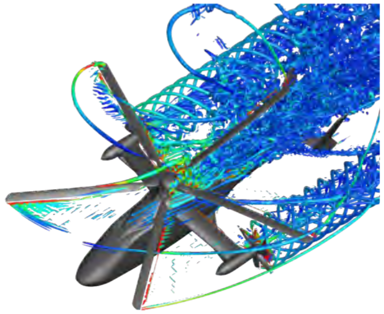
CFD Simulations of Dynamic Stall on Helicopter Rotors

- Computational methods
  - FLOWer: Block-structured FV code by DLR & IAG
  - CAMRAD II or HOST: CFD/CSD coupling and trim
  - HPC: Cray XC40 (#34 TOP500)

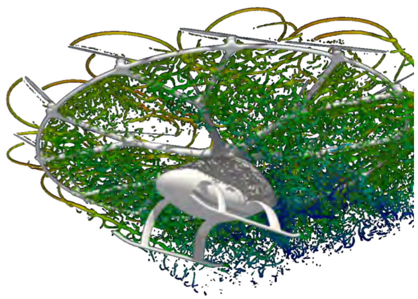
High-Performance Computing Center | Stuttgart



Airbus Helicopters Bluecopter



Airbus Helicopters RACER,
courtesy of Constantin Öhrle



Volocopter,
courtesy of Ulrich Schäferlein

Contra-Rotating Open Rotor,
courtesy of Lukas Dürrwächter

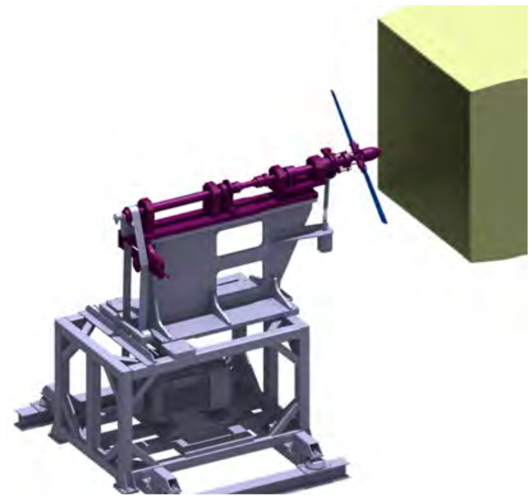
Dynamic-Stall Case 1:
Model Rotor in Rotor Axial Flight

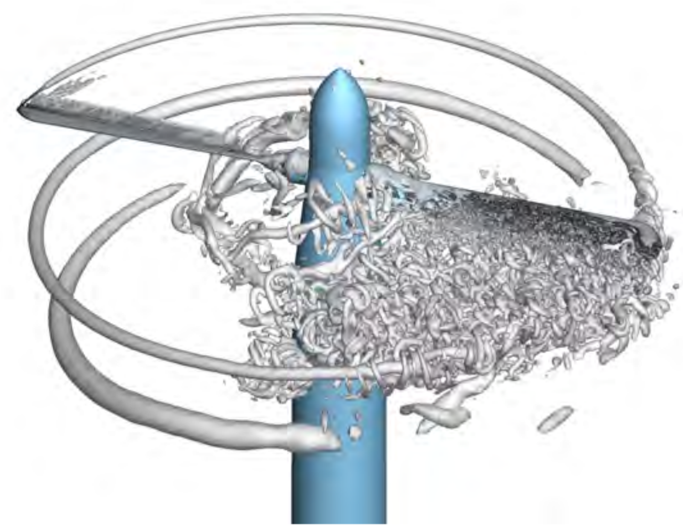
Model Rotor in Rotor Axial Flight[1,2]

Setup

- Experiment by DLR, Schwermer et al.[3]
  - Rotor Test Facility Göttingen (RTG)
  - $R = 0.65$ m, $M_{75} = 0.21$, $Re_{75} = 350k$
  - Cyclic-pitch variation triggers DS

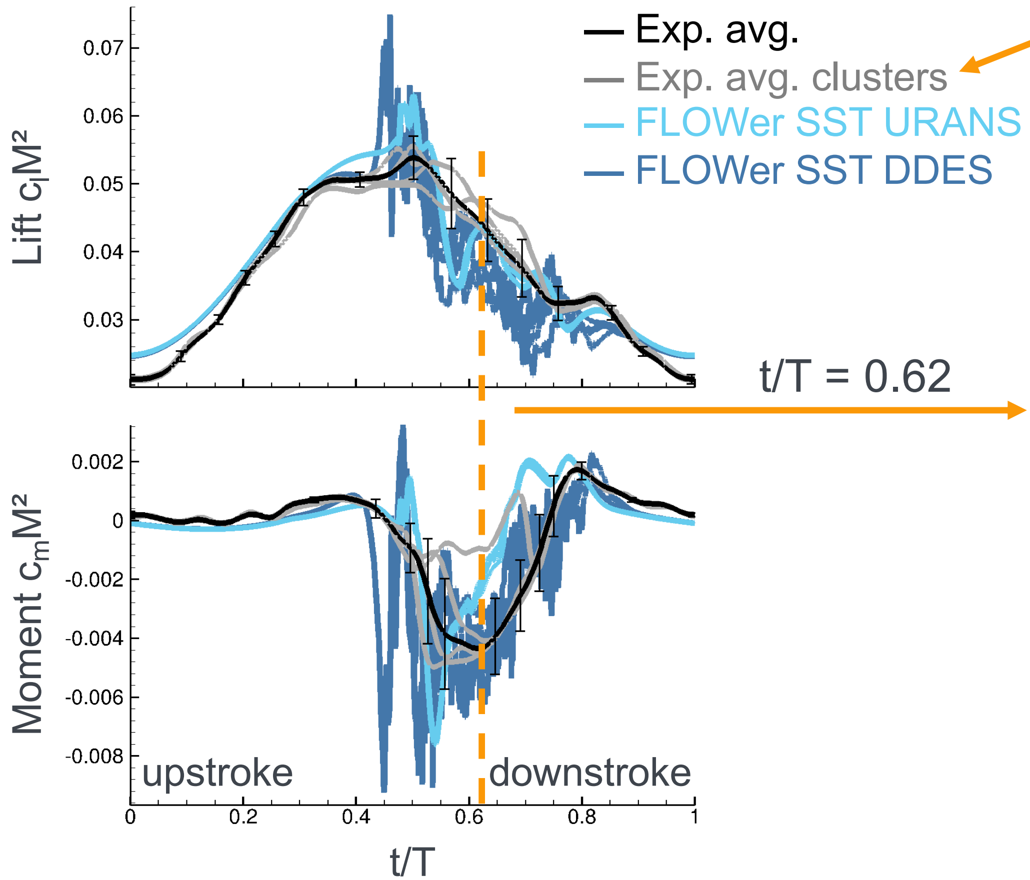
- FLOWer and TAU computations
  - Simplified setup, rigid blades
  - SA/SST URANS and DDES
  - 30 to 240 million grid cells

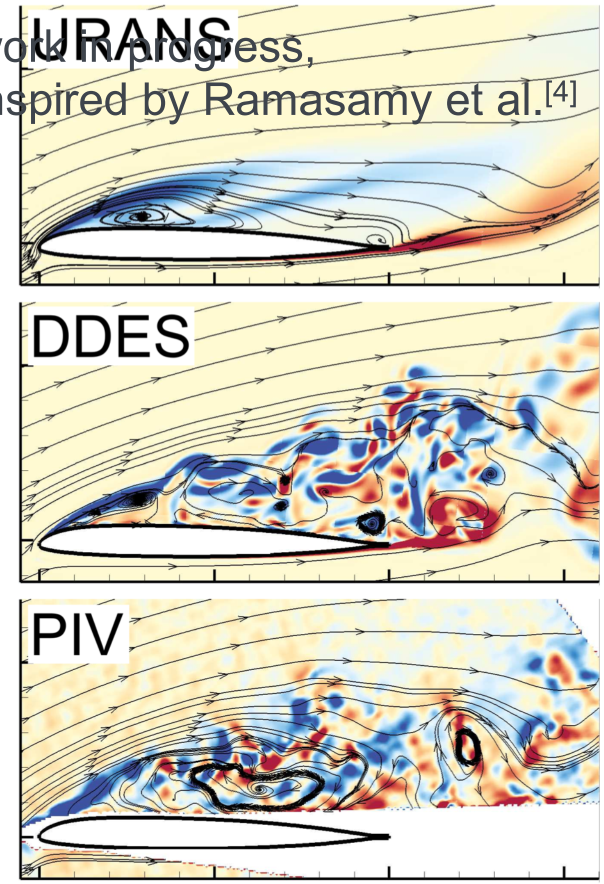




Model Rotor in Rotor Axial Flight[1,2]

Sectional Loads at r/R = 0.77

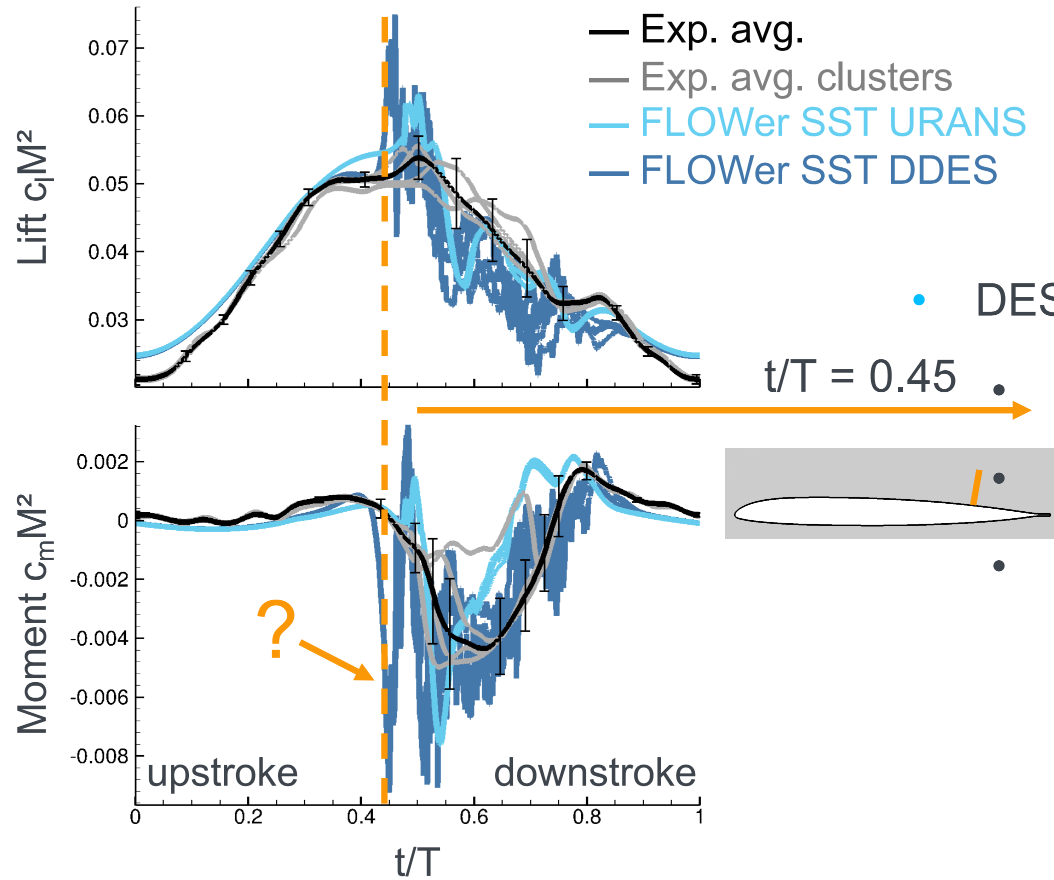


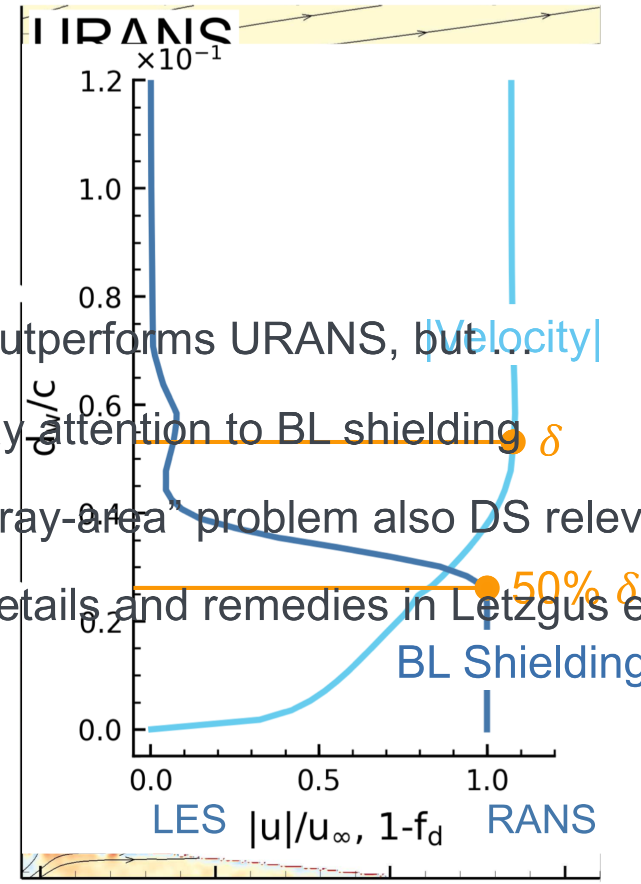


work in progress,
inspired by Ramasamy et al.[4]

Model Rotor in Rotor Axial Flight[1,2]

Sectional Loads at r/R = 0.77

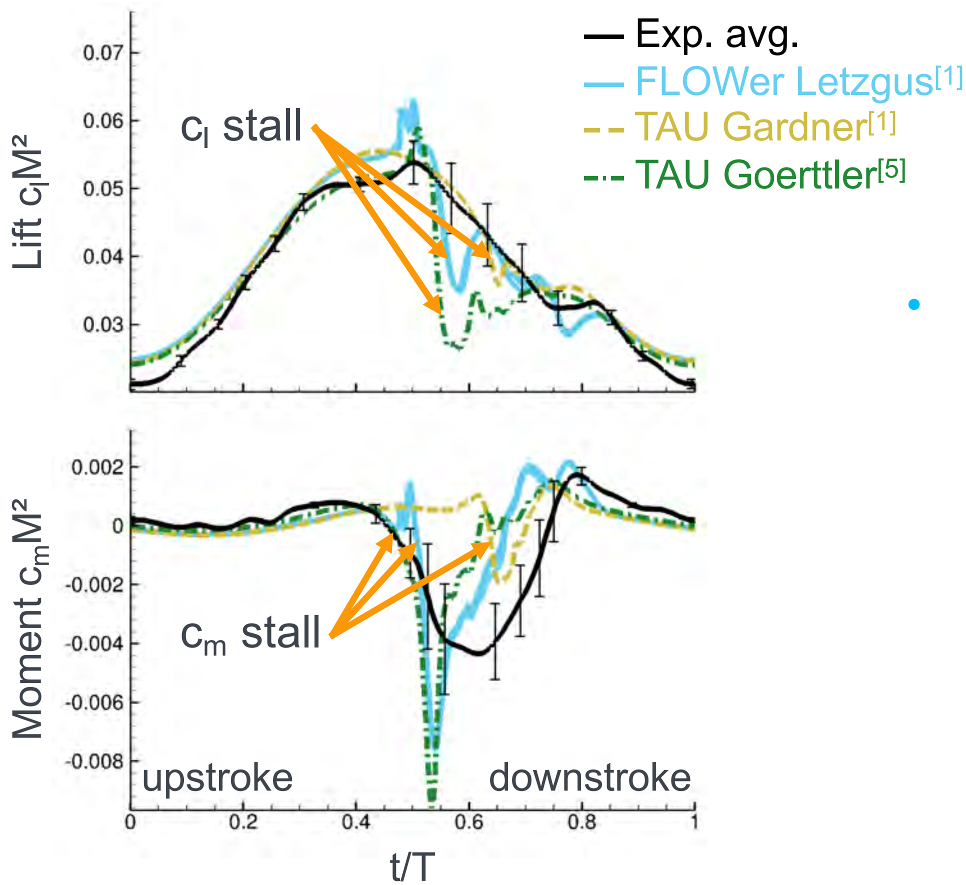




- DES outperforms URANS, but …
  - Pay attention to BL shielding
  - "Gray-area" problem also DS relevant
  - (Details and remedies in Letzgus et al.[2])

Model Rotor in Rotor Axial Flight[1,2]

Sectional Loads at r/R = 0.77 (URANS SST)



- CFD uncertainties regarding complex rotor dynamic stall
  - More participants, public test case?
  - Like drag or rotor-hub-flow prediction workshop

Dynamic-Stall Case 2: Rotor in High-Speed Turn Flight

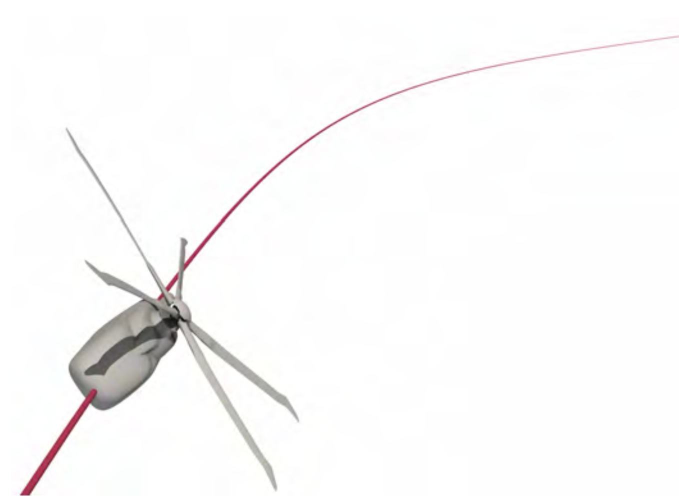
Rotor in High-Speed Turn Flight[6]

Setup

- Flight condition of Bluecopter
  - Highly loaded, high-speed left turn
  - Advance ratio μ: 0.35
  - Rotor thrust C_T/σ: 0.145

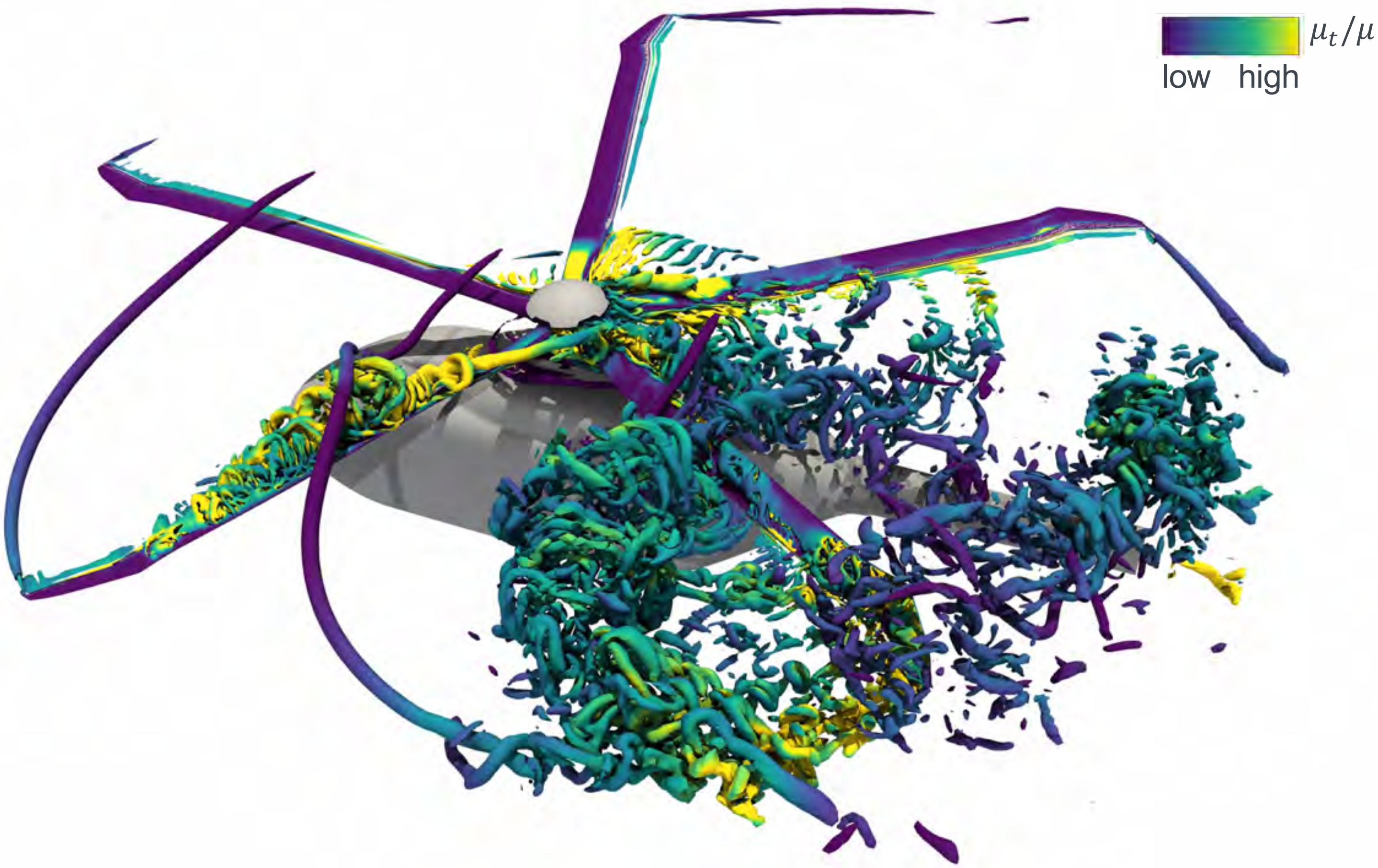
Courtesy of Airbus Helicopters

- Loose CFD/CSD with FLOWer/CAMRAD II
  - 3-DOF isolated-rotor trim
  - SA/SST DDES, with and without fuselage
  - 160 million grid cells



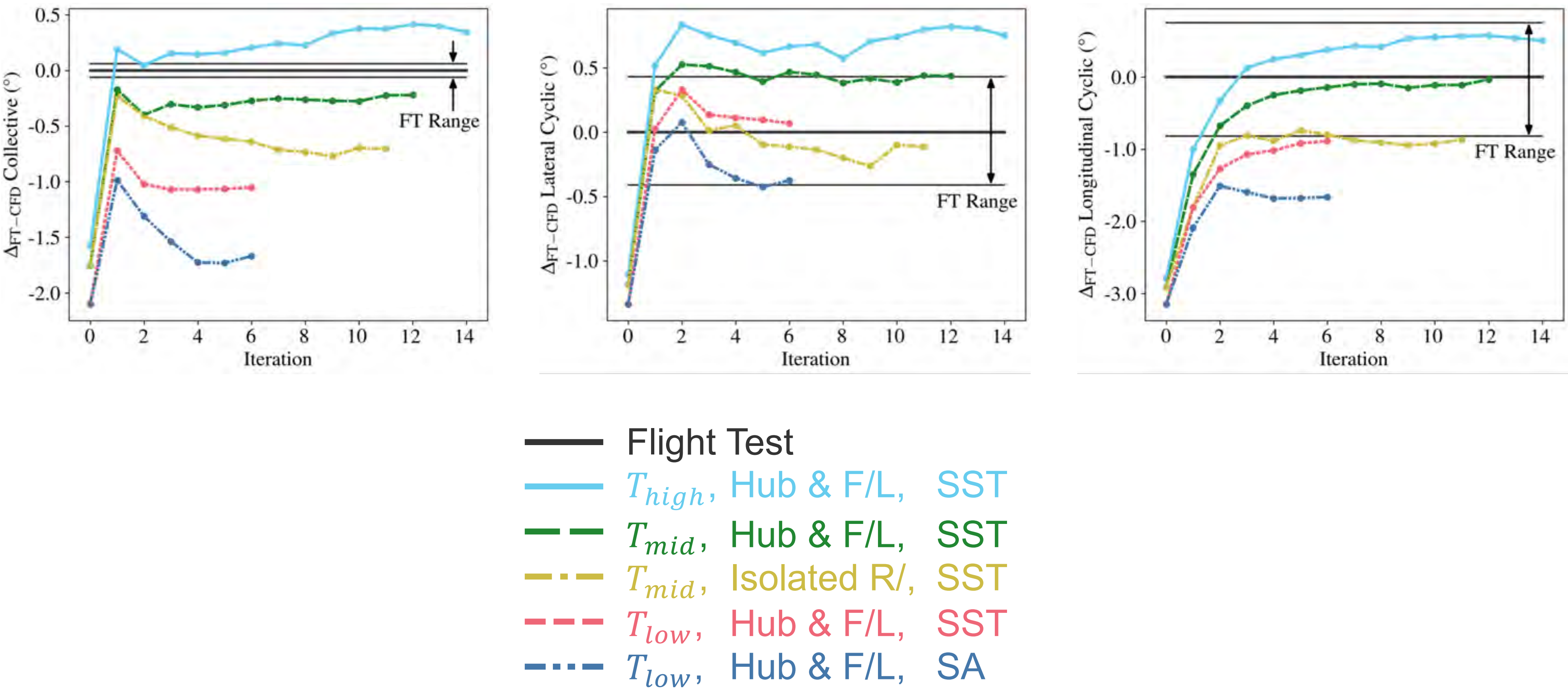
Rotor in High-Speed Turn Flight[6]

Flow-Field Analysis



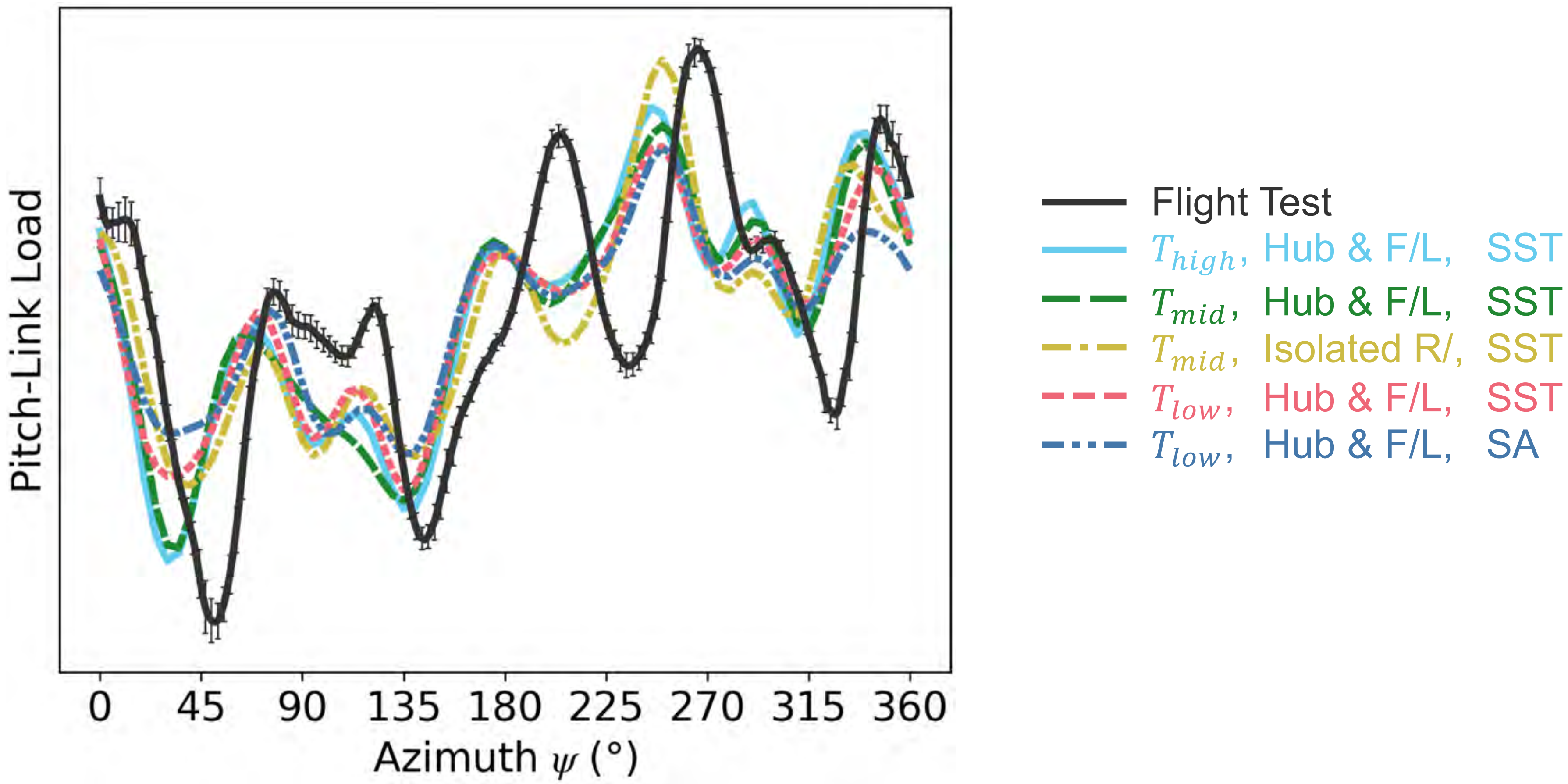
Rotor in High-Speed Turn Flight[6]

Rotor-Trim Convergence History



Rotor in High-Speed Turn Flight[6]

Pitch-Link Loads

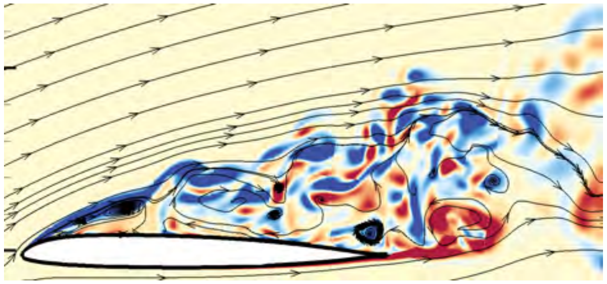


Conclusions

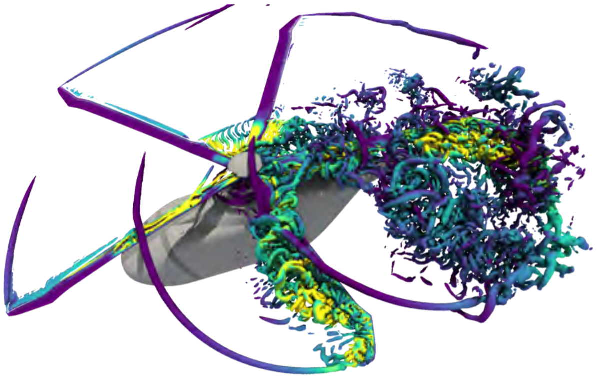
Conclusions

CFD Simulations of Dynamic Stall on Helicopter Rotors

- Model rotor in rotor axial flight
  - CFD loads[1] match well with RTG measurements[3]
  - DDES flow field agrees well with PIV after stall …
  - … but well-known DES weak spots appear[2]
  - Uncertainties in CFD, more participants desirable



- Bluecopter rotor in high-speed turn flight[6]
  - Complex flow field similar to UH60 or 7A DS cases
  - CFD/CSD underpredicts FT pitch-link loads
  - Overall trends agree well



References

References

- [1] Letzgus, J., Gardner, A. D., Schwermer, T., Keßler, M., and Krämer, E., “Numerical Investigations of Dynamic Stall on a Rotor with Cyclic Pitch Control,” Journal of the American Helicopter Society, Vol. 64, (1), 2019, pp. 1–14.
- [2] Letzgus, J., Weihing, P., Keßler, M., and Krämer, E., “Assessment of Delayed Detached-Eddy Simulation of Dynamic Stall on a Rotor,” Proceedings of the 7th Symposium on Hybrid RANS-LES Methods, Berlin, Germany, September 17-19, 2018.
- [3] Schwermer, T., Gardner, A. D., and Raffel, M., “A Novel Experiment to Understand the Dynamic Stall Phenomenon in Rotor Axial Flight,” Journal of the American Helicopter Society, Vol. 64, (1), 2019, pp. 1–11.
- [4] Ramasamy, M., Sanayei, A., Wilson, J., Martin, P., Harms, T., Nikoueeyan, P., and Naughton, J., “Data-Driven Optimal Basis Clustering To Characterize Cycle-to-Cycle Variations in Dynamic Stall Measurements,” Proceedings of the 75^{th} Annual Forum of the Vertical Flight Society, Philadelphia, PA, May 13-16, 2019
- [5] Goerttler, A., Braukmann, J. N., Schwermer, T., Gardner, A. D. and Raffel, M., “Tip-Vortex Investigation on a Rotating and Pitching Rotor Blade”, Journal of Aircraft, Vol. 55, (5), 2018, pp. 1792-1804.
- [6] Letzgus, J., Keßler, M., and Krämer, E., “Simulation of Dynamic Stall on an Elastic Rotor in High-Speed Turn Flight,” Proceedings of the 75^{th} Annual Forum of the Vertical Flight Society, Philadelphia, PA, May 13-16, 2019.

Acknowledgements

Acknowledgements

- This work was partly funded by DFG (German Research Foundation) grant "*Untersuchung der dreidimensionalen dynamischen Strömungsablösung an Rotorblättern*" (investigation of three-dimensional dynamic stall on rotor blades).

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Thank you!

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Collaborative Airfoil Design for Dynamic Stall Performance

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US Army Aviation Development Directorate

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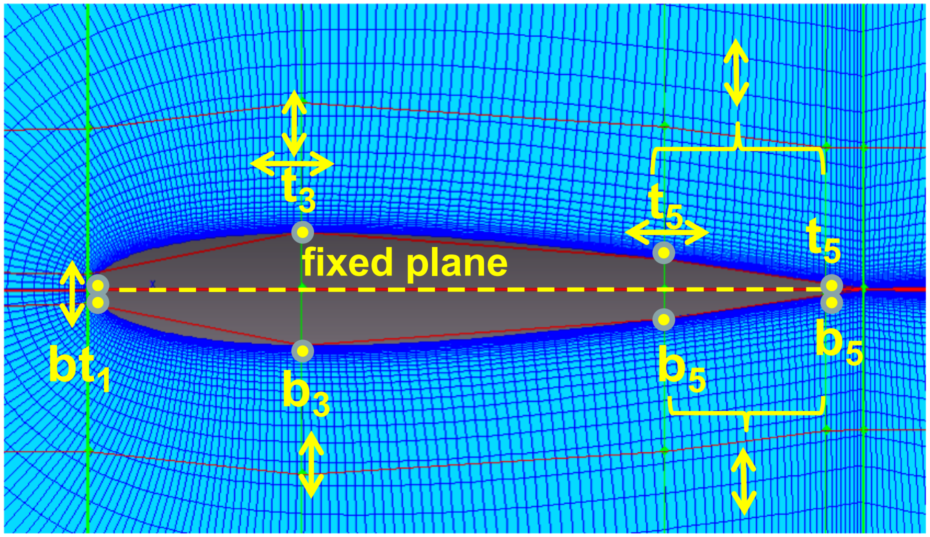
Supported by ARMY SBIR Program Contract W911W60160C-0021

What Progress has been made?

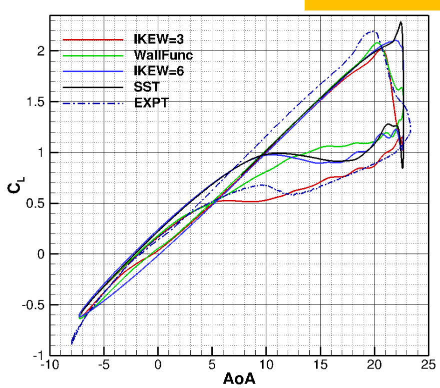
- Concepts Used to Delay the Onset of Dynamic Stall
  - Leading Edge Slats, Trailing Edge Effectors, Vortex Generators etc.
- Retreating Side Powered Blowing Concepts (Min, B-Y et al)
  - Penalties due to Pumping Torque, Complexities with Valve Operation make approach less appealing
- Morphing Airfoil Shape Concepts
  - Dynamically Deforming Leading Edge Concepts (DDLE)
  - Leading Edge Curvature is Dynamically Varied (Chandrashekhara, M.S. et al)
  - Variable Droop Leading Edge Concept (VLDE)
  - Airfoil is Dynamically Drooped on Retreating Side to Delay Separation (Martin, P.B. et al)
- Understanding of Dynamic Stall as a BVI-Induced Stall Event in a Rotor
  - Explanation of 3D Dynamic Stall with BVI Visualization (Neal Chaderjian)
  - Preponderance of Mid-to-Outboard Sections of Blade Seeing Onset of Dynamic Stall
- Re-Interpretation of Wind-Tunnel Data
  - Influence of Cycle-to-Cycle Data especially where bifurcations in separated flow are seen
  - Data Driven Clustering for Characterizing Observations (Ramaswamy, M. et al, Harms, T., et al)

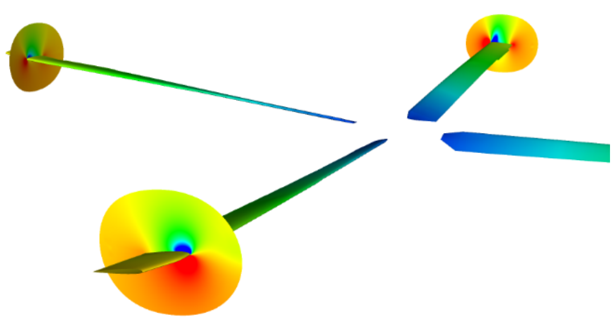
Shape Optimization For Mitigating Dynamic Stall

Parameterization Strategies



CFD Solvers





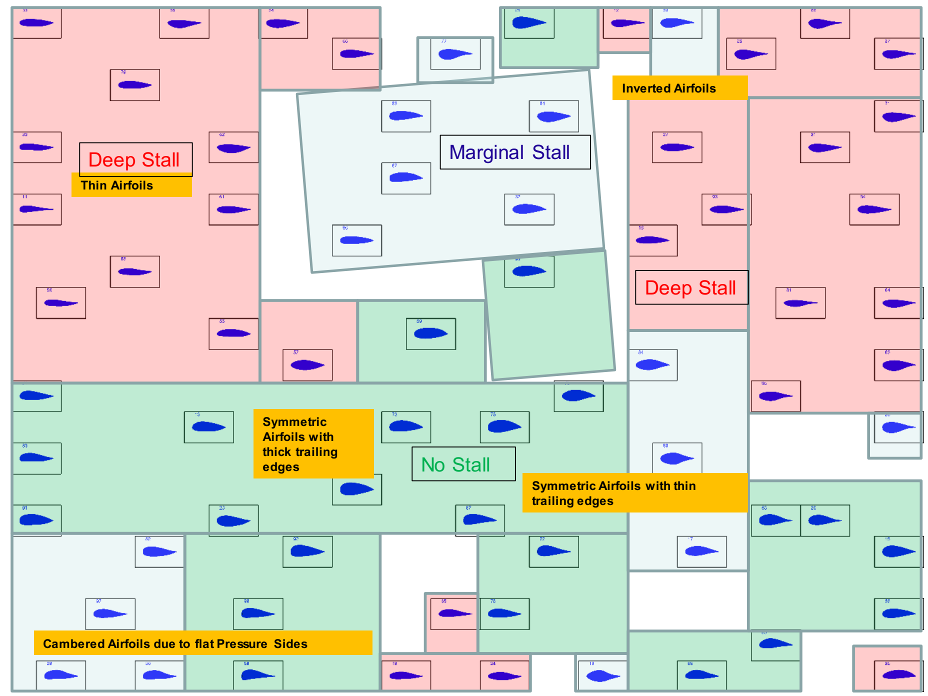
Helios

CRUNCH CFD

Key Question: Can Design of 2-D Airfoil Sections Improve Rotor Performance ?

Knowledge Extraction Process

Design Space Analysis Data → **S**elf **O**rganizing **M**aps (**SOM**) → Correlations between design variables and performance / Design Rules



Design Optimization

Global Optimization Algorithm → Design Variables → Automated Shape Morphing → Reconstructed Unsteady Solution → Time Domain Response → Objective Functions → Global Optimization Algorithm

CRAFT Tech

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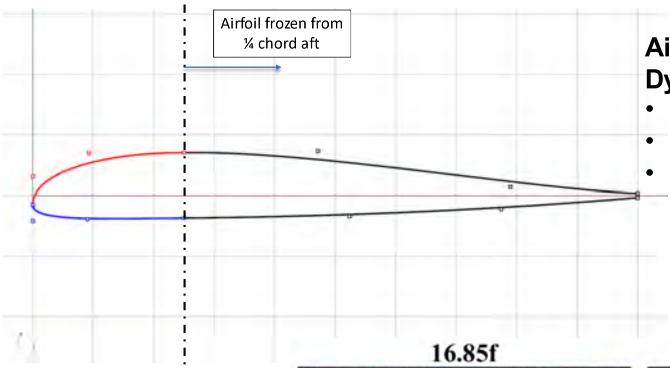
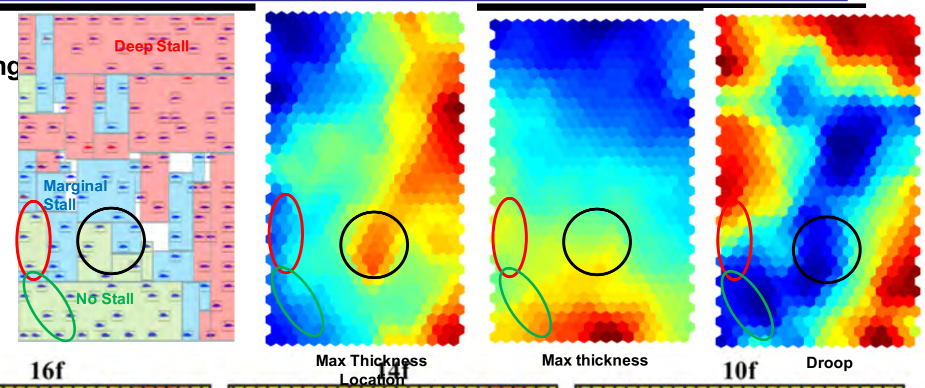
Design of Airfoil Shapes to Alleviate Stall



Airfoil Design Considerations Mitigating Dynamic Stall

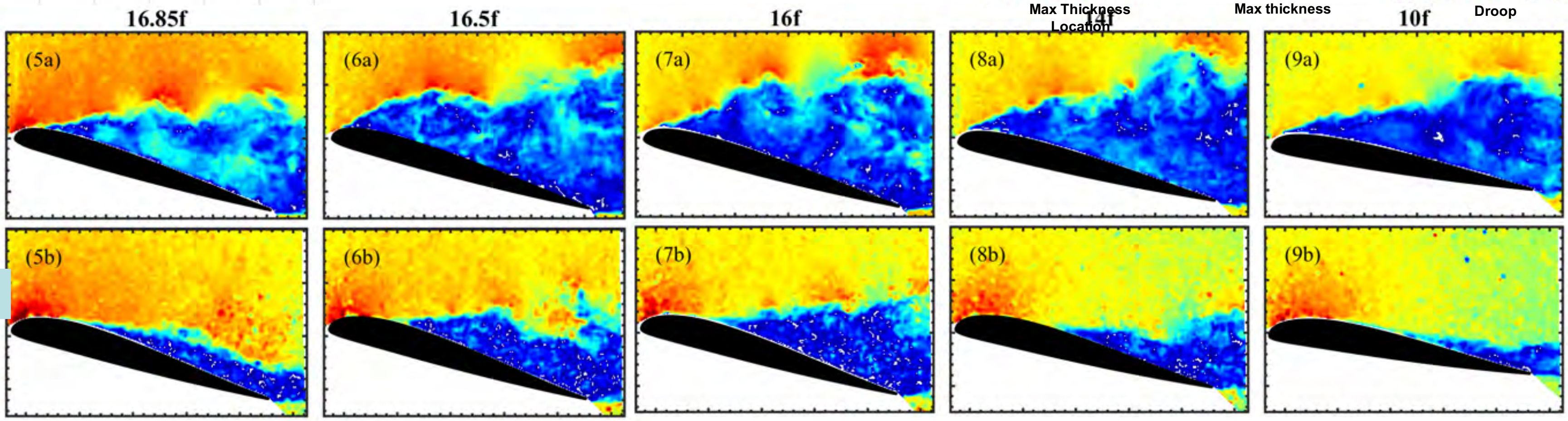
- Leading Edge Shape
- Droop at Leading Edge
- Transition from Quarter chord Thickness to Leading Edge

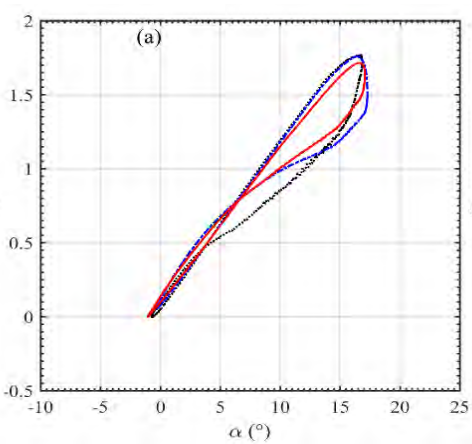


SC1094r8

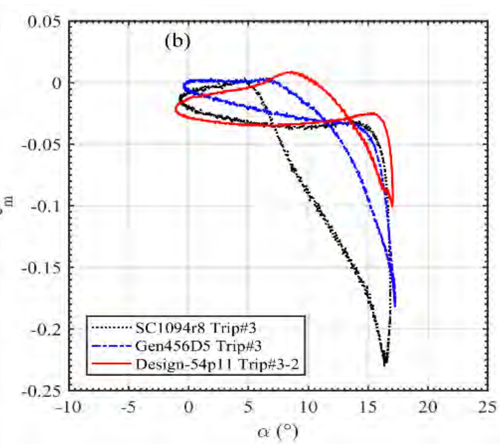
PIV Images

Optimal Design



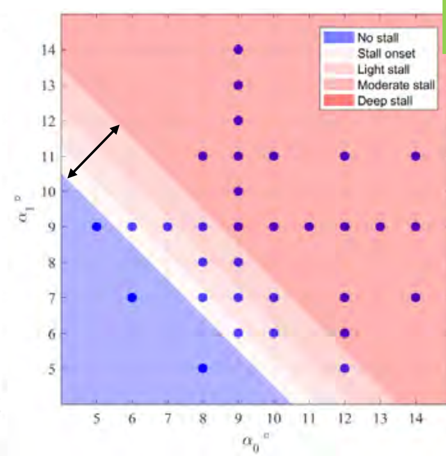


Lift

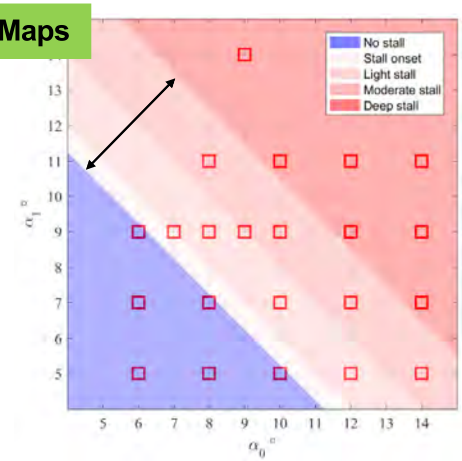


Moment

Stall Maps



SC1094r8



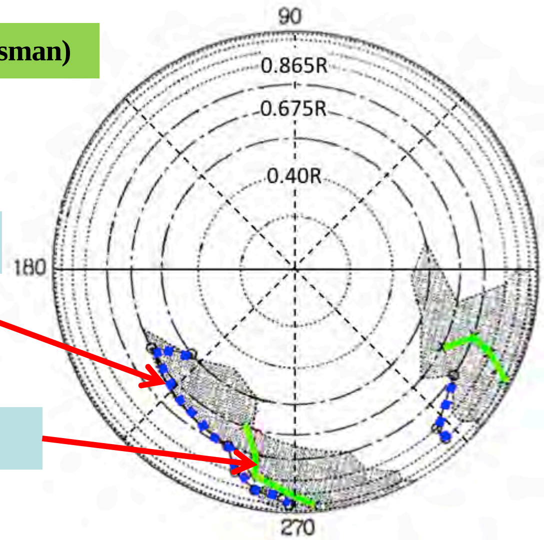
Optimal Design

CRAFT Tech

UNIVERSITY OF WYOMING

Application of Airfoil Designs to Rotor Performance

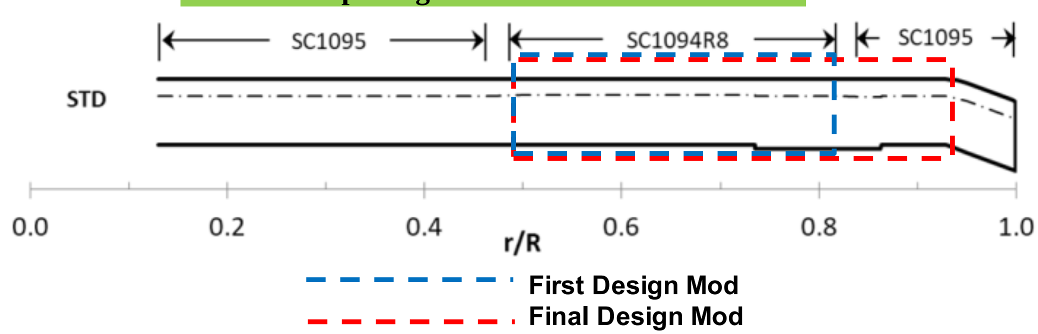
Airloads Data (Bousman)



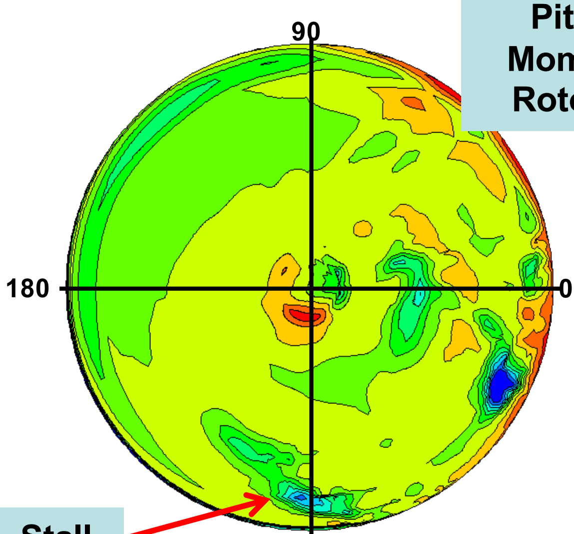
Moment Stall

Lift Stall

Modified UH-60 Rotor with Design Airfoil Sections Replacing SC1094R8 Airfoil

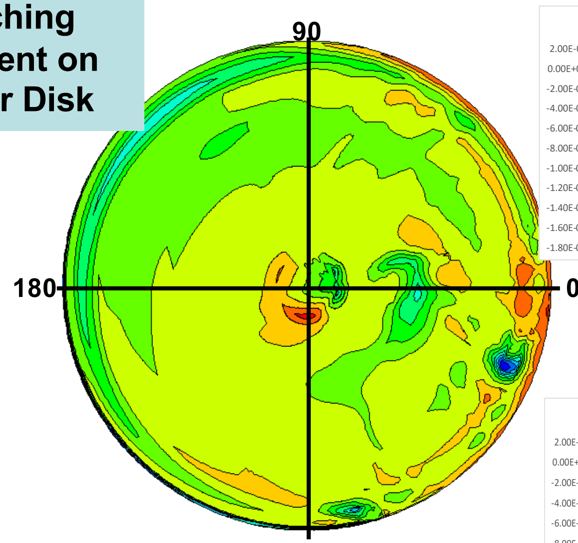


Pitching Moment on Rotor Disk



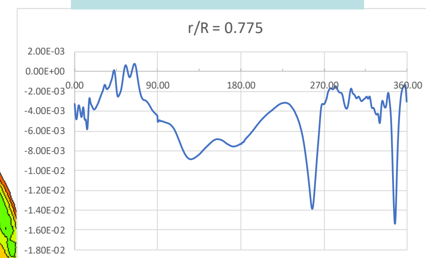
Stall

UH-60A Rotor

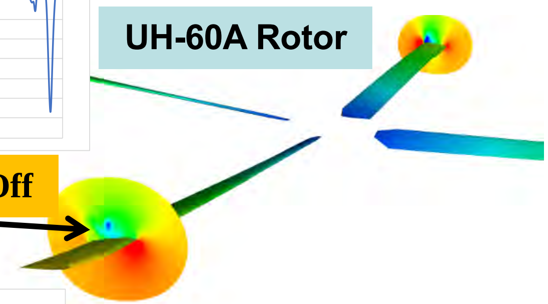


Modified Rotor

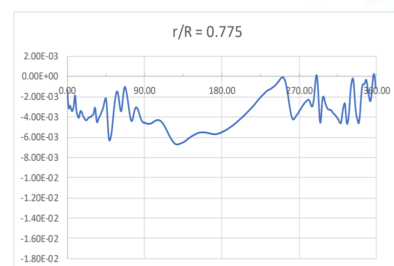
Normal Force



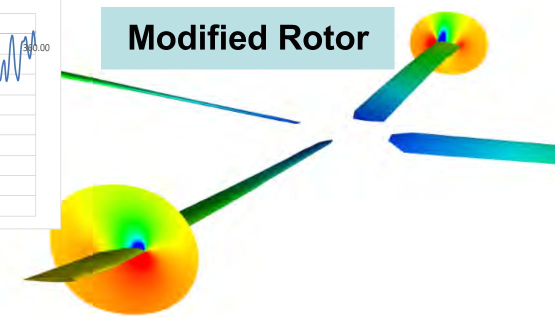
UH-60A Rotor



Stall Vortex Lift-Off



Modified Rotor



C9017 High Thrust Condition
18% Reduction in Shaft Power Requirements

CRAFT Tech

University of Wyoming

What is Next?

- Multi-objective, Multi-Fidelity, Multi-Disciplinary Rotor Design Development
  - The Trade-space between Improving Dynamic Stall Performance and Other Aerodynamic Characteristics has to be mapped out (Advancing Side Drag, Drag-Divergence Mach Number etc.)
  - Since BVI is critical to the onset of stall, design of Rotor Tip may be as important as the Outboard Sections where stall is initiated
  - The optimization process has traditionally been driven by the hysteresis and unsteadiness of the problem; proceed with a multi-fidelity approach where later stages of design take advantage of the advances is modeling
  - Recent Advances such as the Wall model LES approach can be used for separated flows at reduced computational cost
  - Dynamic Stall Rotor Performance in Flight Maneuvers

Flow Control and Mitigation

State of the Art in
Control and Mitigation of Dynamic Stall

Ari Glezer
Woodruff School of Mechanical Engineering
Georgia Institute of Technology

Aerodynamic Flow Control

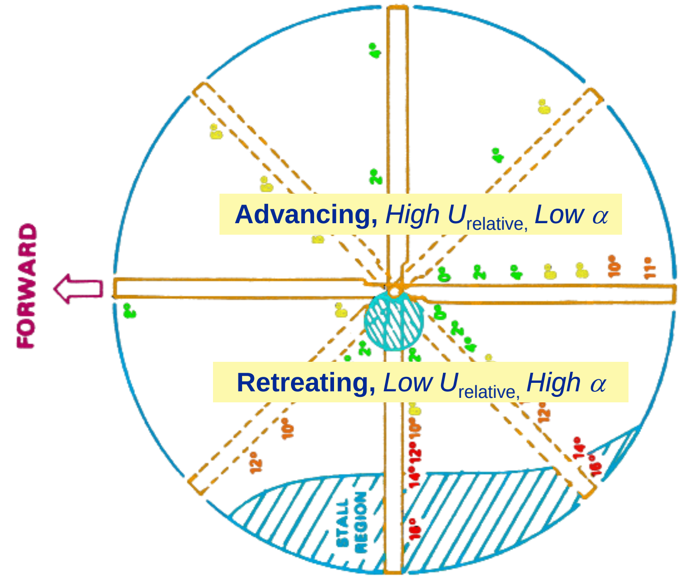
- Improved performance of aerosurfaces by “tailoring” their aerodynamic shape
- External flow control for aerodynamic performance
  - » Maneuver: alter aerodynamic loads ***without moving control surfaces***
  - » Efficiency: reduce drag, mitigate separation losses
  - » Aeroelastic control
  - » Dynamic stall
- Global modifications
  - » “Effect scale” 1-2 orders of magnitude larger than the scale of the actuation.
- Must be effective in two “limits” of separated and attached flows

Actuation Approaches

- “Momentum-based” actuation effective off-surface
  - » Synthetic jets
  - » Fluidic oscillators
  - » Impulse actuation
  - » Active aero breather (surface bleed)
- Plasma actuation (body force)
  - » Dielectric barrier discharge (DBD)
  - » nSec Pulsed
  - » Rail Plasma
- Electromechanical
  - » Piezoelectric
  - » Shape memory alloy

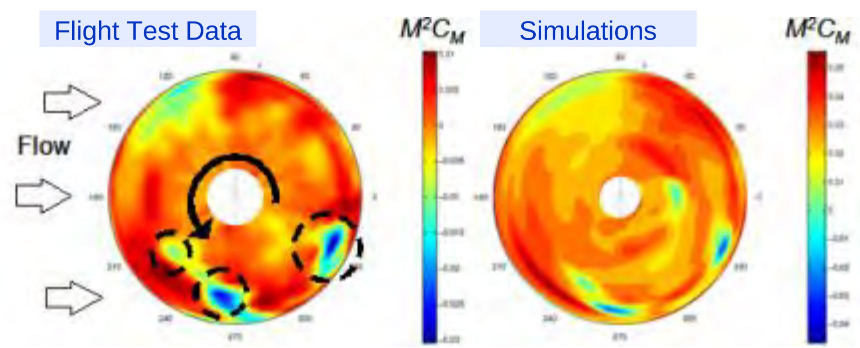
Controlling Dynamic Stall

- Retreating (transitory) blade stall
  - » Primary factor in limiting forward flight speed.
  - » Rotor blade chord is sized for stall (maneuvers).
  - » Production rotorcraft cannot suppress RBS.
- ***Involves two states of transition: flow separation and flow reattachment***
  - » Pitching moment excursions are the most destructive. AFC can mitigate it.
- Flow control for RBS suppression
  - » Mechanical devices (LE slats, TE flaps, and vortex generators) have shown some success, but face challenges.
    - – Achieving **short time-scales** with sufficient **authority**.
    - – Overcoming advancing-side **drag penalt**y.
- ***The primary control challenge is that RBS is 3D and transitory in nature***.
  - » Stall duration for UH-60 about 60 msec [O(10T_{conv})].
  - » Control only needed for portion of rotor cycle.
  - » Stall conditions vary along the blade owing to variation in direction of local tangential velocity and the angle of attack.
  - » ***Active Flow Control***



Army Field Manual 1-203

Azimuthal distribution of blade pitching (Mishra et al., 2009)



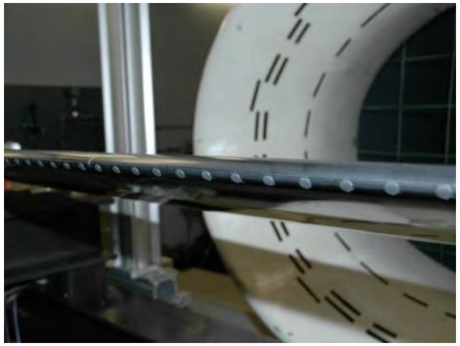
DLR activities in flow control to mitigate dynamic stall

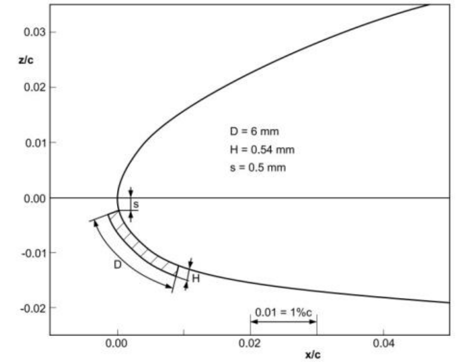
A.D. Gardner
DLR Göttingen

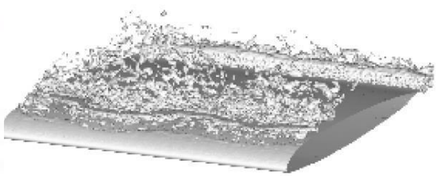
DLR

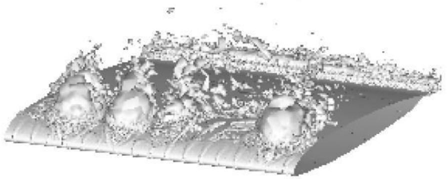
Leading edge vortex generators

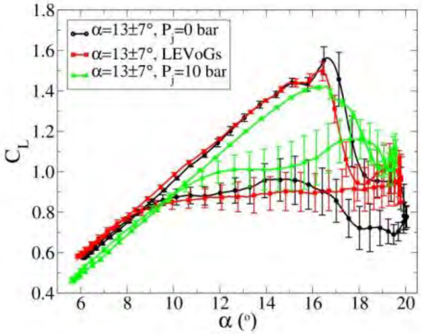
- **Passive flow control method with stick-on discs**
- Easy to apply, tested up to LBA “right to fly” approval as retrofit
- Wind tunnel on multiple pitching airfoils (OA209, EDI-M109, EDI-M112, DSA-9A) and wind tunnels (TWG, 1MG, Onera F2), with CFD and flight testing
- Pitching moment reduction ~25% in deep stall
- Drag increase 5-30 drag counts depending on angle of attack and flow condition



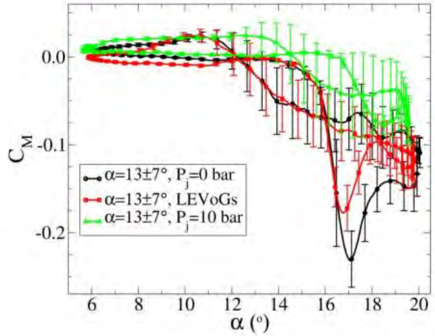








(a) C_L vs α

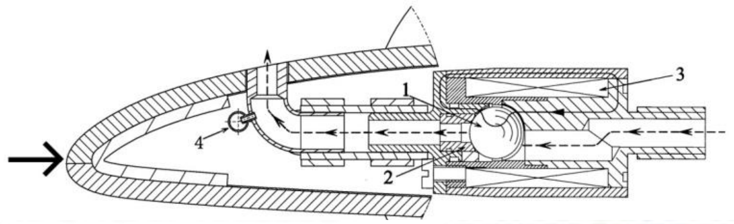


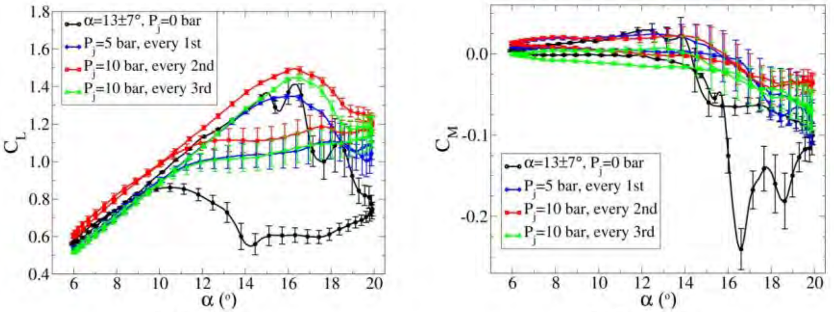
(b) C_M vs α

DLR

Fluidic control devices

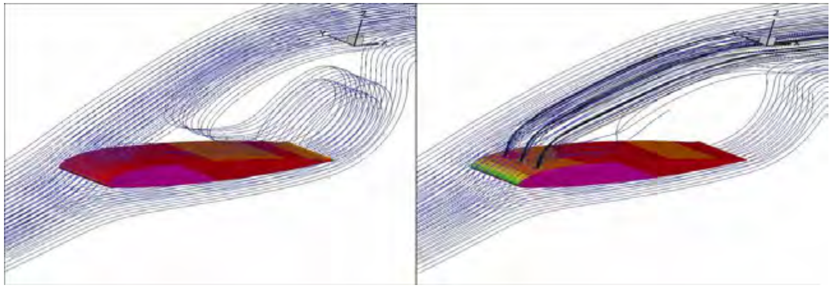
- **Active flow control method using cold air jets**
- Would require new blades with internal tubing and a high-pressure air buffer (a fireman's 10L SCBA tank would offer 1-10 seconds of operation)
- Wind tunnel testing of constant and pulsed blowing on an OA209 airfoil up to Mach 0.5 and CFD
- **Pitching moment reduction 80-90% in deep stall**
- **Instantaneous power on the order of main rotor power (**but probably only needed intermittently)
- No drag increase when turned off.
- **Pulsed operation showed that no increased effect compared to continuous blowing could be achieved**. The flow control effect was only a function of the introduced momentum.
- Experimental difficulties:
  - Pressure integration of the strongly 3D flow from pressure taps needed to be carefully validated
  - **Pulsed high-pressure flow was difficult to achieve**
  - Force-balance measurements were affected by the presence of the pressure-lines
  - PSP was affected by the strong temperature differences between freestream and injected gases

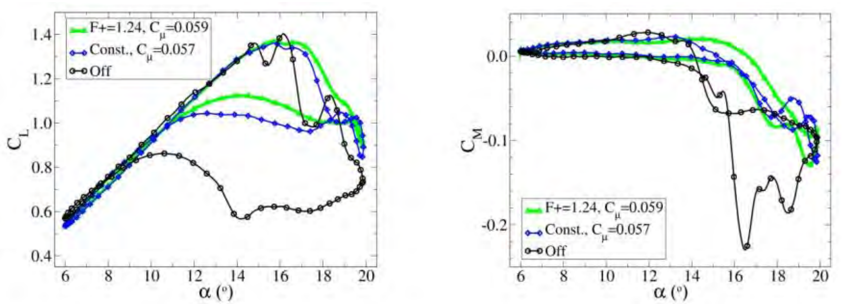




(a) C_L vs α

(b) C_M vs α

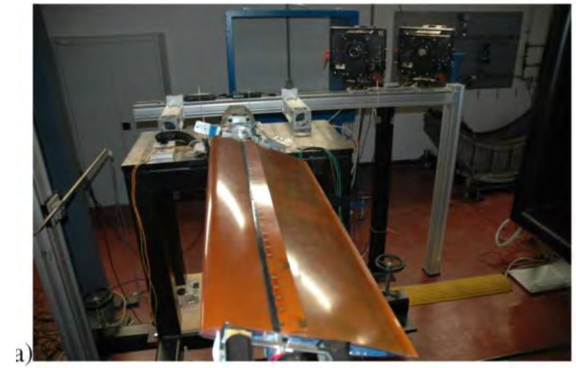




Back-flow flap

- **Passive actuation requiring flap integration**
- Production demonstrator showing single-cure EPDM/Carbon-fibre structure
- Single wind tunnel test (1MG), OA209 airfoil
- **Automatic opening on stall**
- No drag penalty when closed
- Wind tunnel model included active actuation, but could show that it never reached the performance of the passive actuation
- Pitching moment reduction of 20-25% in deep stall

- **For the “Light Stall” case care must be taken with active opening of the flap or it can make the dynamic stall worse**
    - The passive flap completely suppresses light dynamic stall using small opening angles
- For deep stall the stall peaks are reduced by 20-25%, by splitting the single stall vortex into smaller vortices, moving it away from the surface and slowing the flow speed



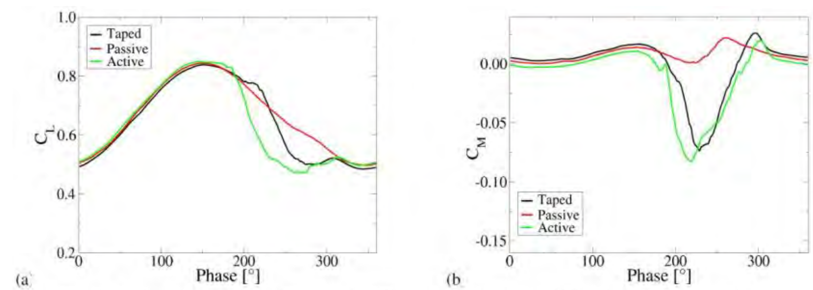
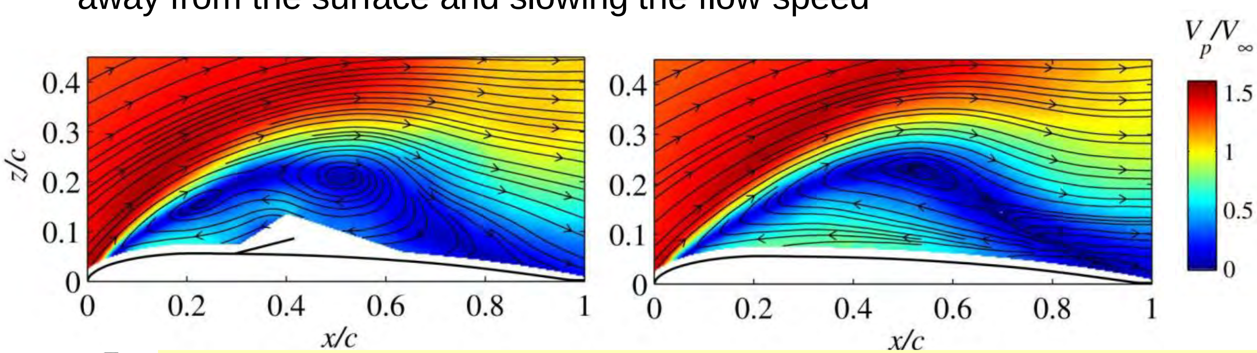
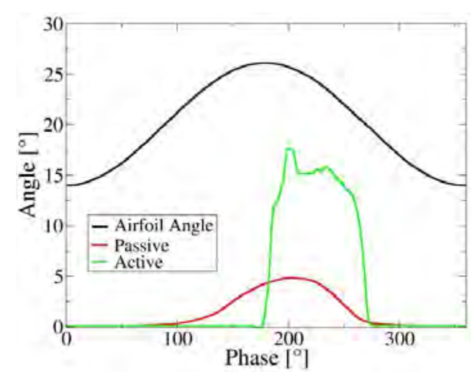


Fig. 19. Effect of the flap for $\alpha=20\pm6^\circ$ at 2.5 Hz (a) Lift coefficient (b) Pitching moment coefficient





- We note that it is difficult to make generalisations due to a lot of details about the implementation

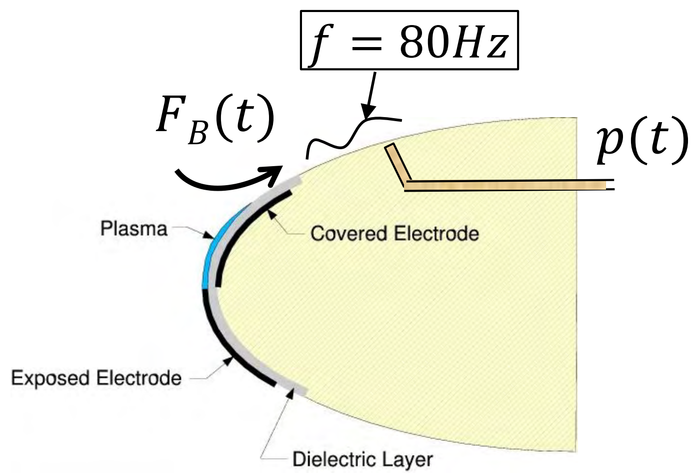
DLR

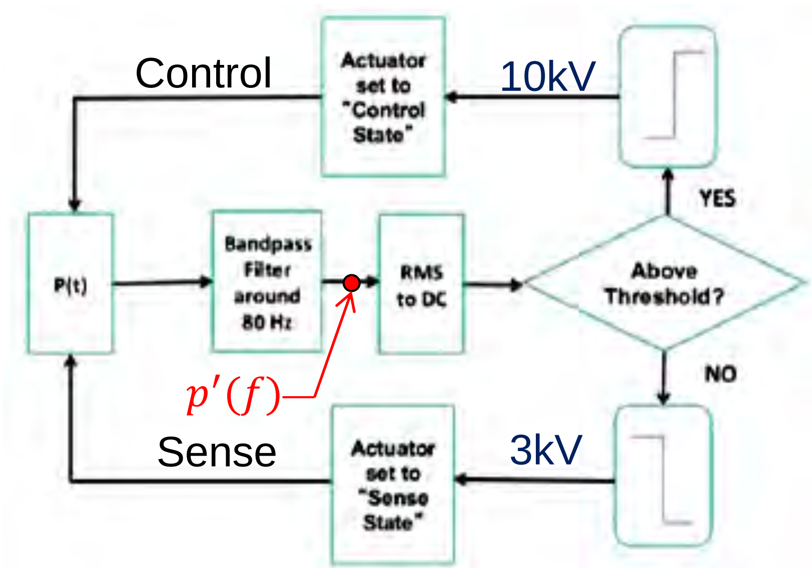
Closed-loop Dynamic Stall Control Using a Plasma Actuator

Thomas Corke
University of Notre Dame
Institute for Flow Physics and Control
Aerospace and Mechanical Engineering
Notre Dame, IN

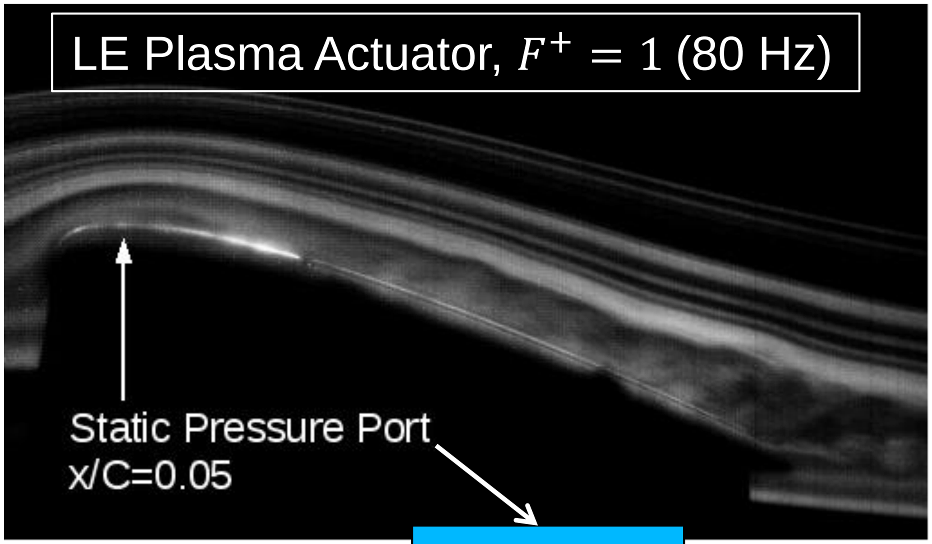
Approach

- Closed-loop control to mitigate the negative impact of dynamic stall
  - Lower power produces a disturbance that can be detected by the pressure sensor located at a downstream position
- Particular focus on torsional instability of the rotor blade resulting from reduced **or negative** aerodynamic damping.
- Plasma actuator located at leading edge of rotor, producing unsteady pulsing at a given reduced frequency, $f^+ = fc/U_\infty = 1$.

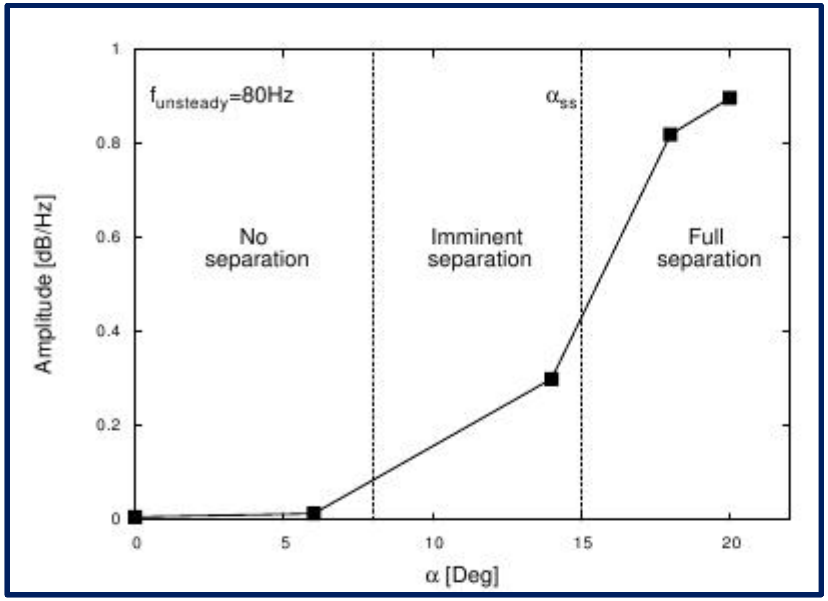


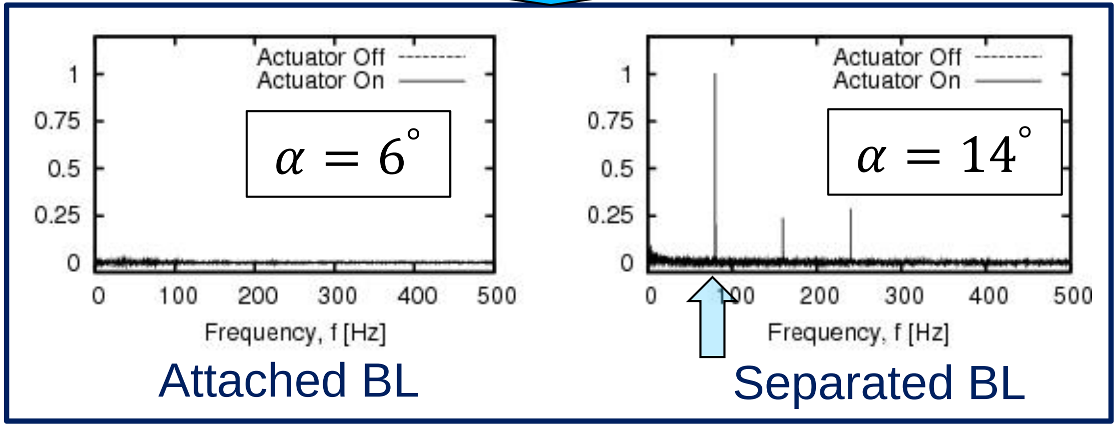


Stall Detection



P' Spectra





Stall detection based on energy in $p'(t) = 80\text{Hz}$

Light Stall Control

<u>Light Stall</u>

$k = 0.08$

$\alpha_0 = 10^{\circ}$

$\alpha_1 = 8^{\circ}$

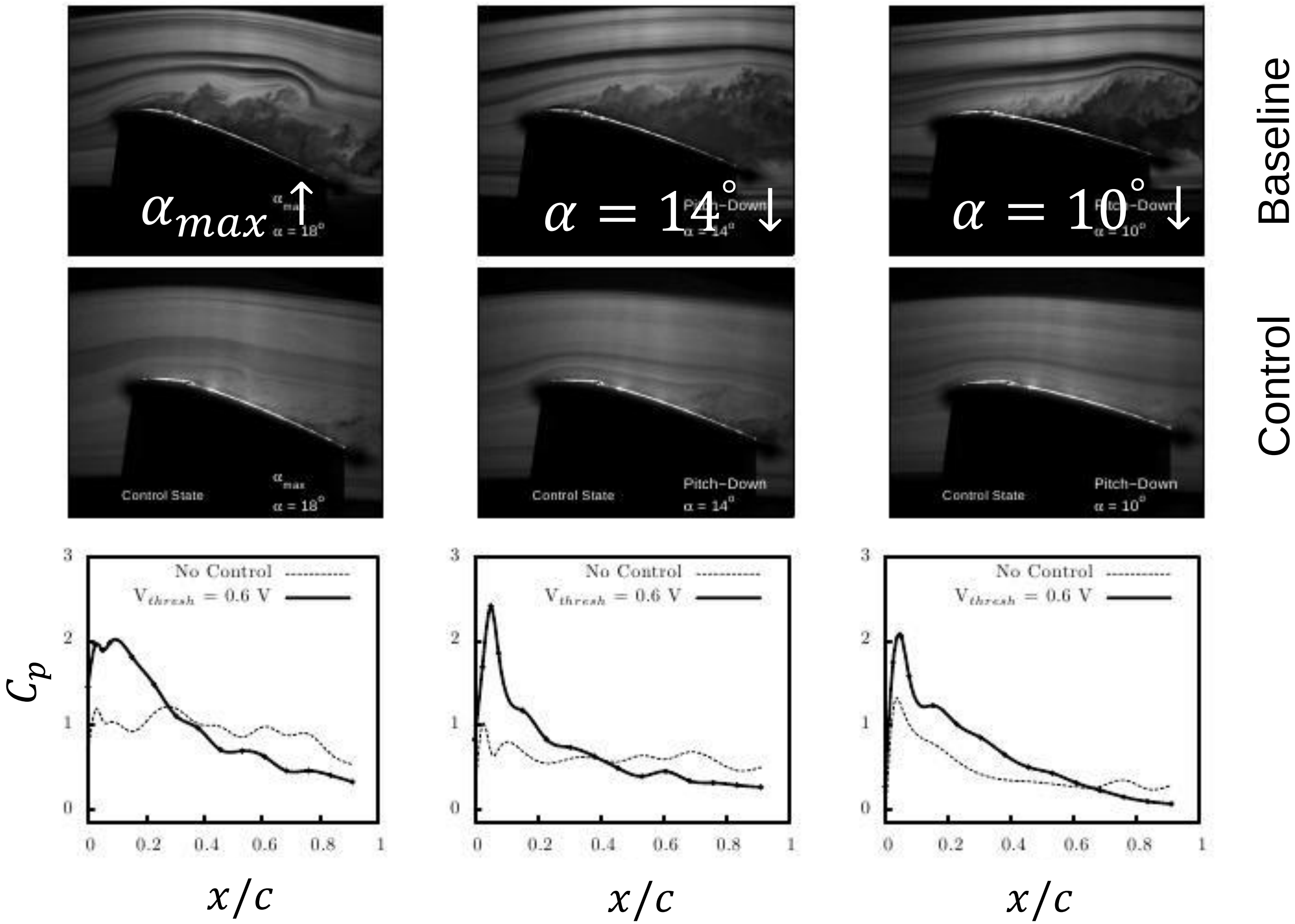
<u>Detection Threshold 1</u>

$F^{+} = 1$

ON: $\uparrow 13^{\circ}$

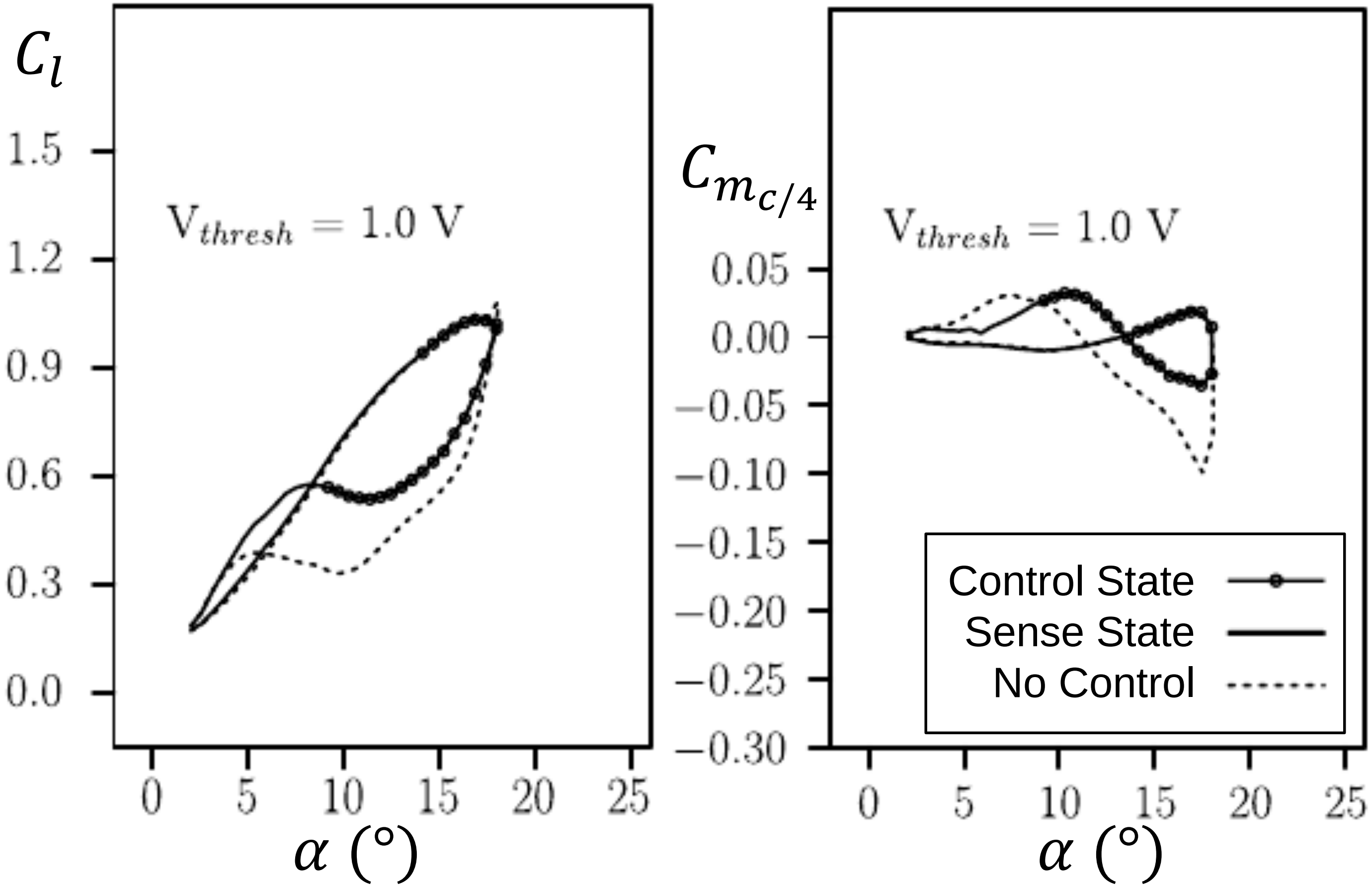
OFF: $\downarrow 8^{\circ}$

46.7% Cycle



Lift and Moment Cycle Improvement

Threshold 1: ON: ↑ 13°; OFF: ↓ 8°; 46.7% Cycle



ΔC_l: +15%
$\Delta C_{m_{c/4}}$: -60%

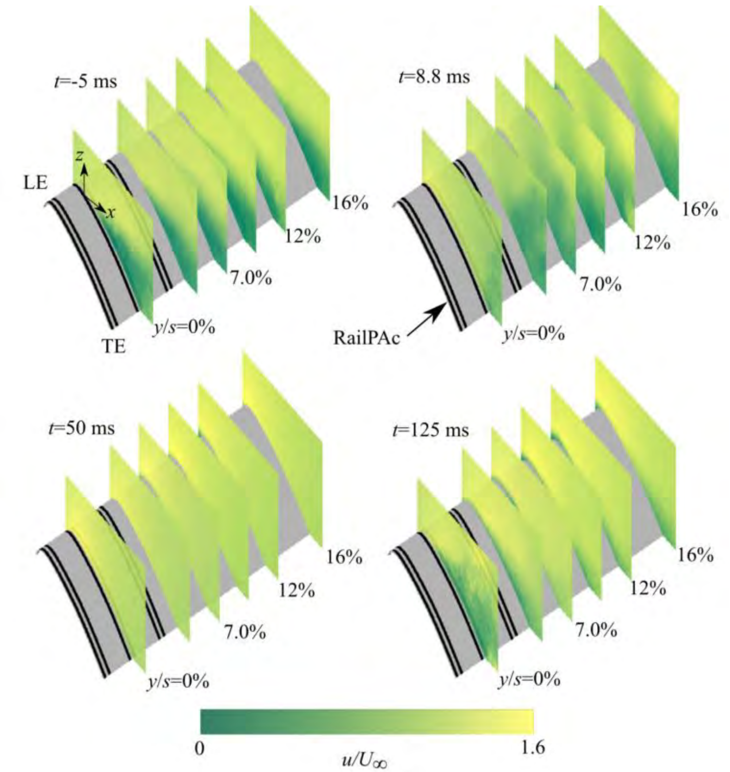
Stall Alleviation using Magnetohydrodynamic Plasma Actuators

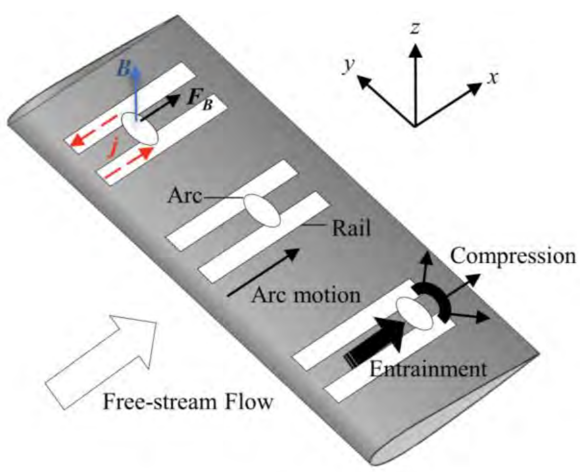
Jayant Sirohi

UT Austin

Magnetohydrodynamic plasma actuators: Most Promising/Significant Findings

- Solid-state, high-bandwidth flow control device
- Can introduce large transient momentum into the flow (comparable to combustion actuators) without needing cavities in the blade
- Momentum imparted by the actuator has been measured – found comparable to combustion type actuators
- Static stall alleviated at *Re* up to 90,000





Dynamic Stall Control

Miki Amitay

Rensselaer Polytechnic Institute

Rensselaer

Center for Flow Physics and Control

CFES

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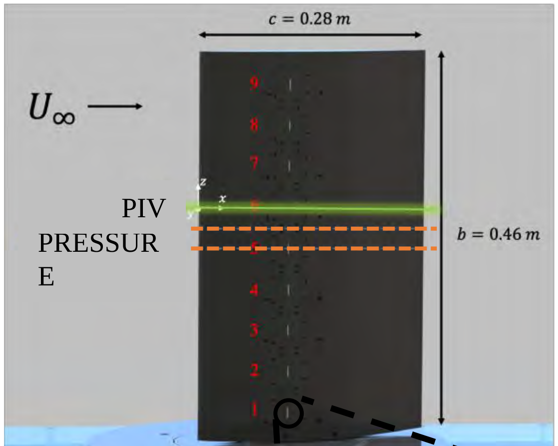
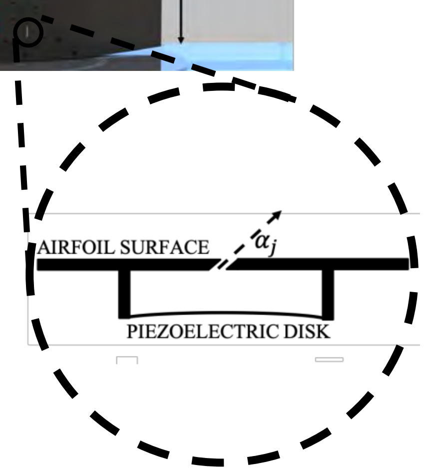
CeFPaC Experimental Setup

MODEL:
c = 0.28 m
b = 0.46 m
AR = 1.64

$U_\infty = 20\ m/s$
$Re = 375{,}000$



ACTUATORS:
$\frac{x}{c} = 0.15, or\ 0.35$
$AR_j = 12$
$U_j\ =\ 75\ m/s$
$C_\mu\ =\ 0.012$
$f_{act}\ = 1800Hz$

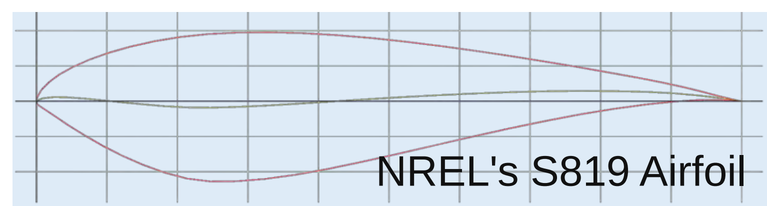


METHODS:

- Surface pressure: **10s** at **125** Hz
- Load cell: **120s** at **5700** Hz
- SPIV:
  - Static: **500** independent images
  - Dynamic: **250** phase locked images at **24** phases along cycle

DYNAMIC STALL:

- $k_f\ = {}^{\omega c}/_{2U_\infty} = 0.025$
- $\bar{\alpha} = 15°;\ \alpha_A = 3°, 5°$
- $\alpha = \bar{\alpha} + \alpha_A \sin(2\pi f_P t)$



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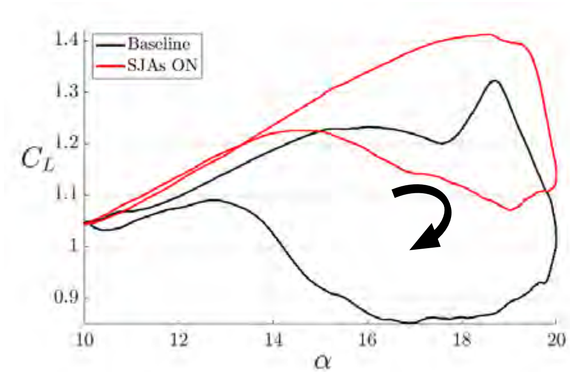
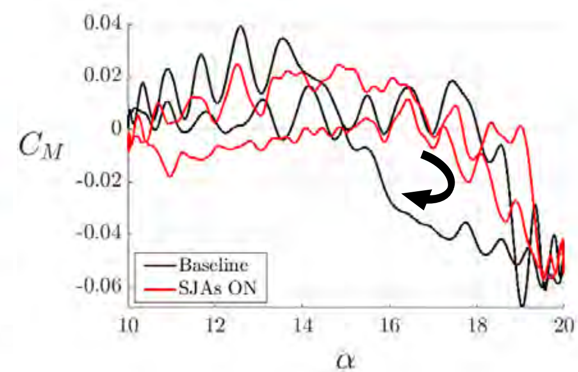
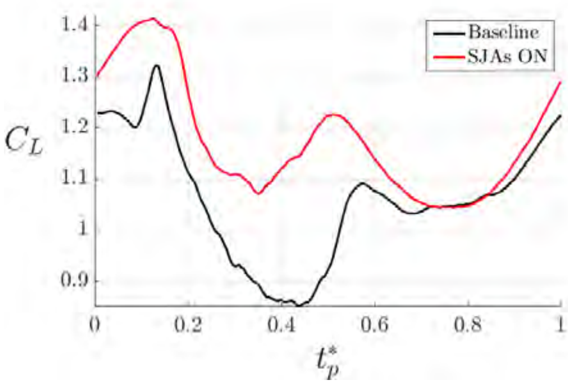
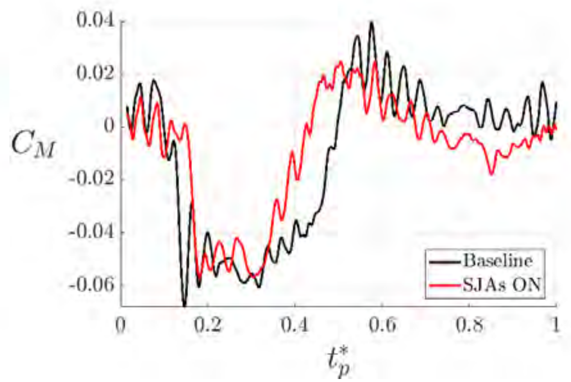
Deep Dynamic Stall Results (2D)









<u>Pitch Parameters:</u>

$\bar{\alpha} = 15°$

$\alpha_A = 5°$

$f_p = 0.57$ Hz

$k_f = 0.025$

<u>Actuation Parameters:</u>

$f_{act} = 1800$ Hz

$F^+ = f_{act}c/U_\infty \sim \mathcal{O}(10)$

$U_{peak} = 75$ m/s

$C_\mu = 0.012$

$x/c = 0.35$

<u>Takeaways:</u>

- Vortex induced lift overshoot eliminated
- Pitching moment deviation *reduced.*
- Area within hysteresis loop reduced by 47% for C_L and 24% for C_M
- Range of loads reduced by 25% for C_L and 21% for C_M.

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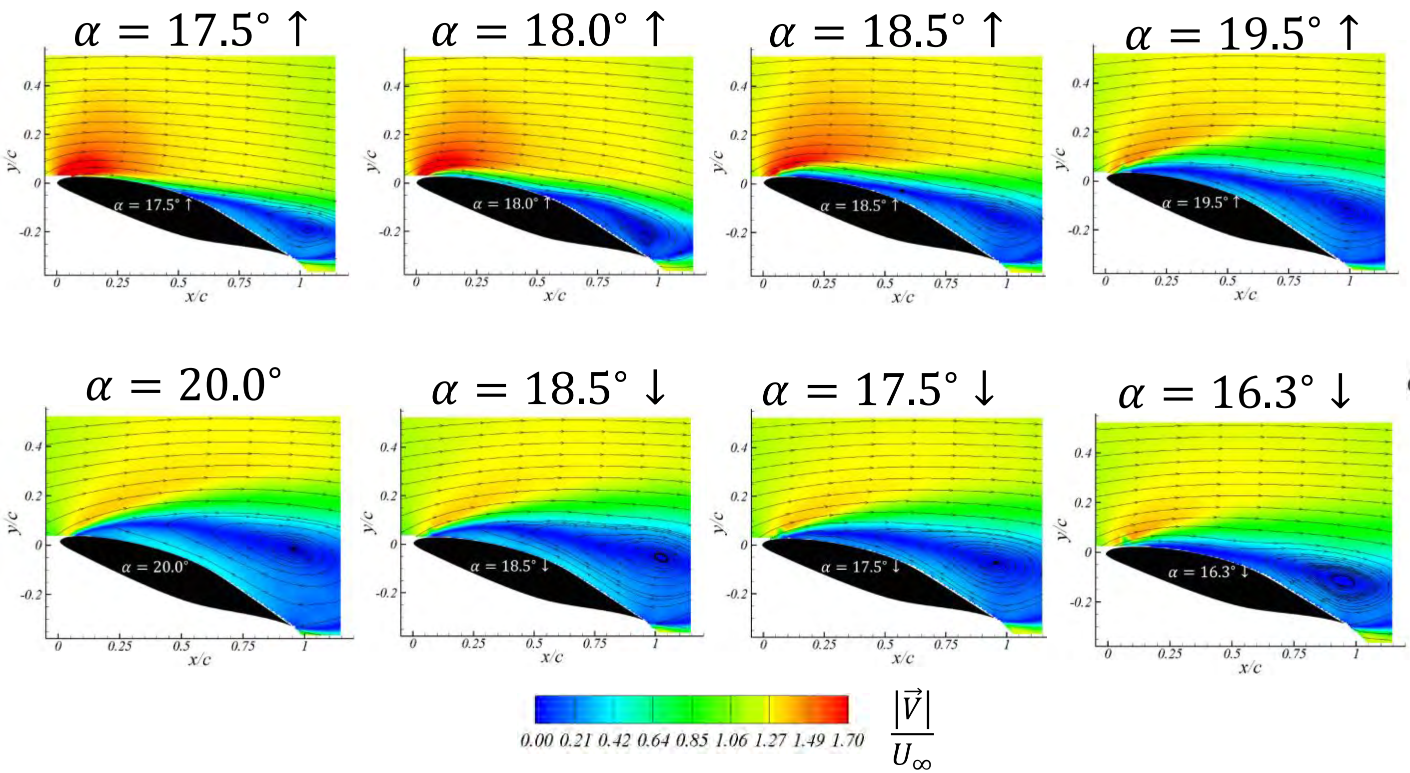
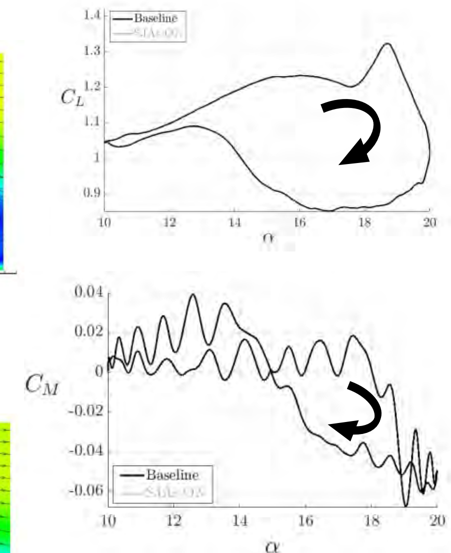
Deep Dynamic Stall Results: Baseline (2D)





<u>Pitch Parameters:</u>
$\bar{\alpha} = 15°$
$\alpha_A = 5°$
$f_p = 0.57$ Hz
$k_f = 0.025$

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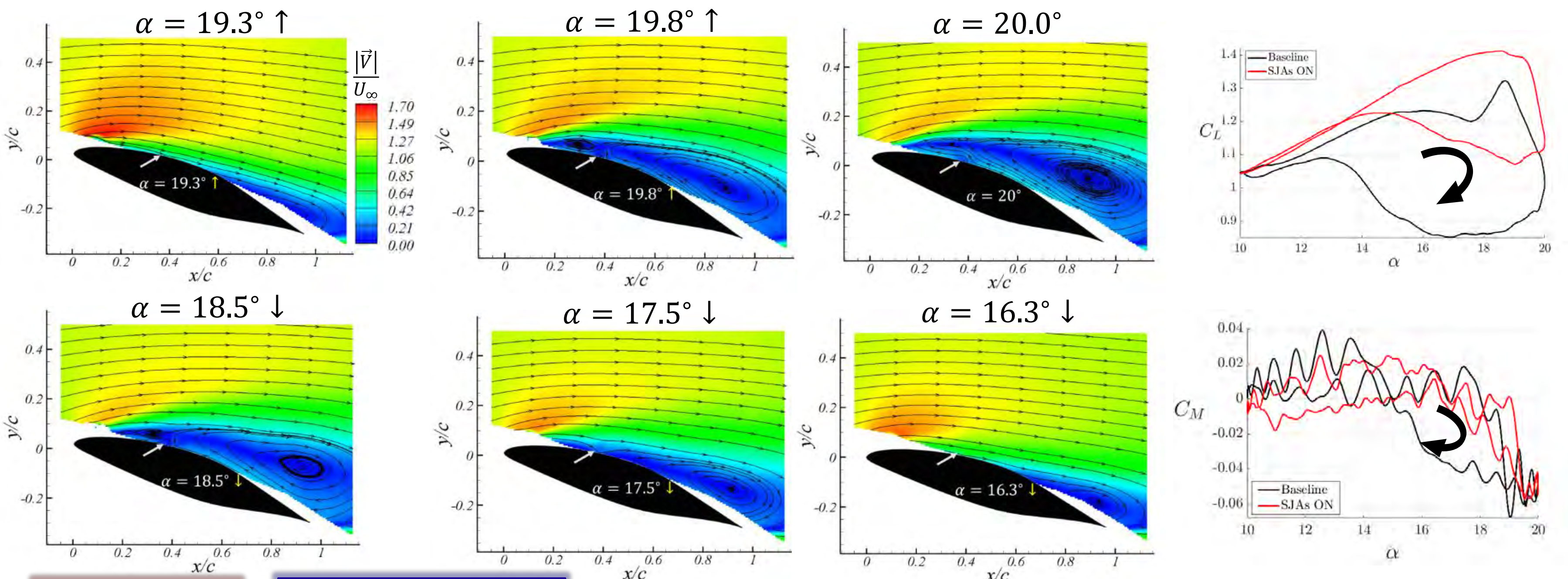
Deep Dynamic Stall Results: SJAs ON (2D)

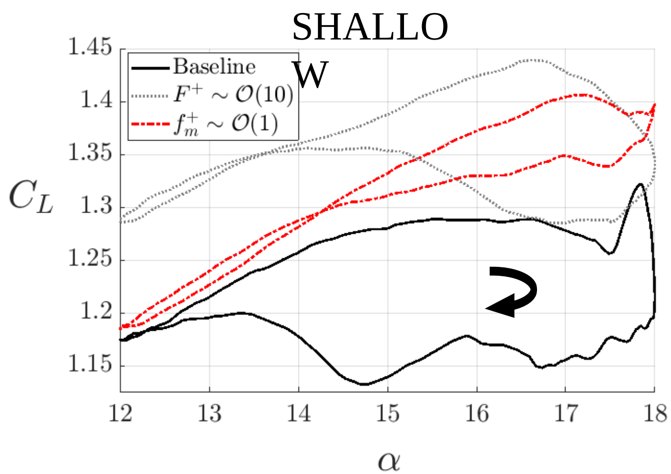


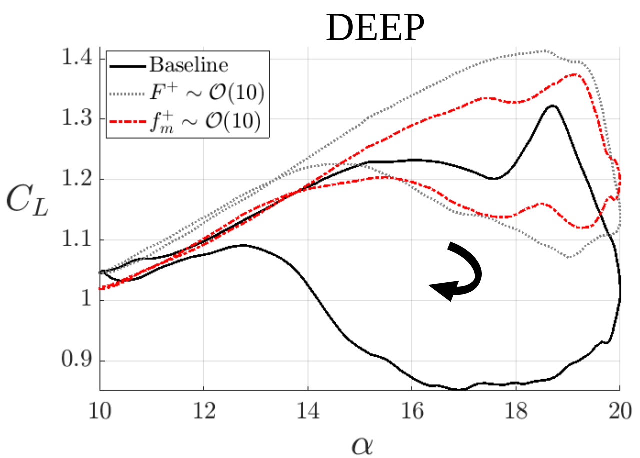
Pitch Parameters:
$\bar{\alpha} = 15°$
$\alpha_A = 5°$
$f_p = 0.57$ Hz
$k_f = 0.025$

Actuation Parameters:
$f_{act} = 1800$ Hz
$F^+ = f_{act}c/U_\infty \sim \mathcal{O}(10)$
$U_{peak} = 75$ m/s
$C_\mu = 0.012$
$x/c = 0.35$

Lift overshoot eliminated, despite allowing separation.
Lift and Pitching moment hysteresis reduced.
Separation (and thus, pitching moment deviation) still occurs.

Dynamic Stall Loads: Lift Coefficient





<u>Pitch Parameters:</u>
$\bar{\alpha} = 15°$
$\alpha_A = 3°, 5°$
$f_p = 0.57$ Hz
$k_f = 0.025$

<u>Actuation Parameters:</u>
$f_{act} = 1800$ Hz
$f_m = 100\ Hz$
$f_m^+ \sim 1$
$DC = 35\%$
$U_{peak} = 75$ m/s
$x/c = 0.35$

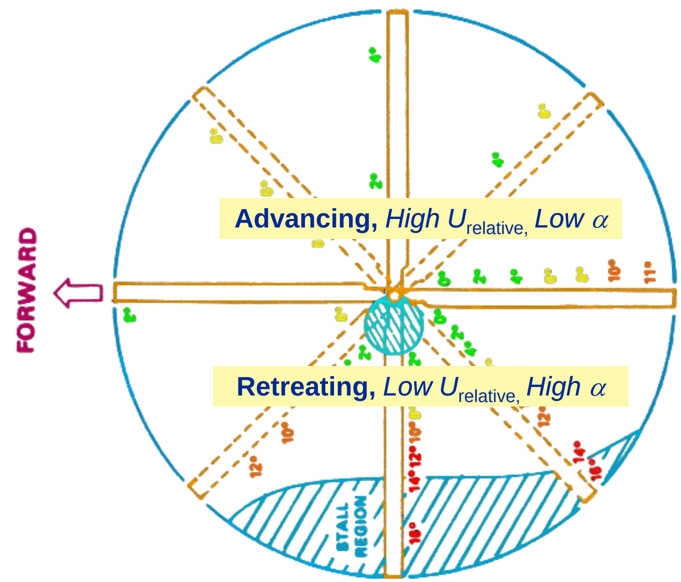
<u>Benefits of pulse modulation:</u>
Further reduction of lift hysteresis
Near elimination of DSV induced lift overshoot
65% less power consumption

Control and Mitigation of Dynamic Stall using Transitory, Pulsed Actuation

Y. Tan, G. Woo, T. Crittenden and Ari Glezer
Woodruff School of Mechanical Engineering
Georgia Institute of Technology

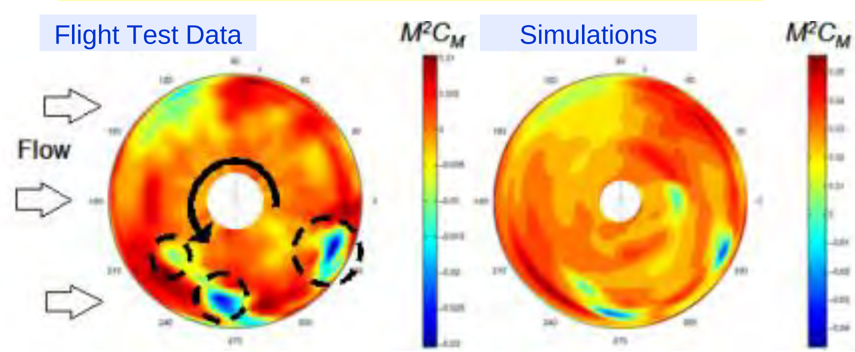
Controlling Dynamic Stall

- Retreating (transitory) blade stall
  - » Results from reduced relative velocity over retreating blade at high forward flight speed, coupled with increased blade pitch to equalize lift.
  - » Primary factor in limiting forward flight speed.
  - » Rotor blade chord is sized for stall (maneuvers).
  - » Production rotorcraft cannot suppress RBS.
- Flow control for RBS suppression
  - » Mechanical devices (LE slats, TE flaps, and vortex generators) have shown some success, but face challenges.
    - – Achieving **short time-scales** with sufficient **authority**.
    - – Overcoming advancing-side **drag penalt**y.
- The primary control challenge is that RBS is 3D and *transitory in nature*.
  - » Stall duration for UH-60 about 60 msec [O(10T_{conv})].
  - » Control only needed for portion of rotor cycle.
  - » Stall conditions vary along the blade owing to variation in direction of local tangential velocity and the angle of attack.
  - » ***Transitory pulsed actuation (COMPACT)***



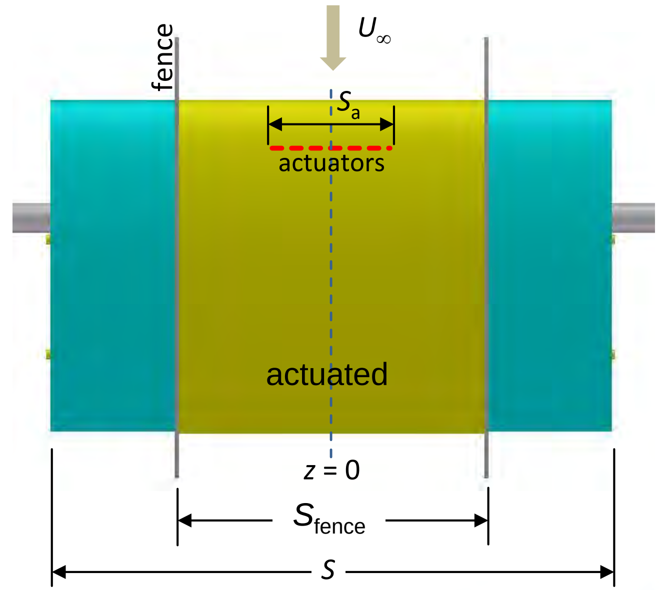
Army Field Manual 1-203

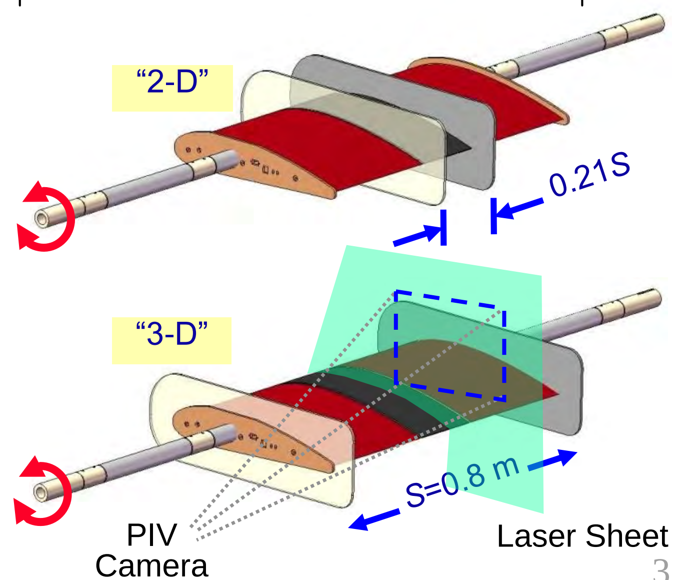
Azimuthal distribution of blade pitching (Mishra et al., 2009)

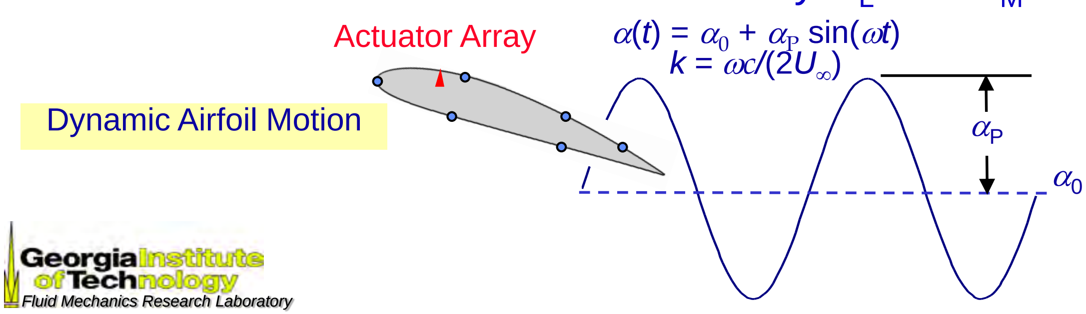


Experimental Setup

- 2D NACA 4415 airfoil
  - » c = 457 mm, S = 0.8 m
  - » 75 static pressure ports at mid-span
  - » Fast-response pressure transducers
- Spanwise COMPACT jet array
  - » $x_a = 0.15c$, $S_{act} \leq 0.21S$
- Wind Tunnel experiments
  - » 0.9 x 0.9 m test section
  - » U_∞ = 20 m/s, Re_c = 570,000
  - » Convective time scale, $T_{conv} = c/U_\infty \approx 25$ ms
- 2-D bounded and 3-D unbounded actuation
  - » Adjustable flow partitions, $0.21 \leq S_{fence}/S \leq 1$
- Model mounted on traverse for pitch oscillations
  - » Load cells measure unsteady C_L and C_M

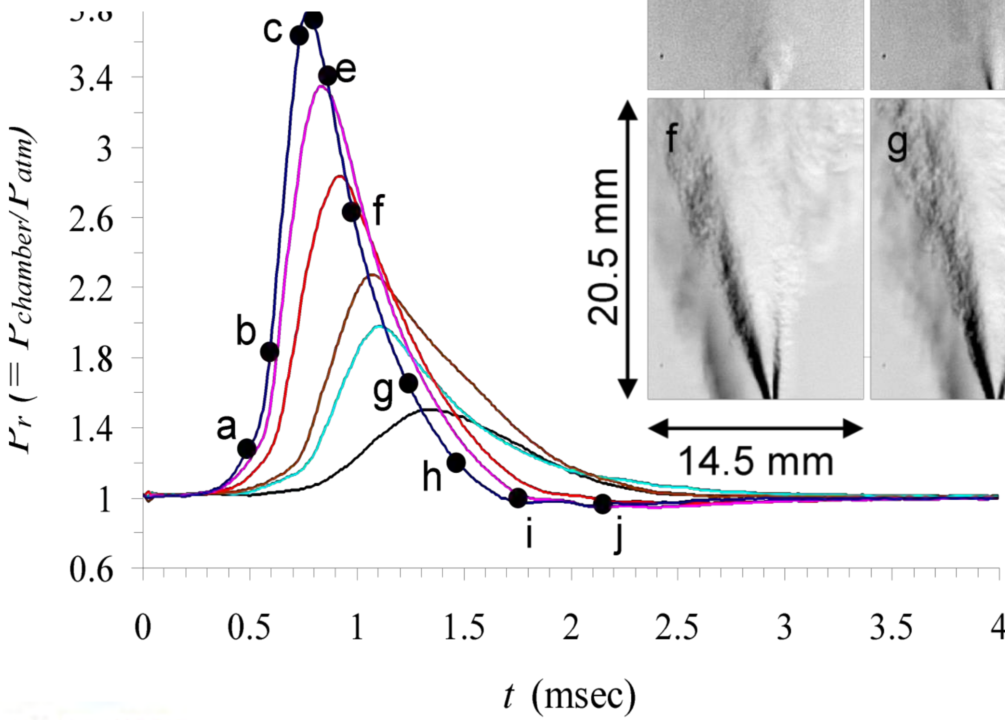


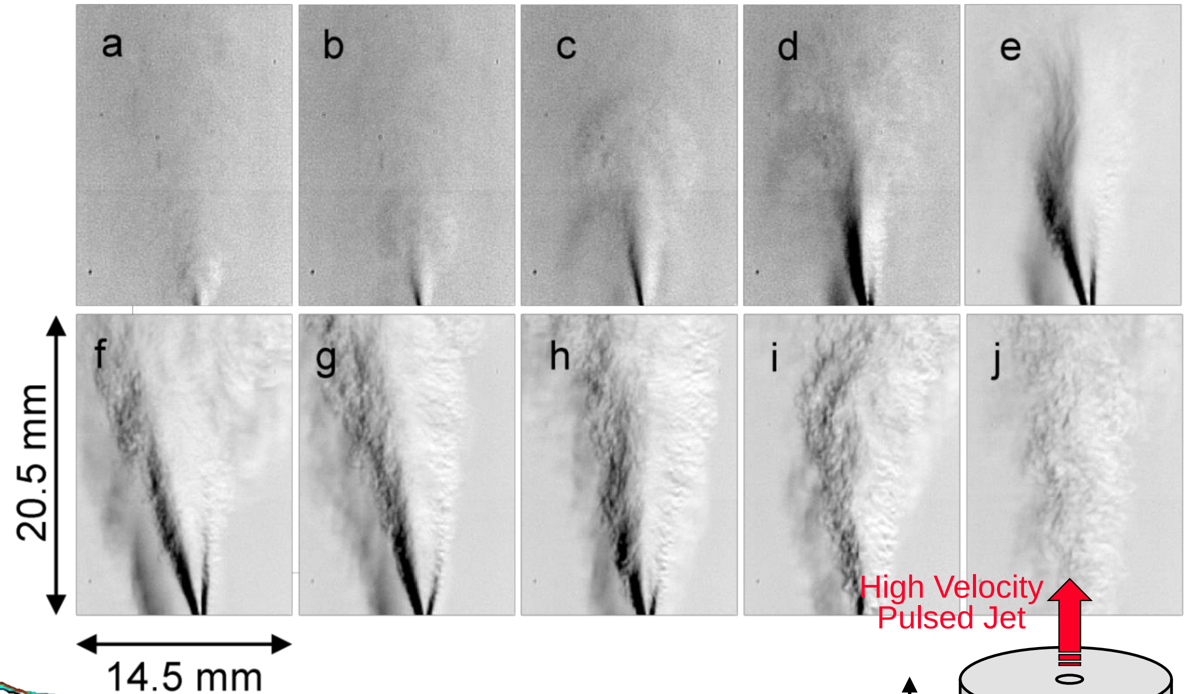


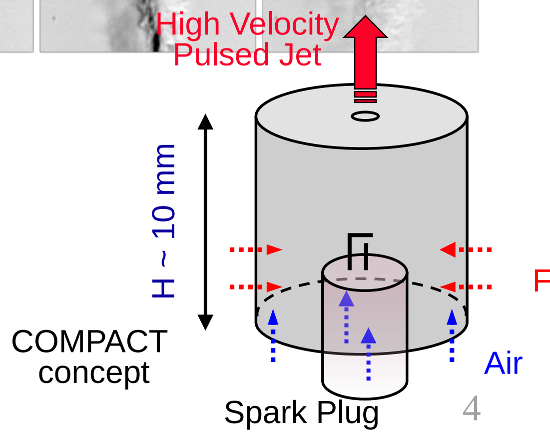


Pulsed Jet

- Near supersonic jet
- Strength of jet is controllable based on combustion parameters (e.g. T_{rep}, ϕ)







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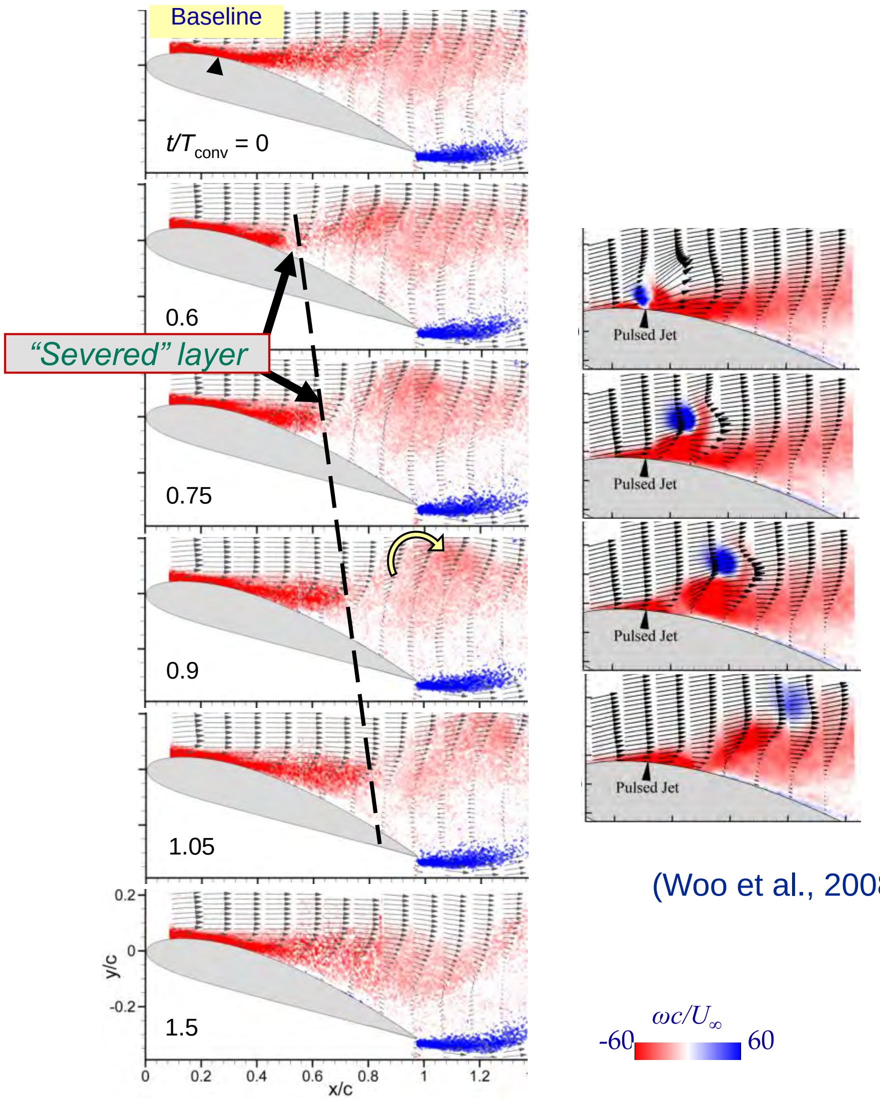
Transitory, Pulsed Actuation

- Earlier work at Georgia Tech demonstrated that a *brief actuation impulse* of a separating flow leads to momentary collapse of the separation domain and to transitory increase in lift.
- *Transitory actuation* exploits the *dynamic coupling* between *vorticity production, accumulation, and shedding*, and the *motion of a lifting surface*.



(Woo et al., 2008)

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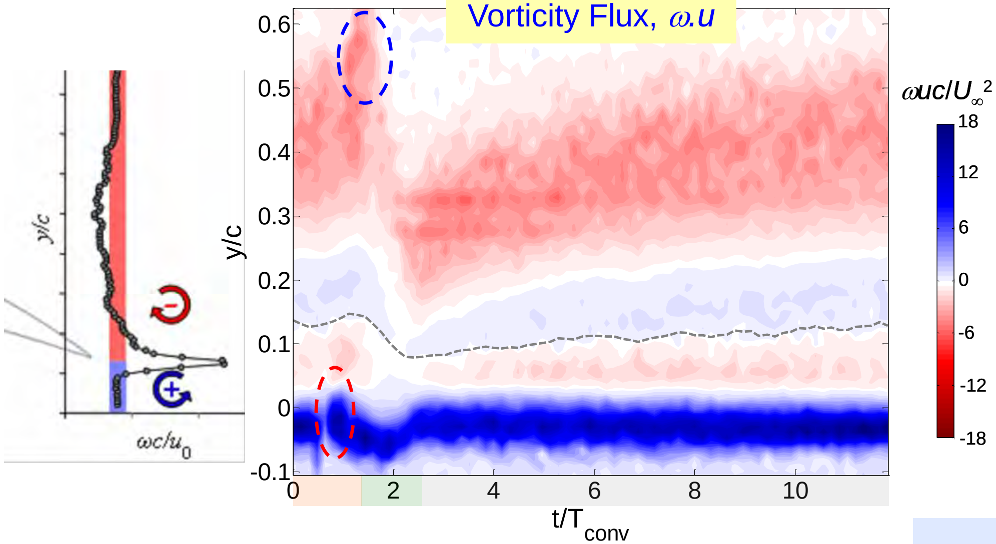
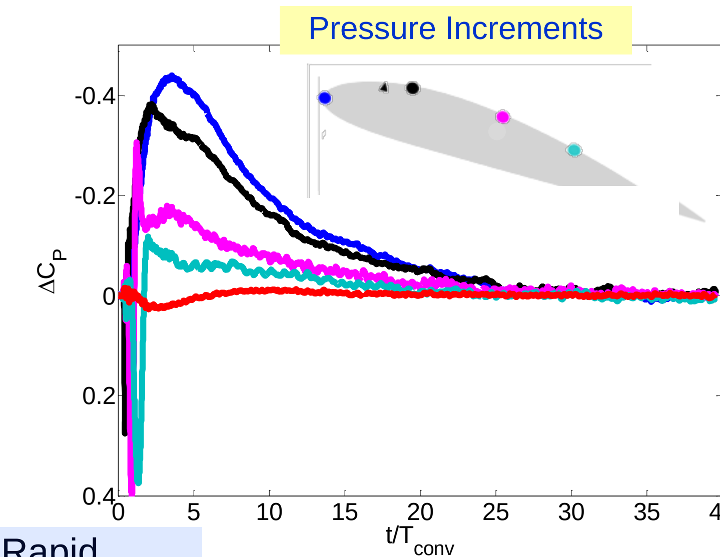
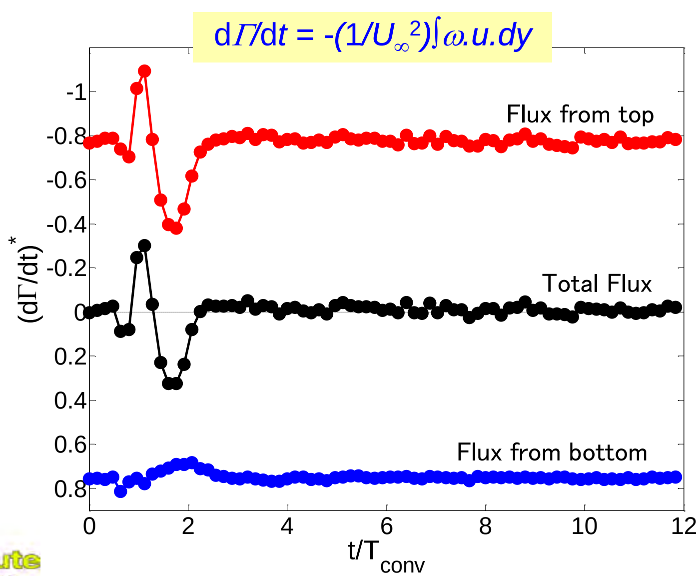
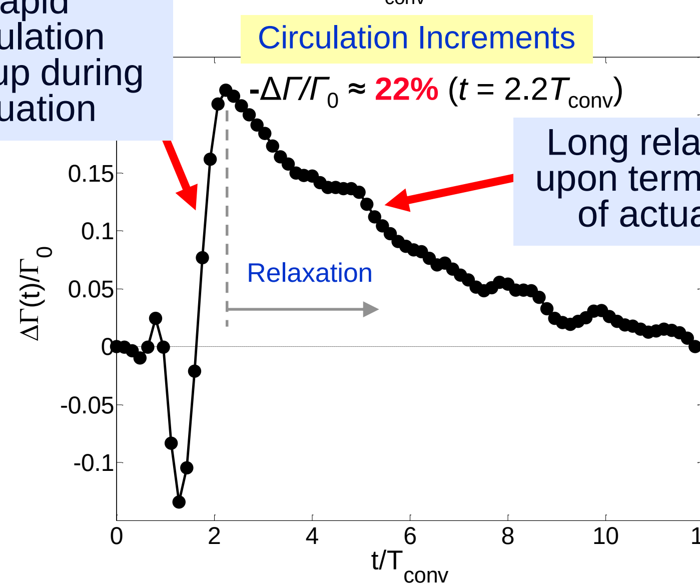
Transient Increase in Circulation and Suction Pressure





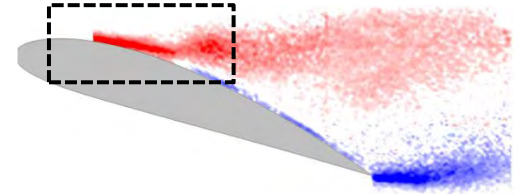


Rapid circulation build-up during actuation

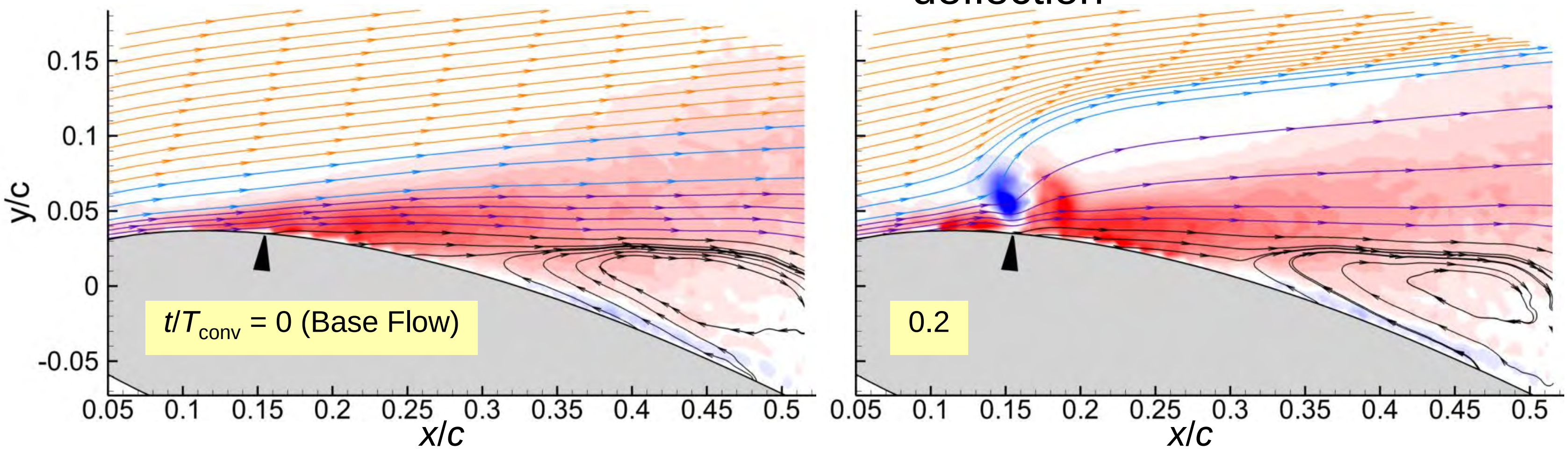


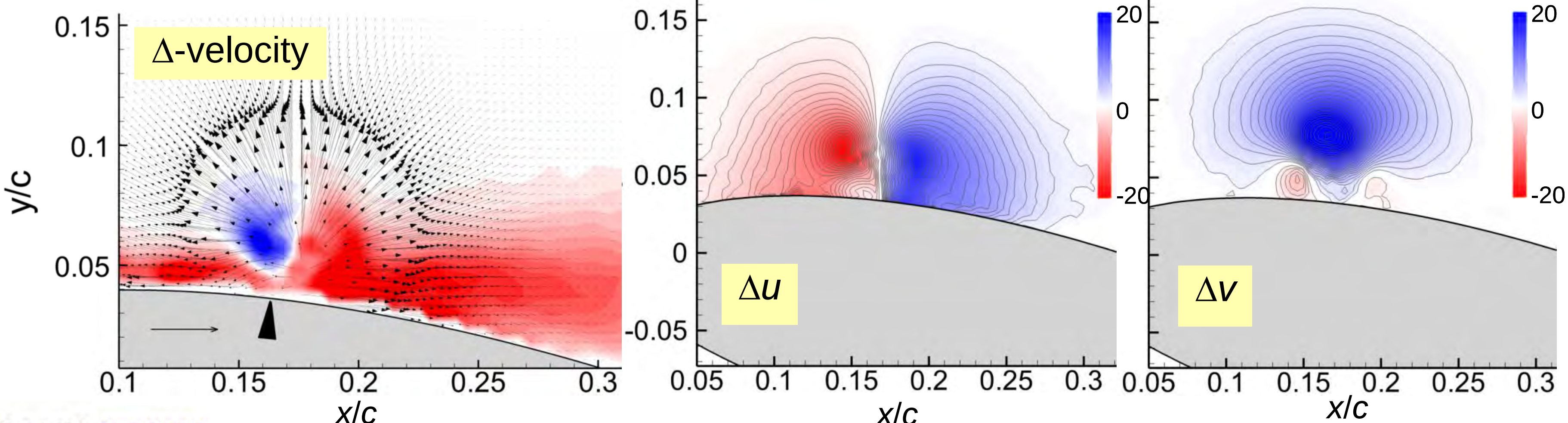
Long relaxation upon termination of actuation

Onset of Pulsed Jet



- Jet-induced flow blockage and deflection





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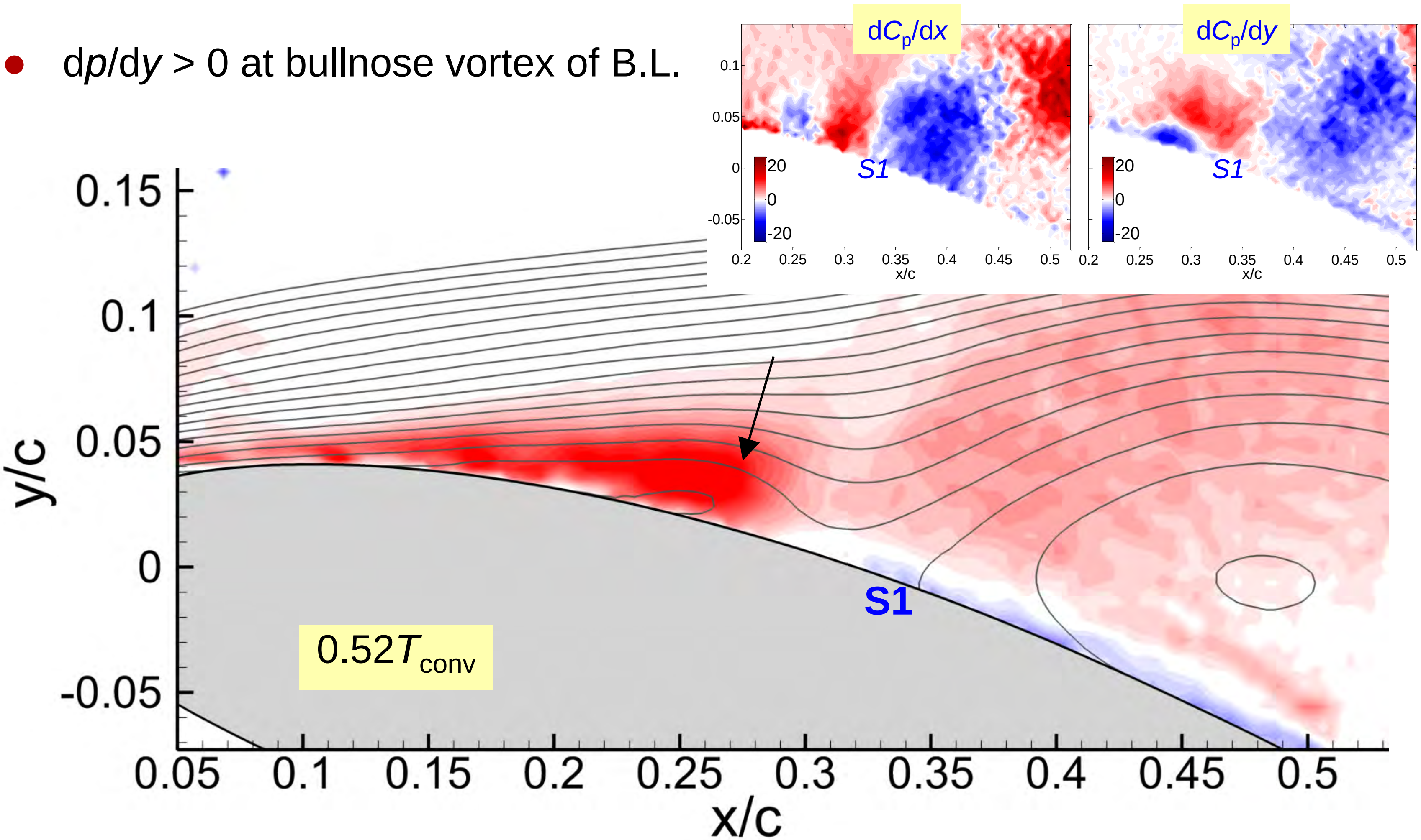
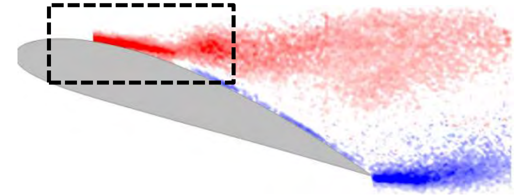
Pulsed Jet Interactions

- dp/dy > 0 at bullnose vortex of B.L.

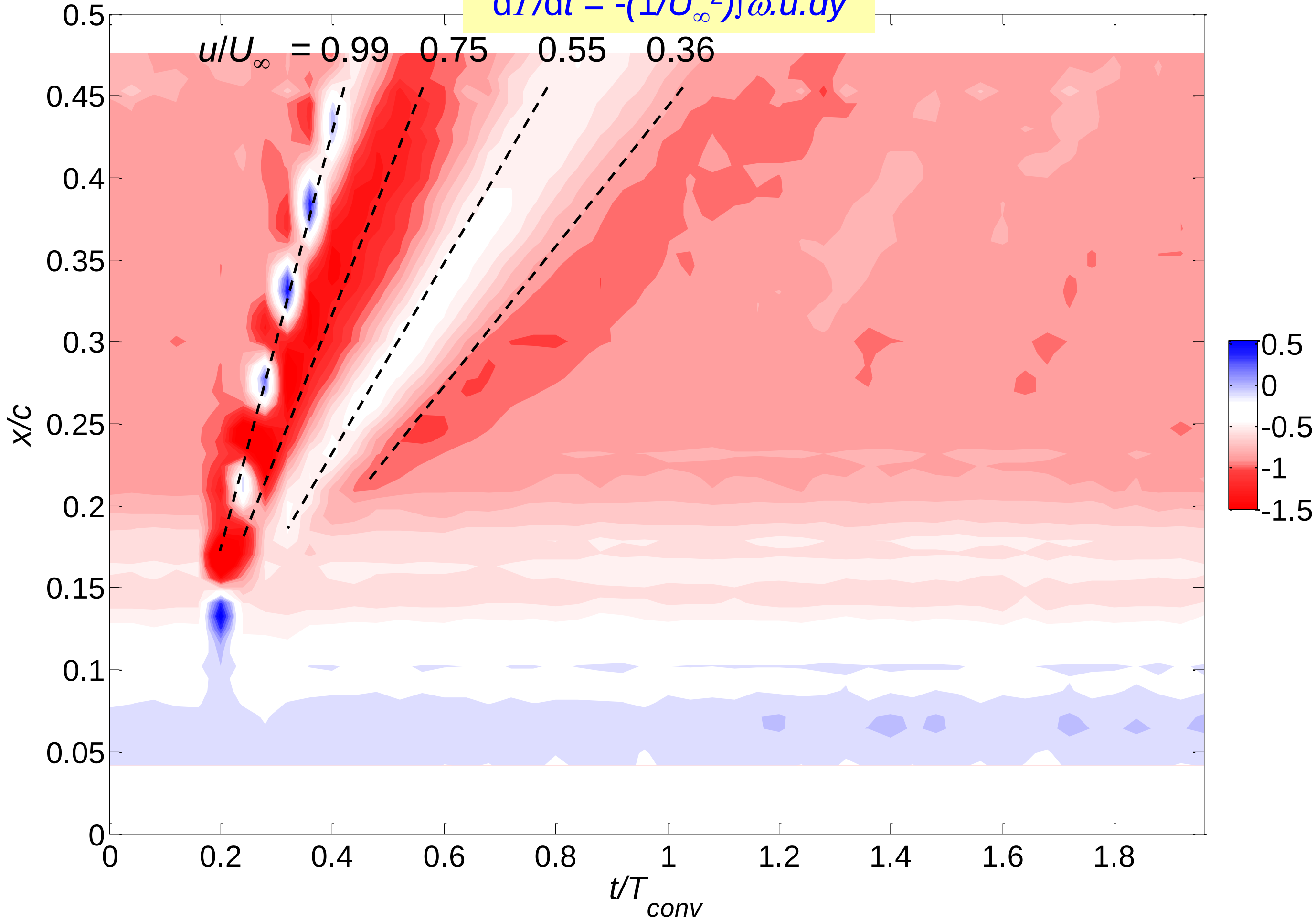


x-t Vorticity Flux



- Slower advection of B.L. compared to the CW vortex

Vorticity Flux
$d\Gamma/dt = -(1/U_\infty^2)\int \omega.u.dy$



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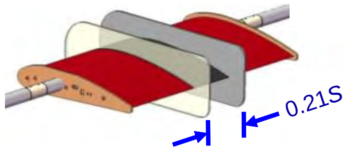
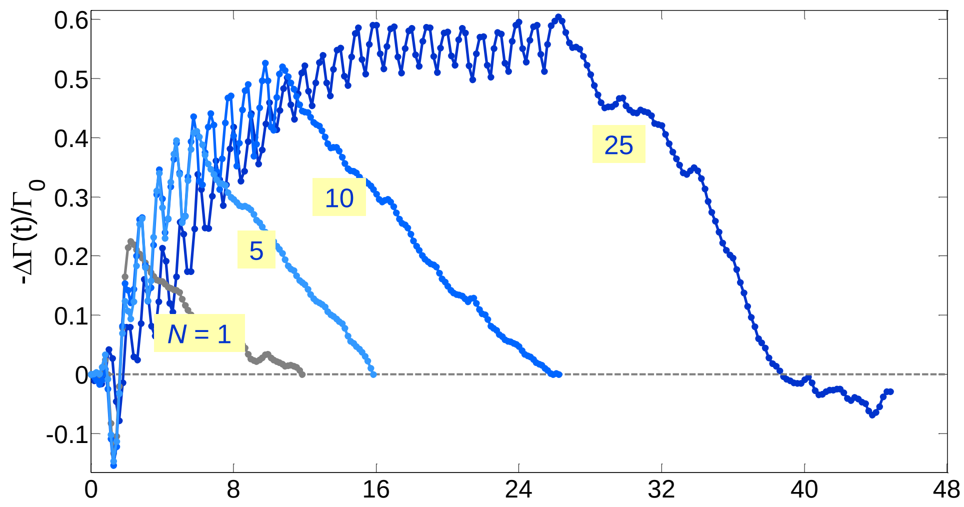
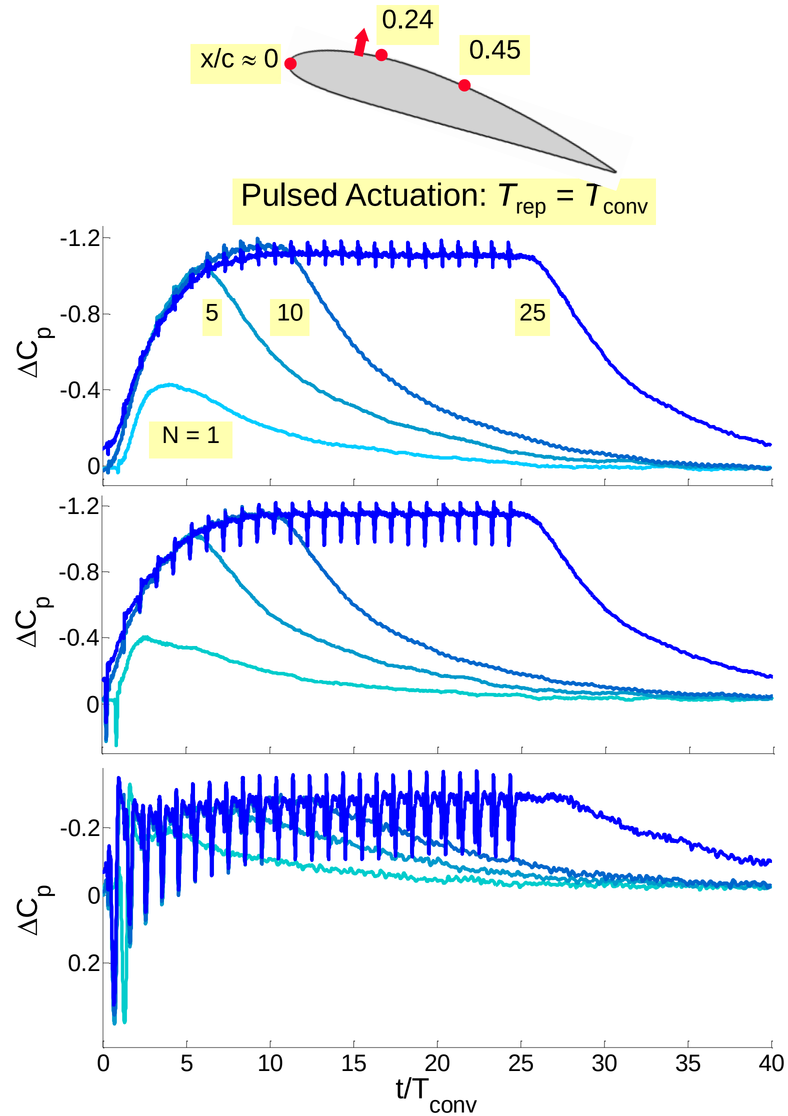
Circulation Build-Up by Successive Pulsed-Actuation

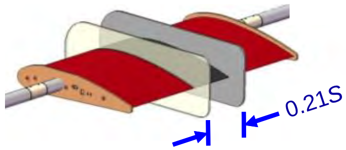


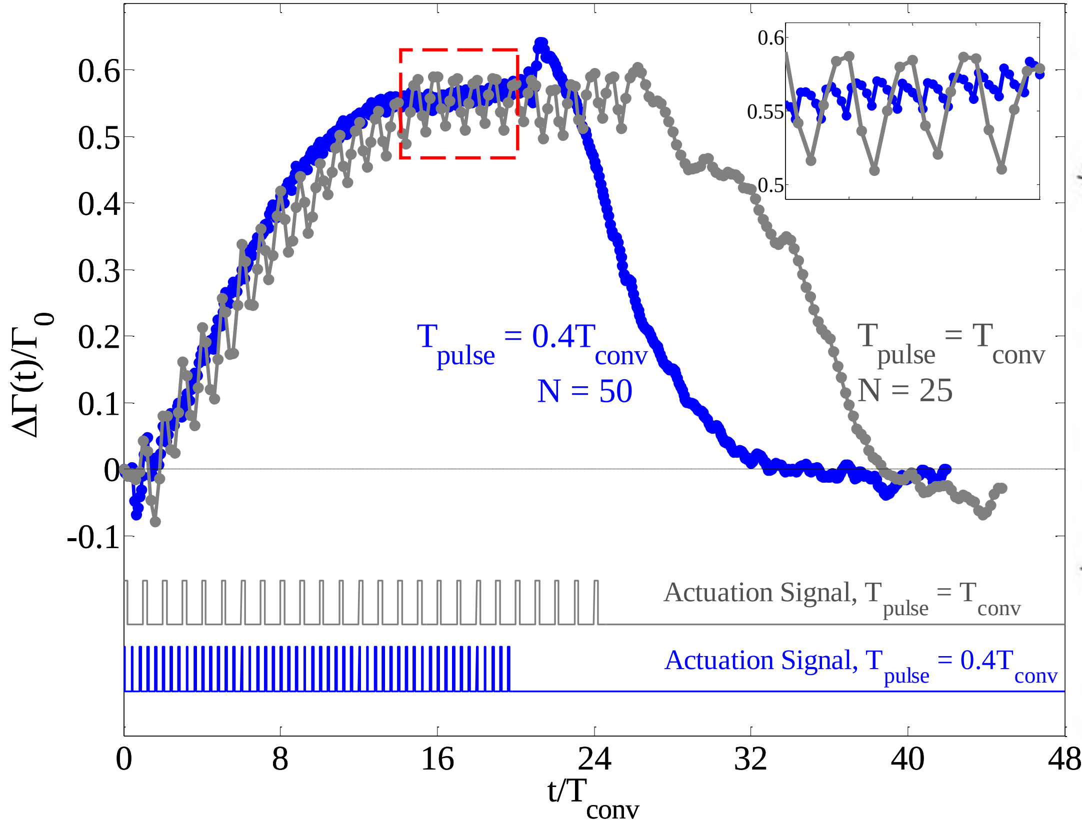


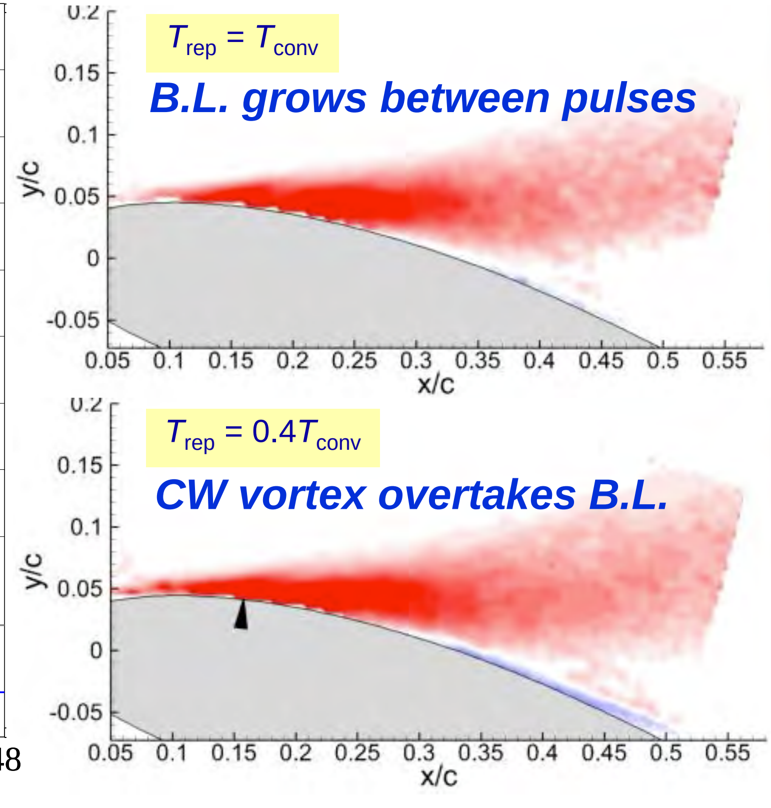


- Rapid build-up in circulation and pressure during actuation
- Long relaxation to baseline upon termination of actuation
- Significant circulation build-up with successive actuation
- Circulation saturates ~58% above baseline for $N > 15$

Successive Pulsed Interactions

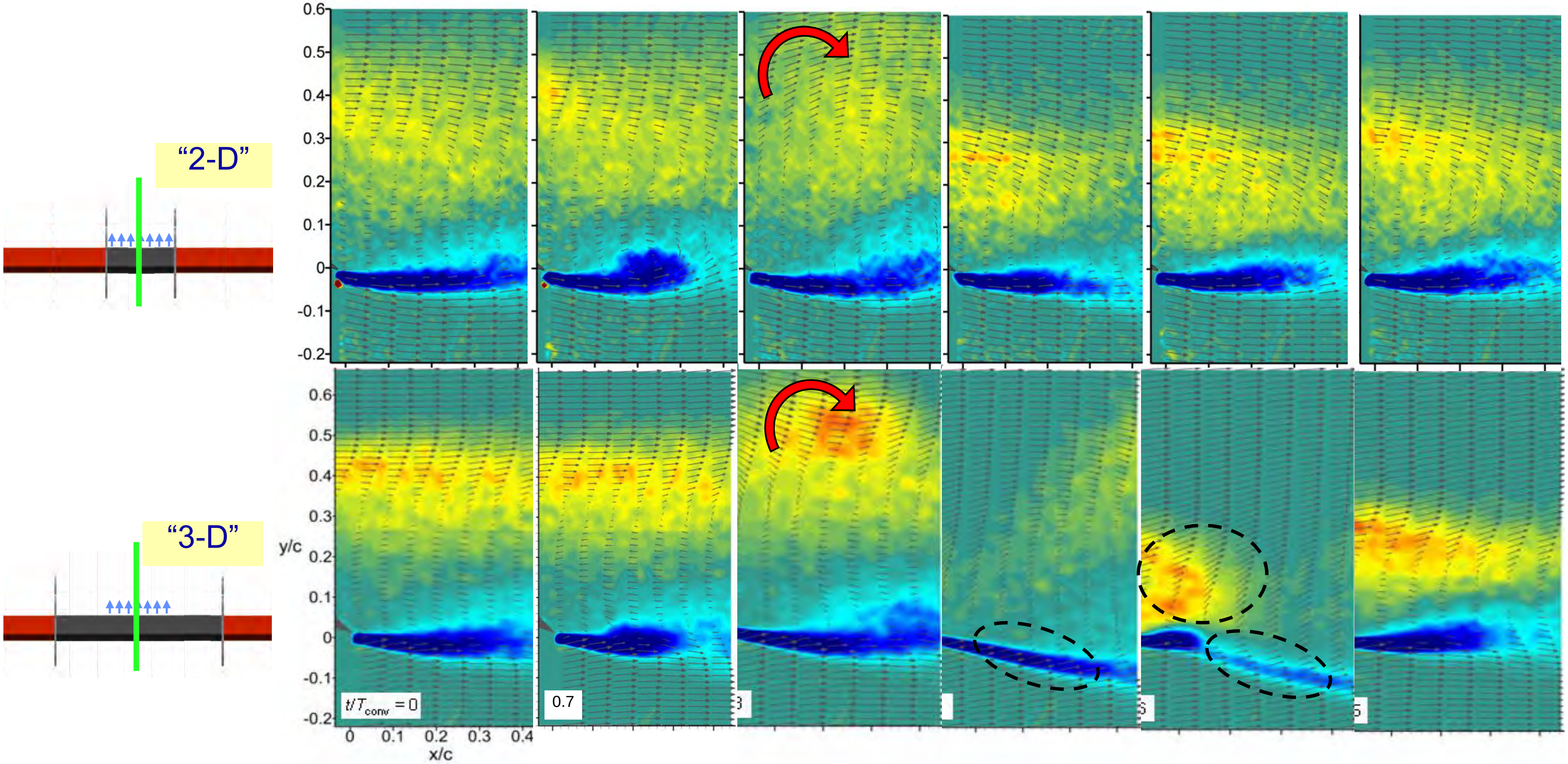






- Increased repetition rate: N = 50, T_{rep} = 0.4T_{conv} *cf.* N = 25, T_{rep} = T_{conv}
- Similar build-up characteristics for the circulation
- Saturation level is reached with greater number of pulses
- Reduced magnitude of oscillations due to interaction of vortices

Single-Pulse Attachment: 2-D & 3-D



- 3-D actuation induces the shedding of a stronger CW vortex
- Prolonged delay in shedding of CW vorticity indicates accumulation and increased circulation

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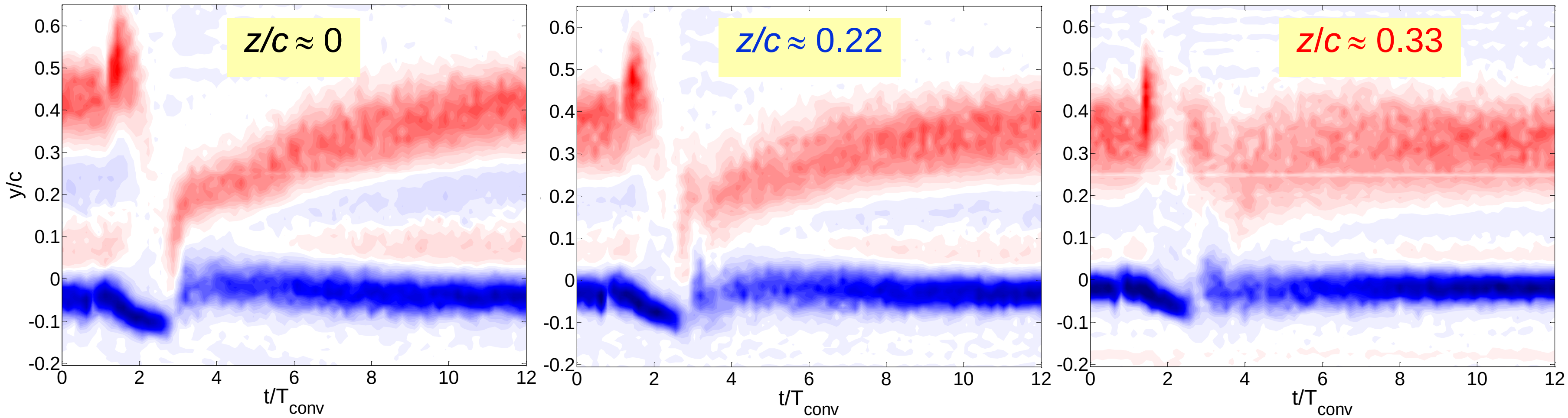
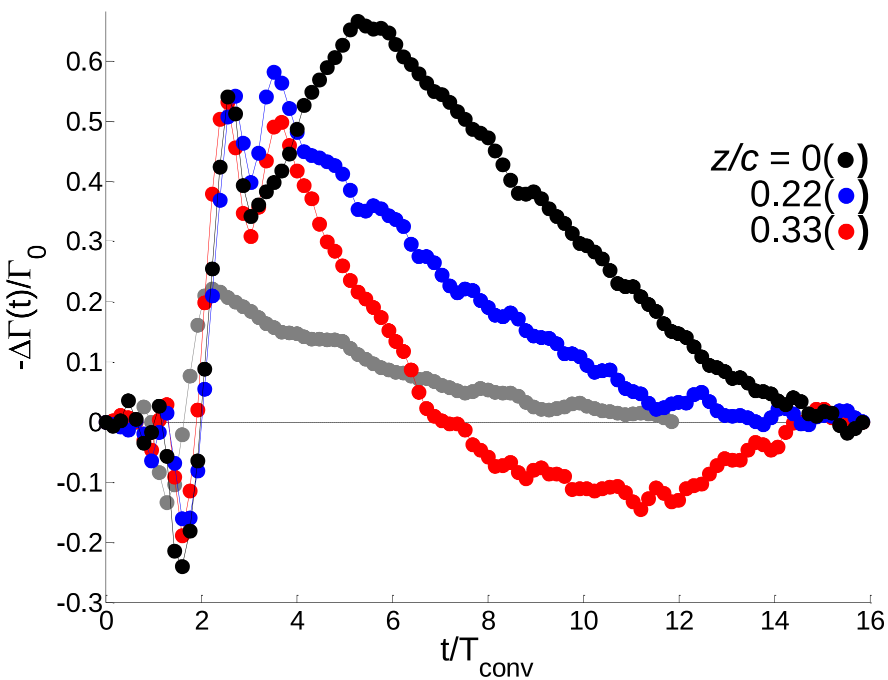
Spanwise Spreading of 3-D Actuation



- Improved attachment results in enhanced circulation over 2-D actuation
- 2nd peak in $\Delta\Gamma$ due to CCW fluxes
- Data suggest spanwise variations in attachment and relaxation



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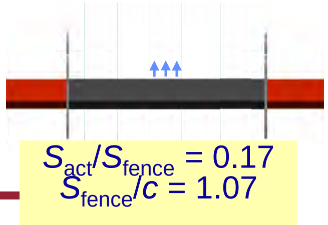
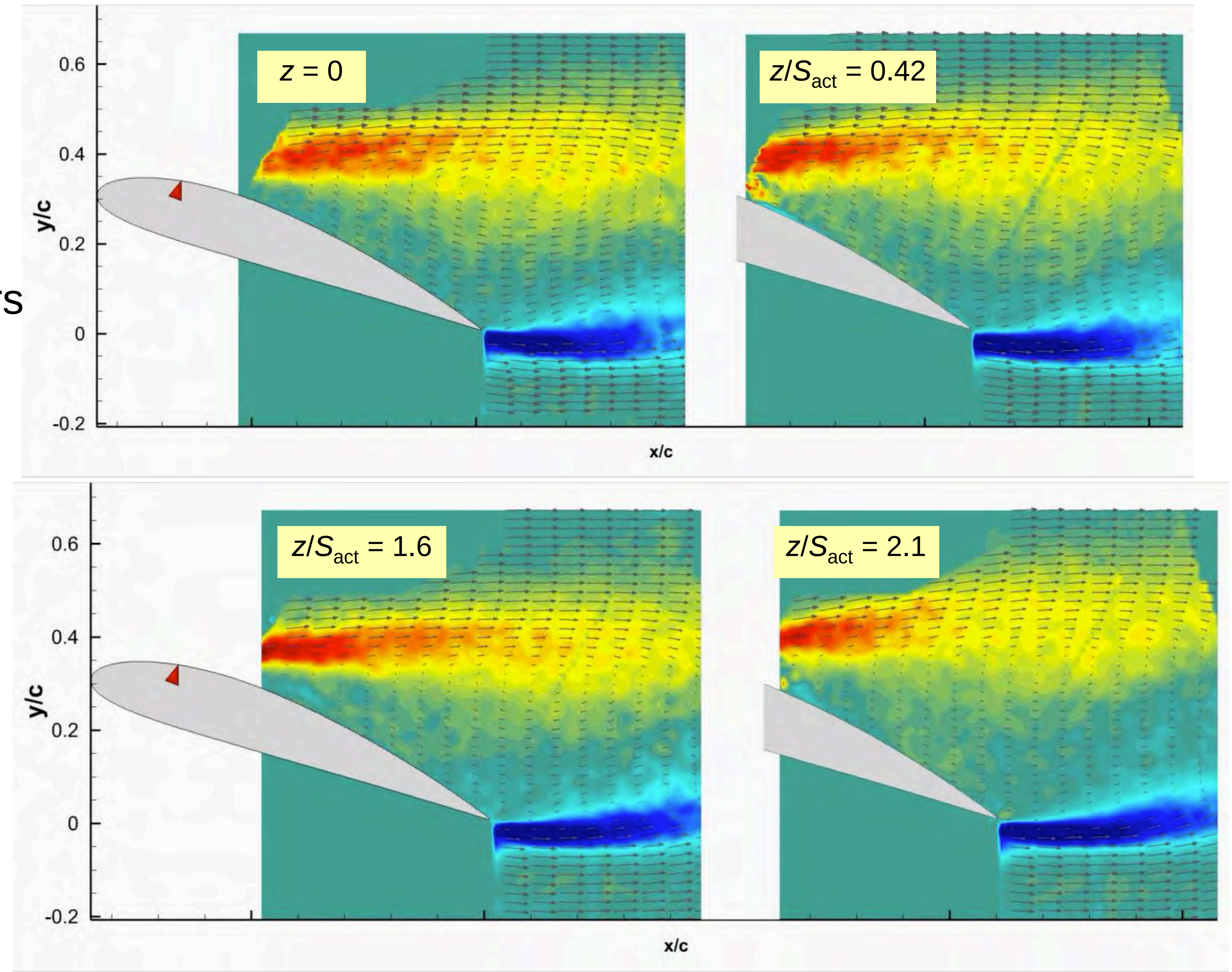
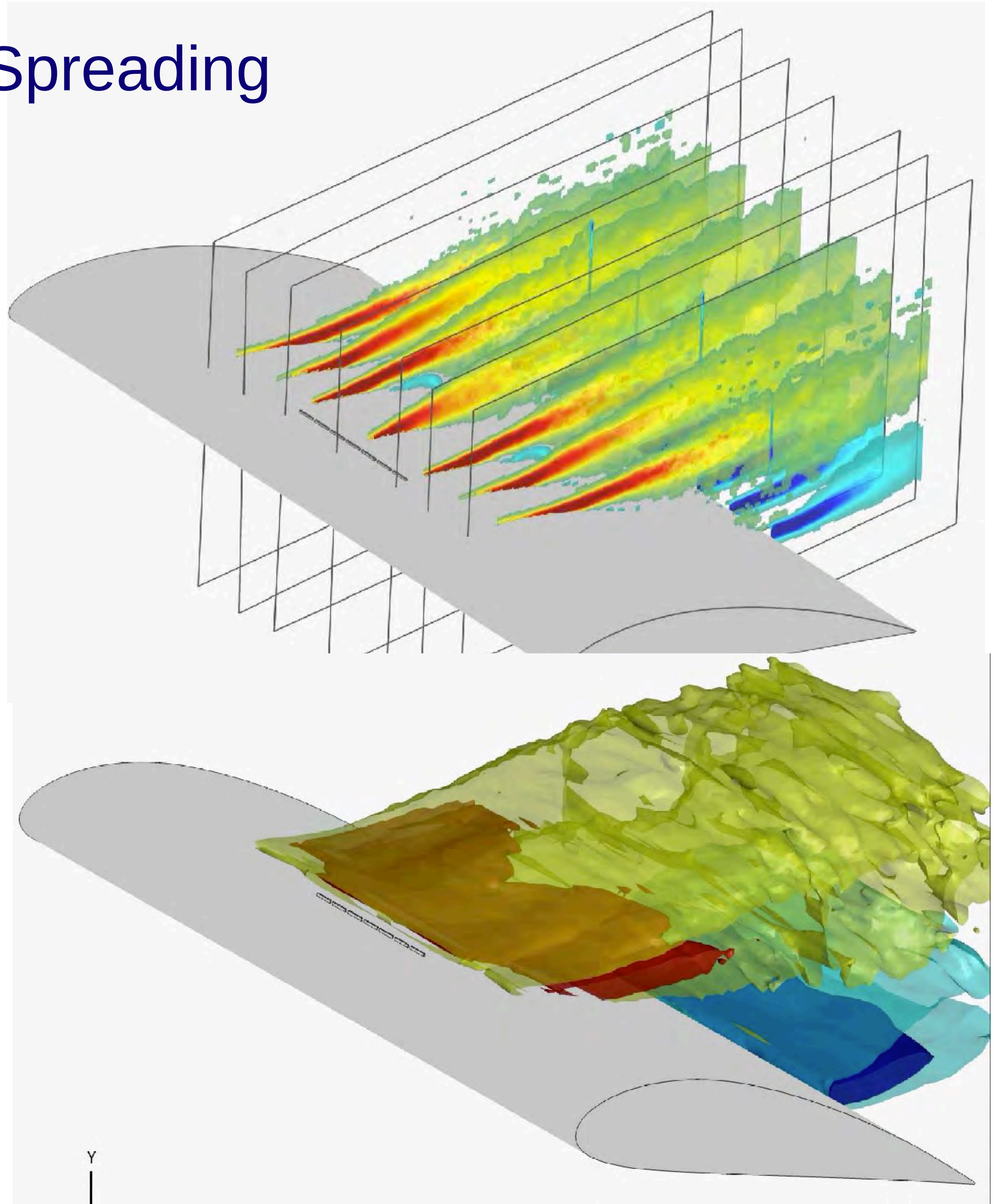
Spatially-Compact, Actuation-Induced 3-D Flow



- Effects spread beyond actuators for $z > 0.5S_{act}$
- Rolled-up CW vortex and attachment diminish with z
- Improved attachment and low-vorticity region



Spanwise Spreading



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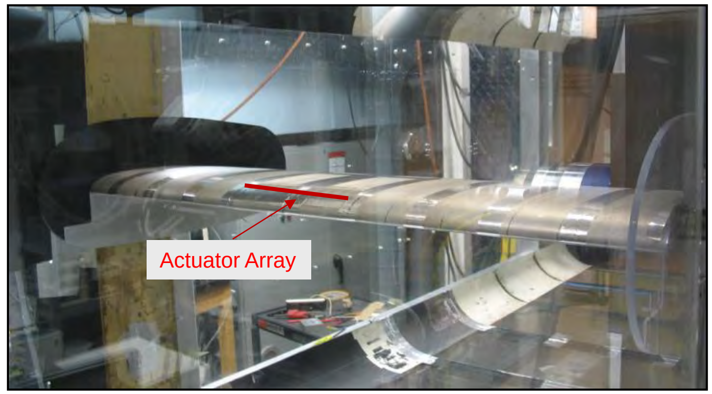
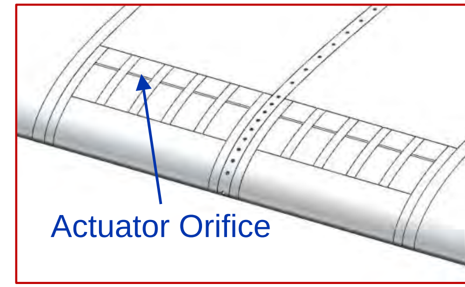
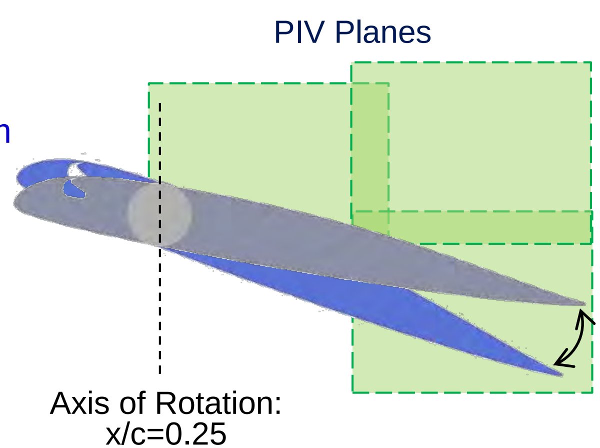
Pulsed Actuation of Dynamically Pitching VR-12

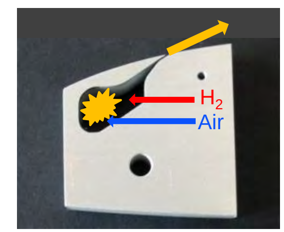
- Low-speed wind tunnel investigations of pulsed actuation on dynamically pitching VR-12
  - » 0.38 m chord, 0.91 m span.
  - » Time-periodic pitch oscillations $+10^{o} < \alpha < +20^{o}$
  - » Pitch frequency $f_{pitch} < 2$ Hz ($k_{pitch} < 0.12$)
  - » *Re* ~ 504,000
- COMPACT actuator array developed for the VR-12
  - » 10 actuators, orifice 12.7x0.3 mm
  - » **Actuation jet is 1-2 msec long**, $x/c = 0.1$, at 20º to surface.
  - » Actuation 0.21*S*.
- Diagnostics
  - » Load cell: C_L,C_M (full span of model).
  - » PIV cross stream plane at actuator center.

VR-12 model in wind tunnel

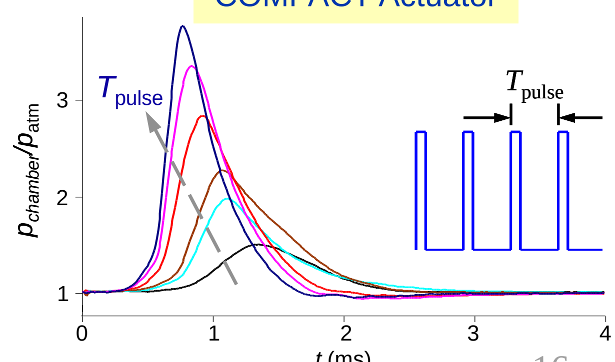








COMPACT Actuator



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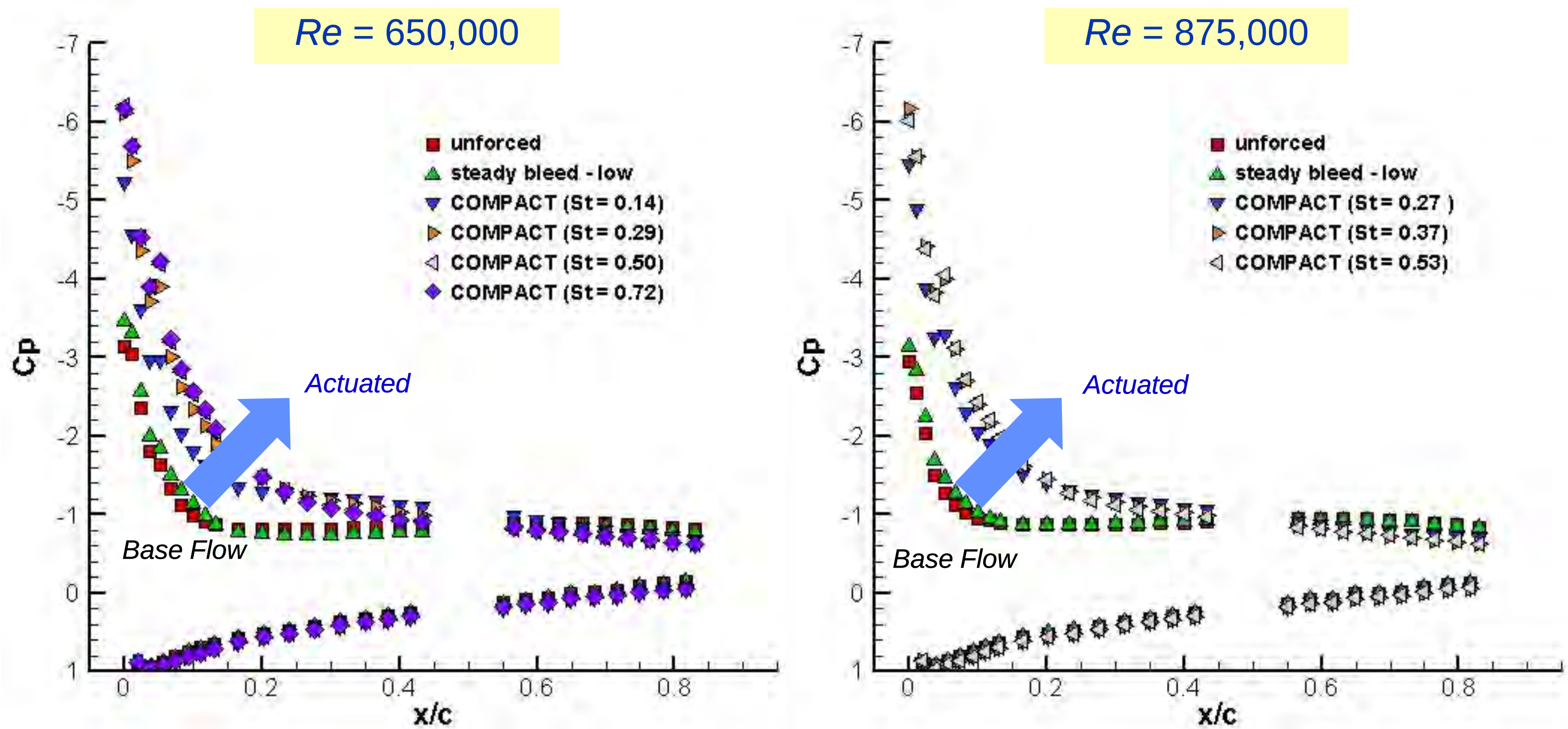
Repetitive Actuation at Reduced Frequencies



- Lower actuation repetition rates at 3 - 4 T_{conv} are sufficient to achieve the full attachment effect

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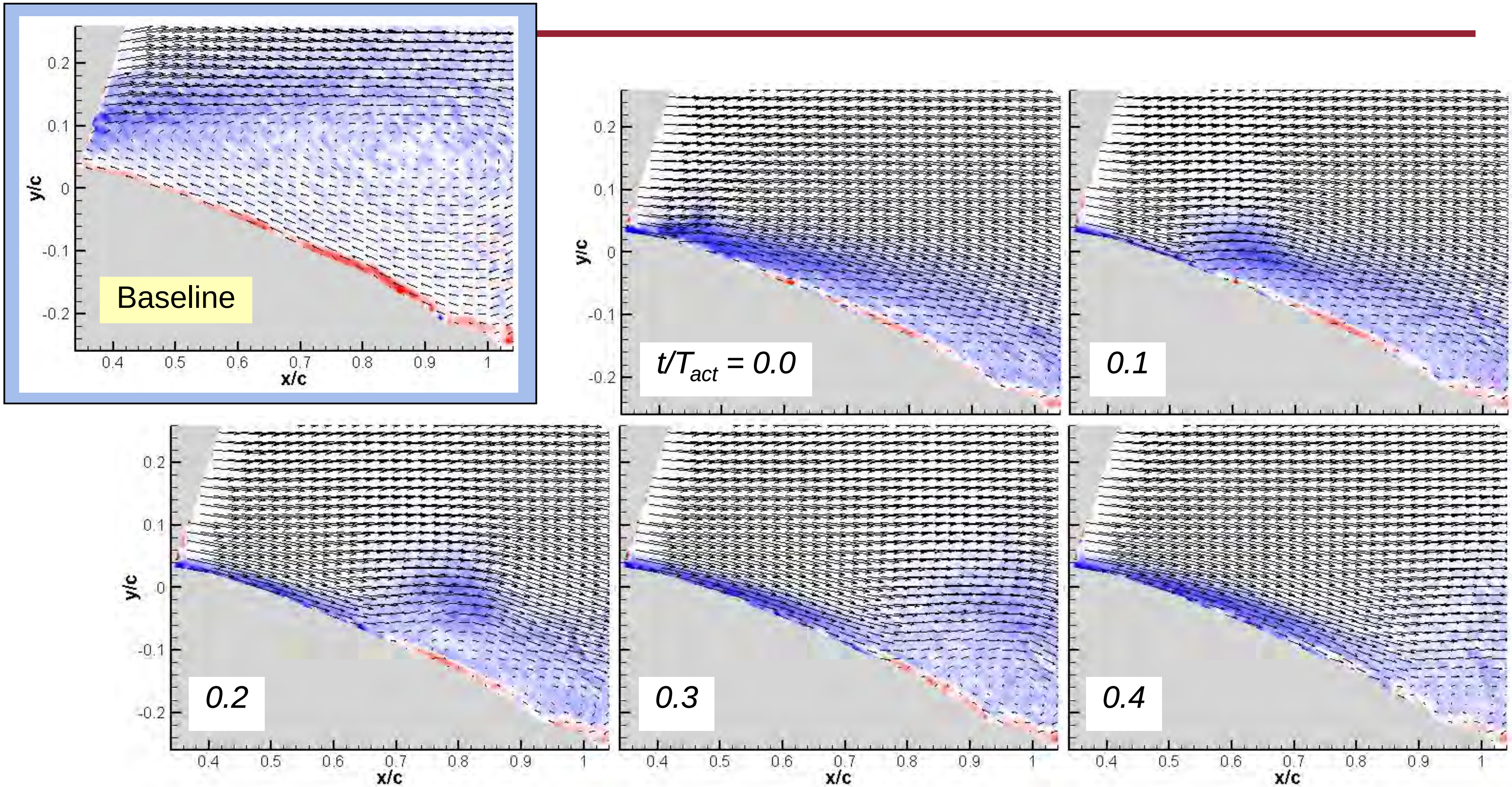
Repetitive Actuation: Phase-Locked PIV Measurements



- *Re* = 632,000, *St* = 0.72 tangential actuation
- The flow does not separate during the actuation cycle.
  - » Large-scale vorticity concentration is advected downstream
  - » Thin boundary layer upstream of this vortex indicating transient favorable pressure gradient.

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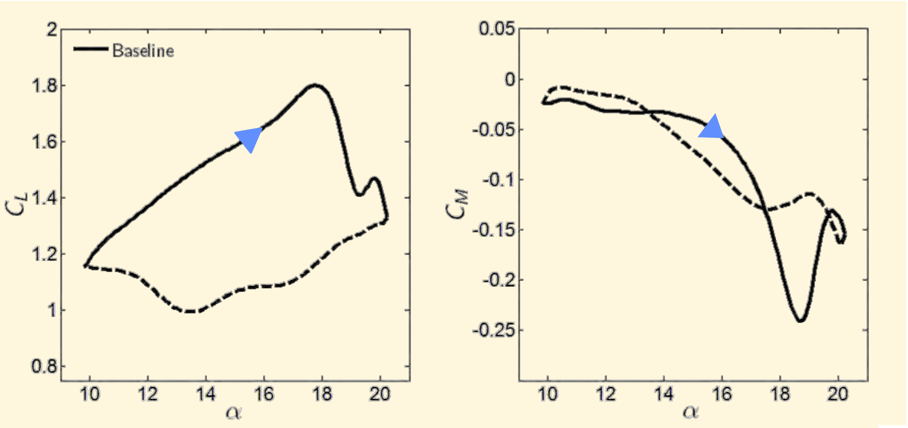
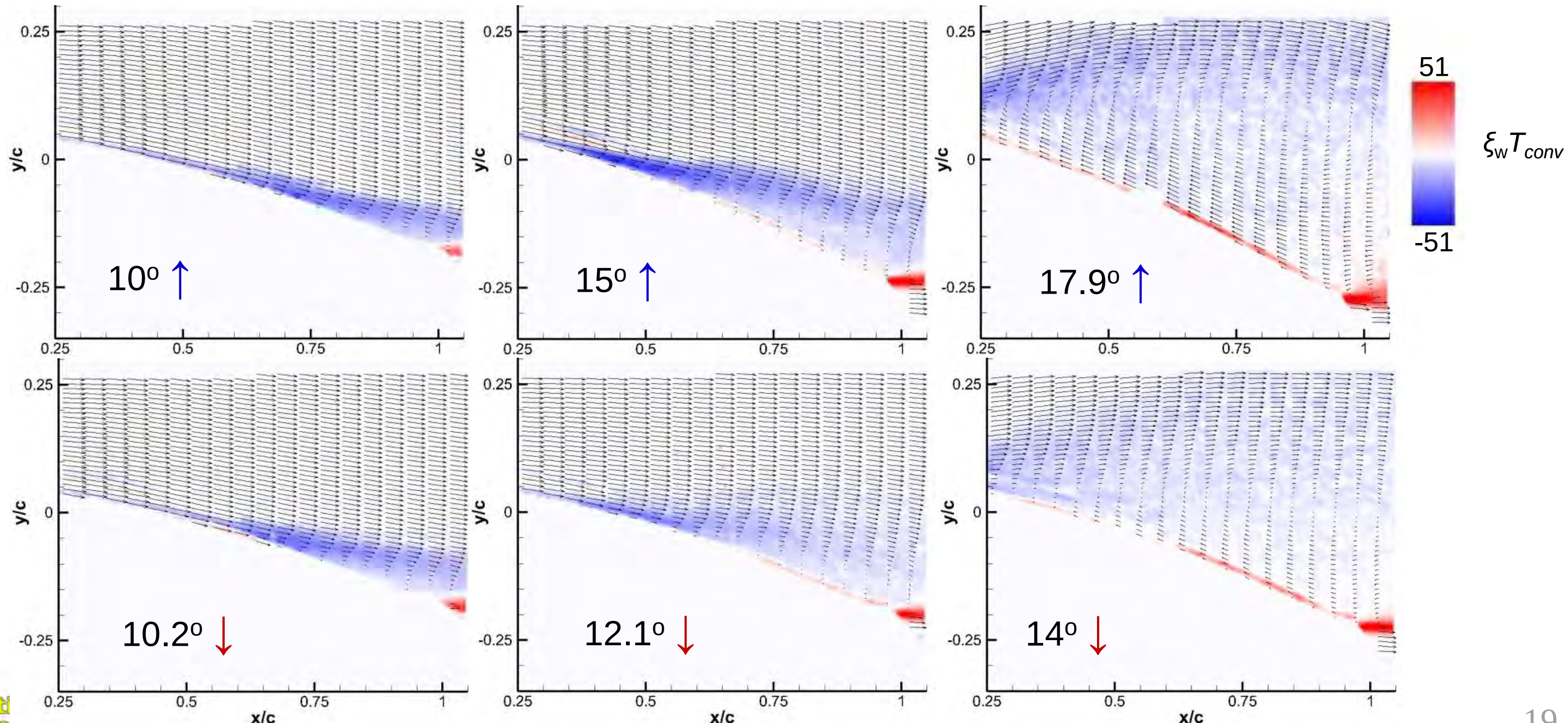
VR-12 Dynamic Baseline Characteristics

- Dynamic pitch: 10° < α < 20°, k = 0.12
- Time-periodic stall
  - » Commences at $\alpha \approx 17^o$
  - » Reattachment at $\alpha \approx 12^o$ on downstroke





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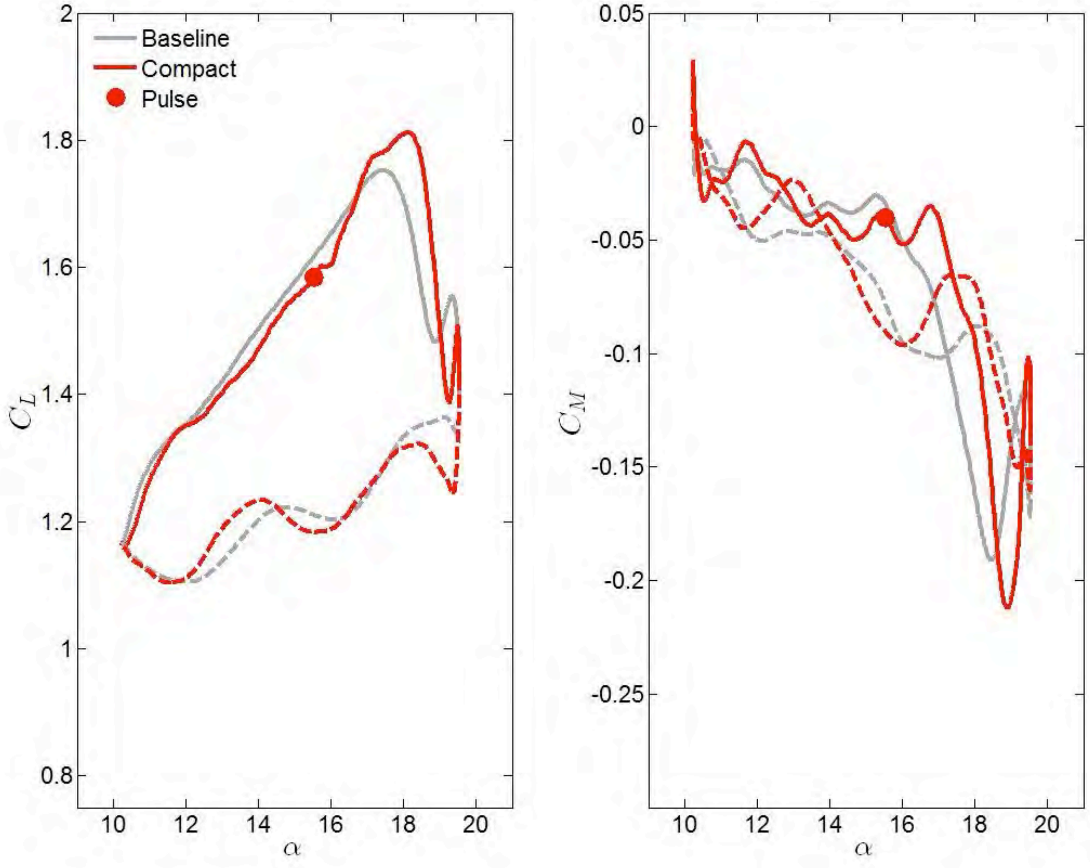
Pulsed Actuation: Timing of Additive Pulses

- Pulse bursts starting at a given α during the pitch cycle.
  - » Pulses added to extend around half of cycle
  - » Pulses subsequently removed from beginning to end
- Actuation timing has a profound effect on the variation of C_L and C_M.



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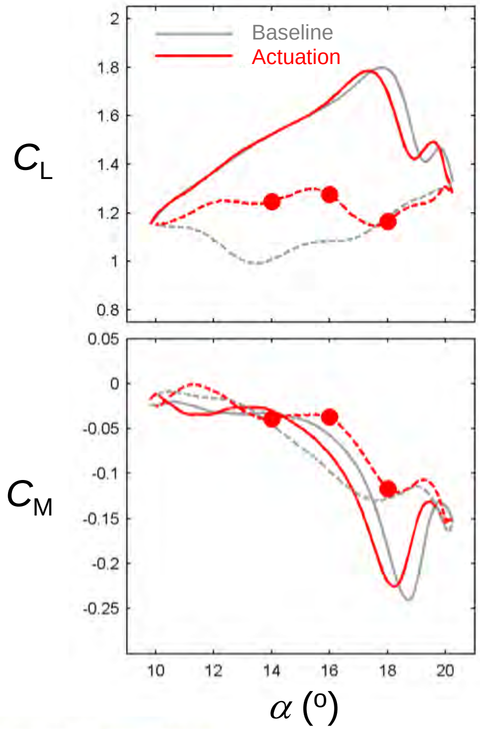
Stability and Lift Improvement with Actuation

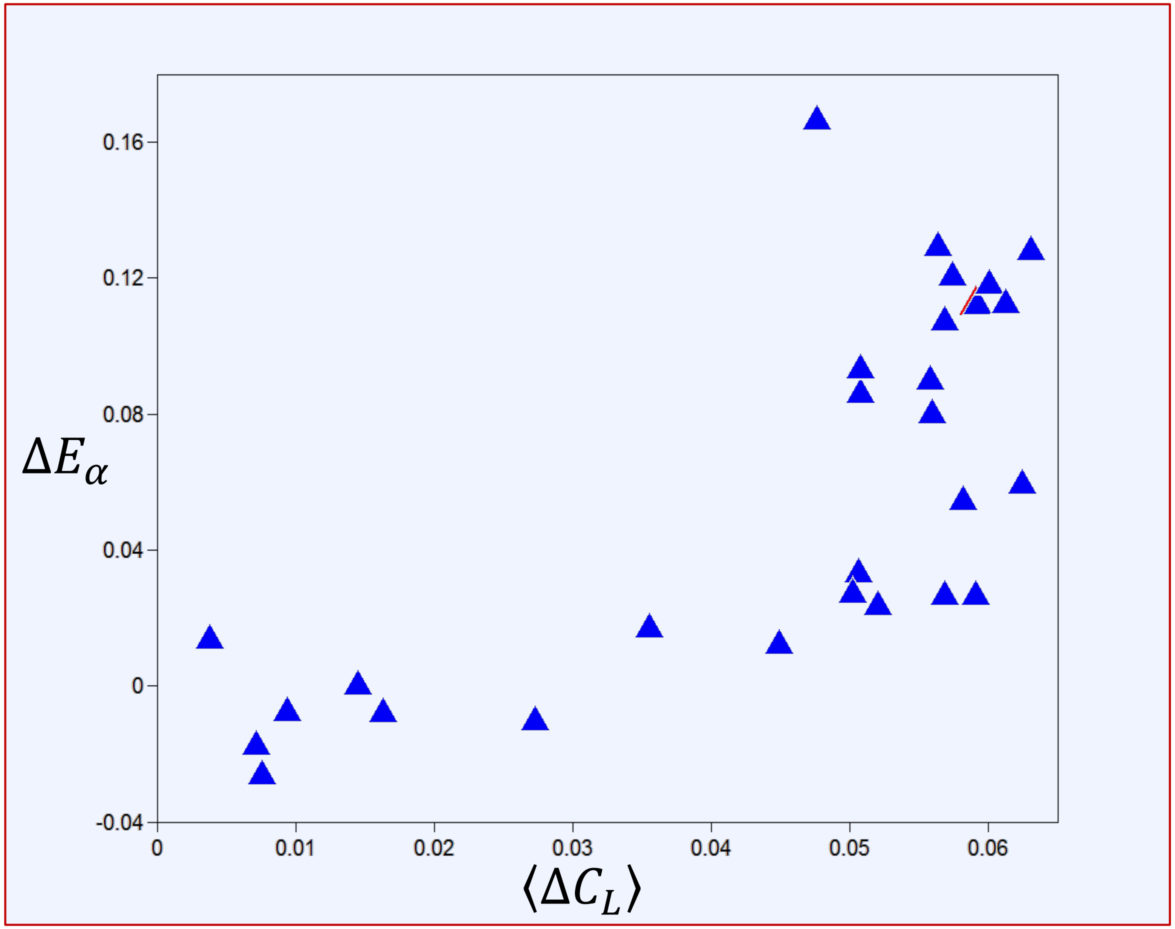
- Stable pitching mode when damping coefficient is positive (Carta, 1967):
  - » Instability (negative damping) occurs when the pitch velocity is in the same direction as the moment applied by the flow.
  - » $C_M(\alpha)$: CW (E_α <0), CCW (E_α >0).

$$E_\alpha = -\frac{\oint C_M \, d\alpha}{\pi \alpha^2} > 0$$

- Cycle averaged lift coefficient:

$$\langle C_L \rangle = \frac{\oint C_L dt}{T_{cycle}}$$





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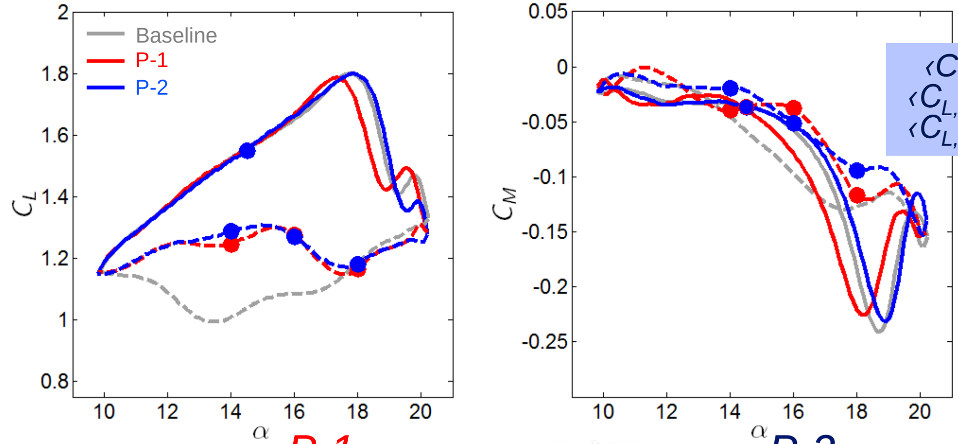
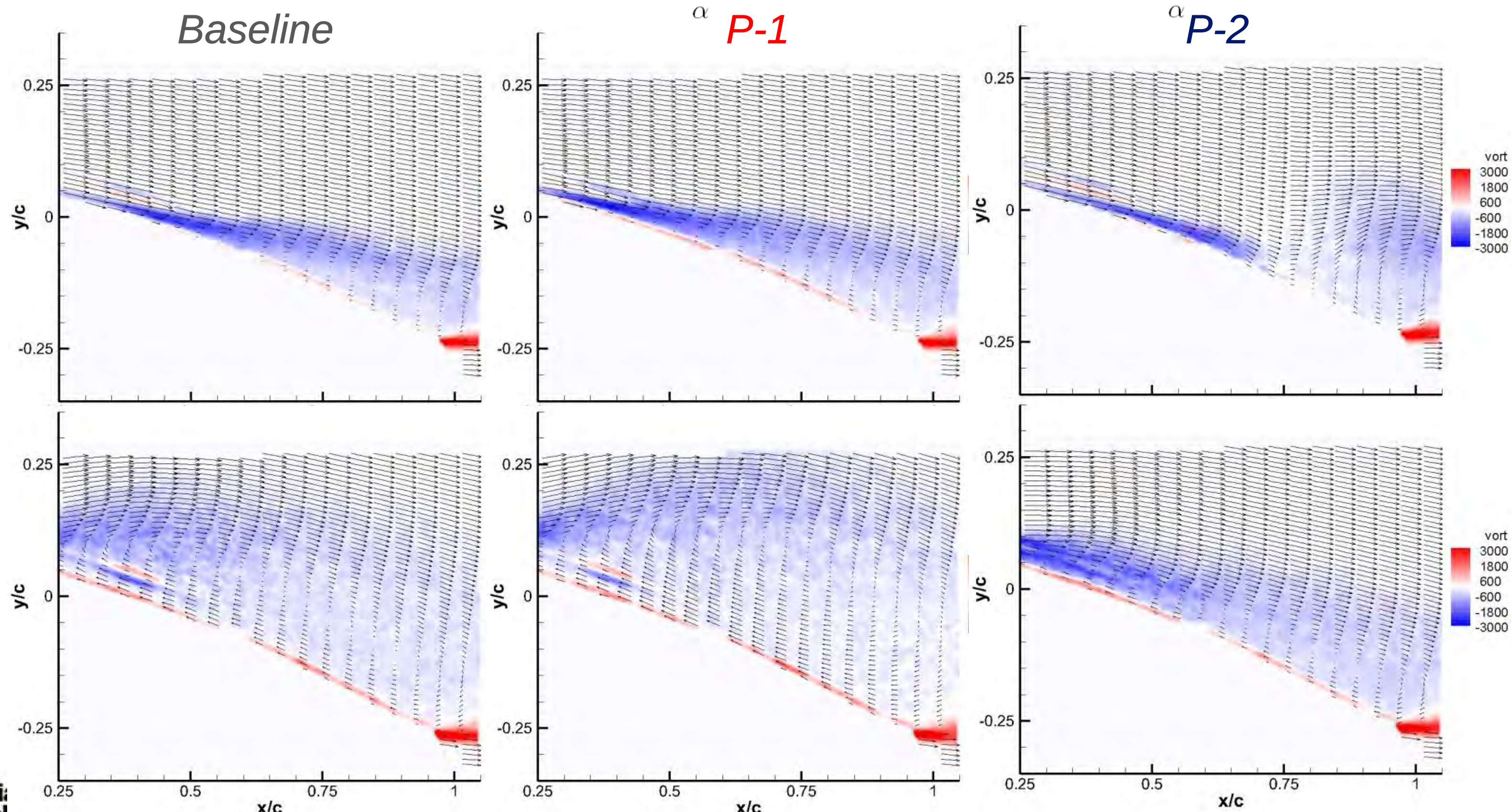
Flow Actuation During Upstroke

- P-2 single actuation pulse at 14.5° ↑.
- P-1 and baseline have no actuation on upstroke.



$\langle C_{L,bl}\rangle = 1.32,\ E_{\alpha,bl} = 0.06$
$\langle C_{L,P\text{-}1}\rangle = 1.36,\ E_{\alpha,P\text{-}1} = 0.22$
$\langle C_{L,P\text{-}2}\rangle = 1.37,\ E_{\alpha,P\text{-}2} = 0.18$



$\alpha = 15^{o}\uparrow$

$17^{o}\uparrow$

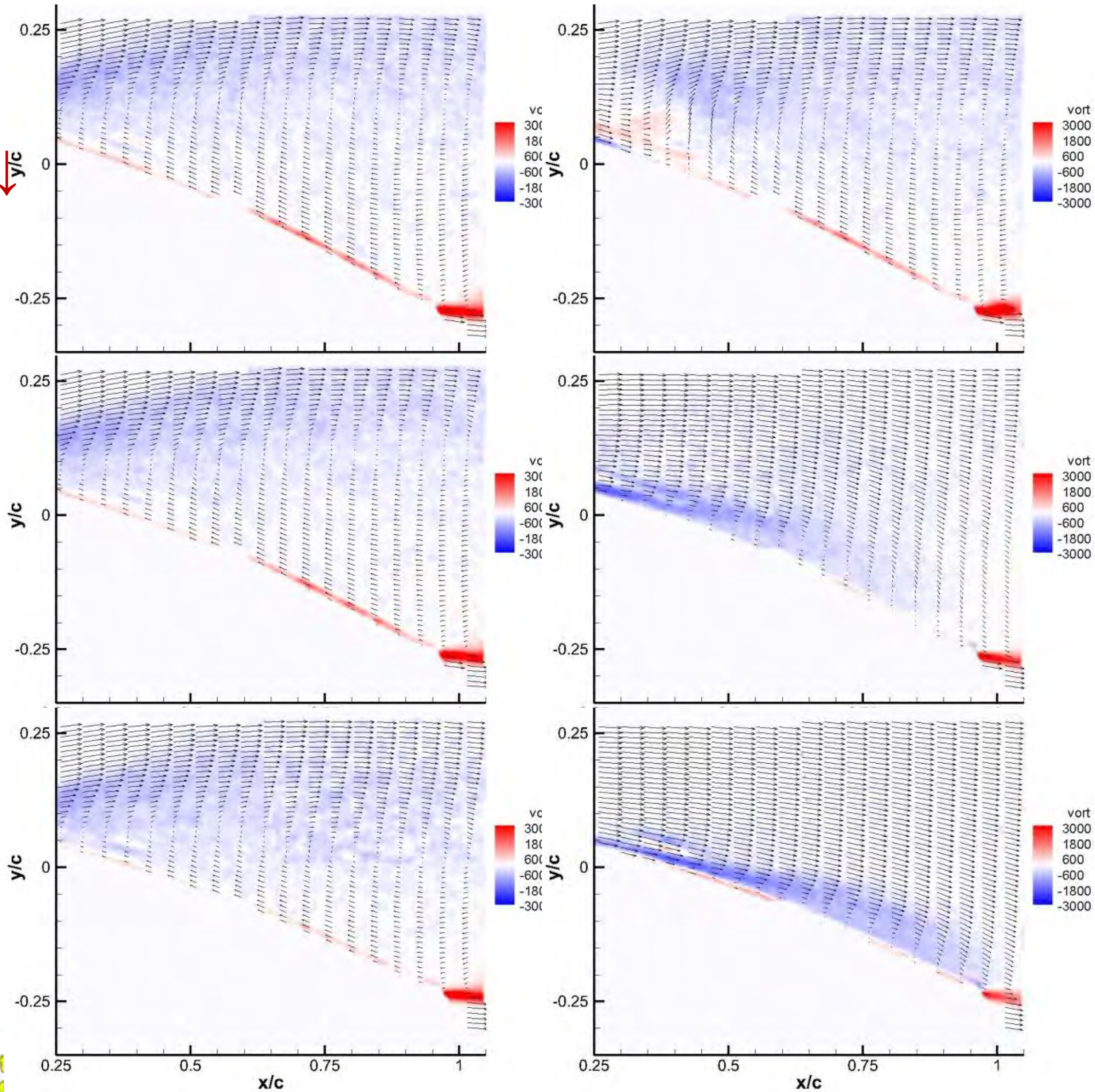
Flow Actuation During Downstroke

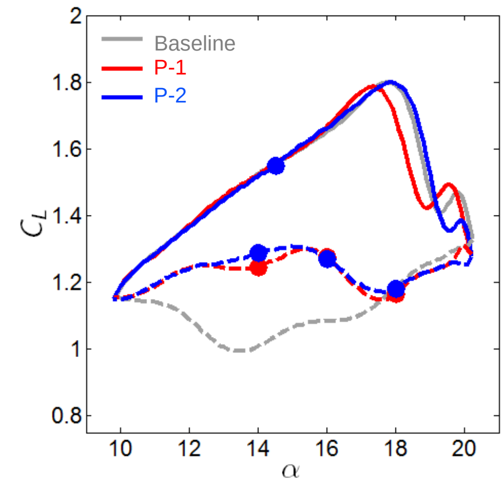
Baseline *P-1*

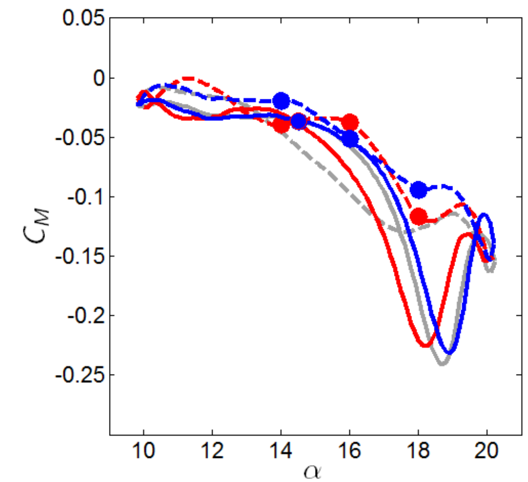
$\alpha = 17.9^o \downarrow$

$17^o \downarrow$

$15^o \downarrow$







$\langle C_{L,bl} \rangle = 1.32,\ E_{\alpha,bl} = 0.06$
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$\langle C_{L,P\text{-}2} \rangle = 1.37,\ E_{\alpha,P\text{-}2} = 0.18$

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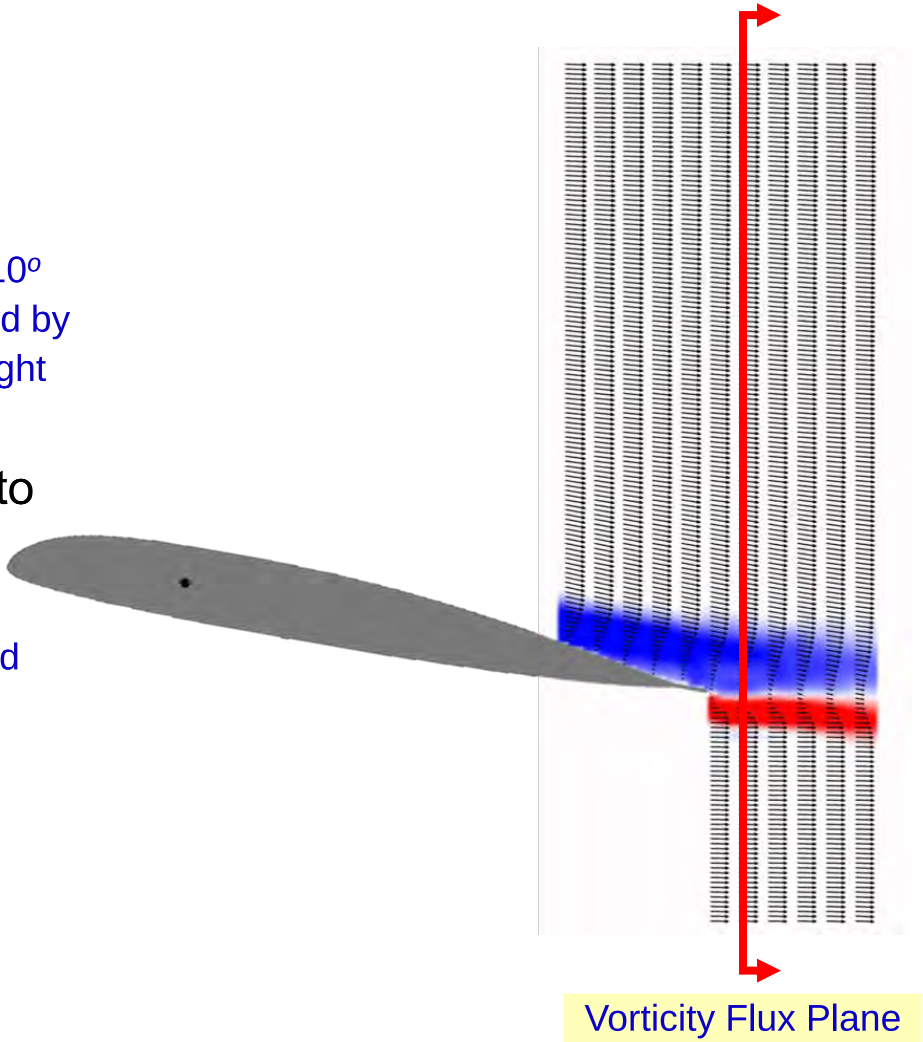
Vorticity Flux

- Vorticity flux across the wake is calculated at a fixed streamwise location in the near wake
  - » Vorticity flux is calculated at x/c = 0.07 relative to the trailing edge, when α = 10^o
  - » The entire width of the wake is captured by two PIV fields spanning 380 mm in height
- PIV data acquired relative to the airfoil's angular position are used to compute the vorticity flux
  - » Temporal resolution Δt = 33 ms
  - » PIV images are processed and grouped based on angle of attack
- Vorticity flux is computed in the absence and presence of pulsed actuation
  - » Baseline
  - » P-1 (max. stability enhancement)
  - » P-2 (max. lift enhancement)



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Temporal Variations

α (°)

Baseline

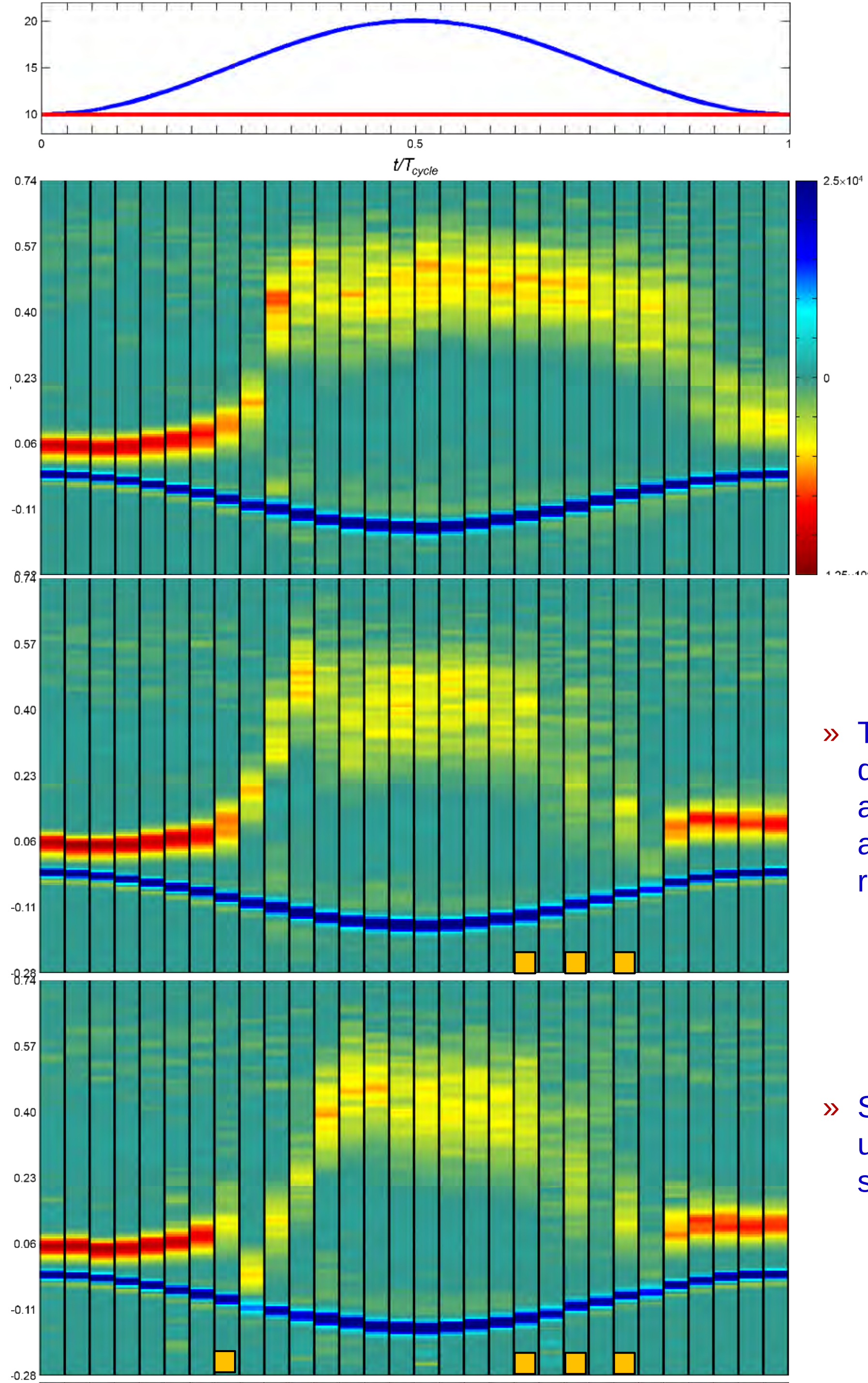
y/c

P-1

y/c

P-2

y/c



» Three actuation pulses during downstroke accelerates flow attachment and lift recovery

» Single pulse during upstroke delays the separation to $\alpha = 18^{\circ}\uparrow$

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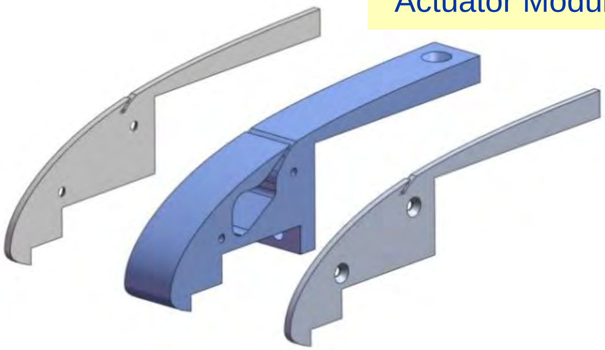
High-Speed Pitching VR-12 Model

- COMPACT-integrated 15” chord VR-12 model tested at NASA Glenn IRT facility
  - » $0.2 \leq M_\infty \leq 0.5$
  - » Same actuator chamber design and streamwise placement ($x/c = 0.10$) as low-speed GT testing
  - » Slot orifice height increased (0.0016c vs. 0.0008c)
- Testing included actuation for static and dynamic conditions
  - » Primarily continuous firing
  - » Limited actuation programs including single pulse firing, varying number of pulses, and pulse start angle

VR-12 model in NASA Glenn IRT

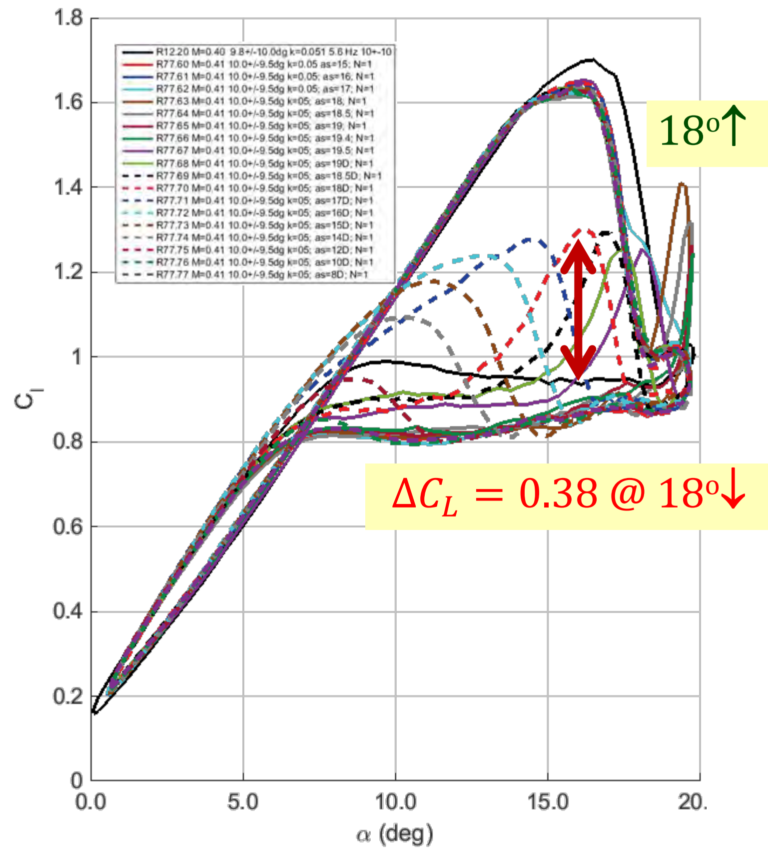
Actuator Module



	GT Model	IRT Model
Model span	36”	69”
Actuated region	21% of span	33% of span
Packing density	0.73	0.8
Pitch amplitude	5º	Up to 10º
Pitch frequency	k ≤ 0.06	k ≤ 0.10
Lift/drag measurements	End load cells	Dynamic pressure

Single-Pulse Actuation: *M*=0.4

- Single actuation pulse per cycle
  - Firing angle: α_t from 15°↑ *to* 8°↓
  - $M = 0.4$, $k = 0.05$, $\alpha = 10^o \pm 9.5^o$
- Similar to the low-speed test results, single pulse actuation has a large impact during downstroke
  - Significant improvements for actuation 19°↓ ≥ α_t ≥ 12°↓
  - Larger lift recovery in high-speed tests due to a larger actuated span segment and local (centerline) measurements
- Single-pulse upstroke firing can recover lift after dynamic stall vortex has passed (e.g., α_t = 18°↑)



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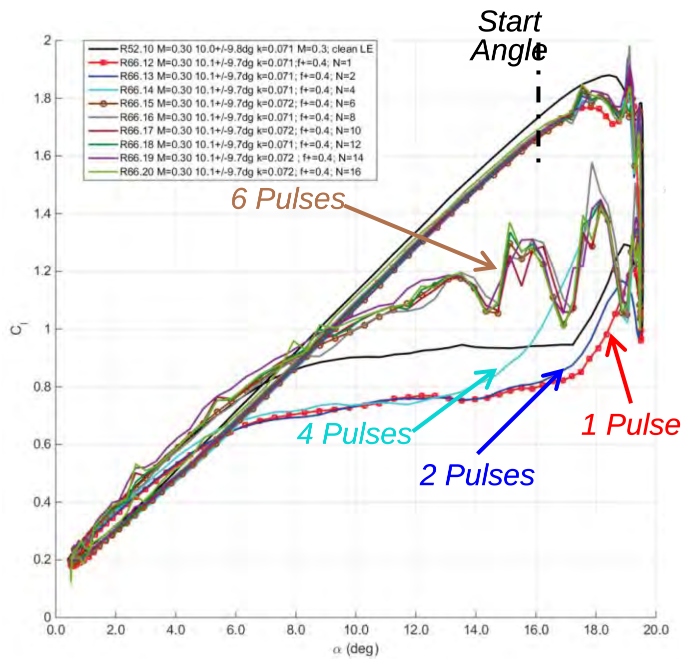
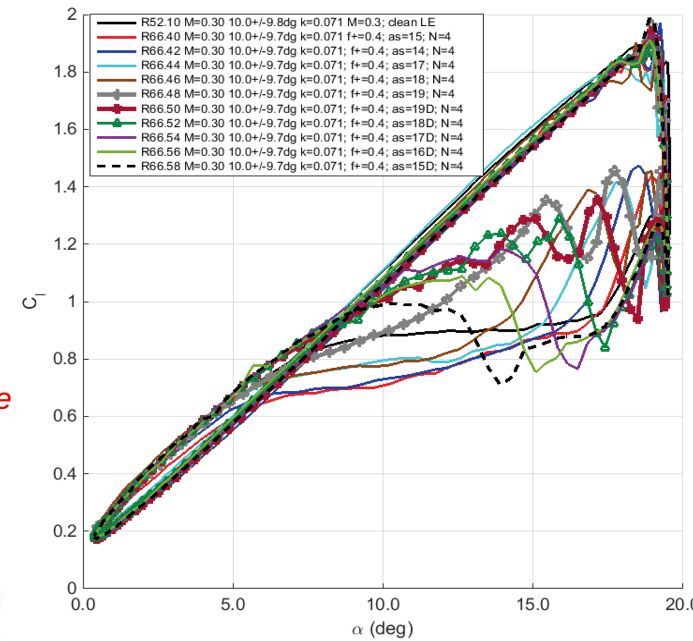
Multi (N)-Pulse Actuation Programs

- Limited testing of actuation programs, primarily focused on variation in number of pulses and start point in pitch cycle
- For fixed starting angle of 17º on upstroke, 6 pulses (~35% of cycle) is sufficient to achieve the full actuation effect
- For fixed actuation pulse count of 4, highest lift improvement with start at 19º on upstroke

Varying N, $\alpha_t = 17^{o}\uparrow$



Varying α_t, $N = 4$



$M = 0.3$, $\alpha = 10° \pm 9.5°$, $k = 0.07$, $F^{+} = 0.4$

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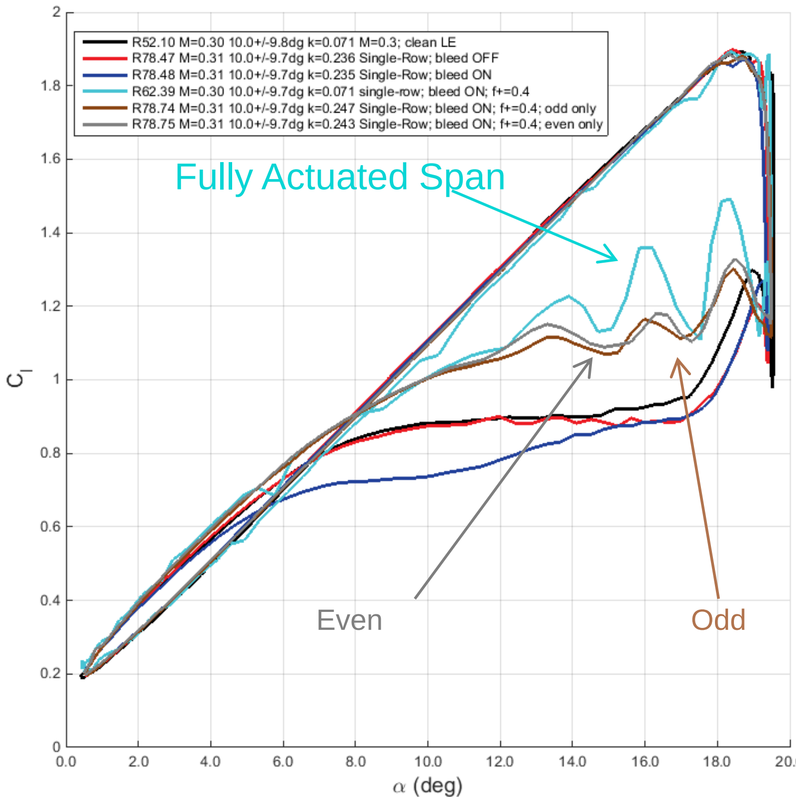
Actuator Spacing Variation

- Limited actuator testing was performed firing every other actuator to examine spanwise spacing effects
  - » Fully actuated span has 3.2 mm spacing between actuators and 0.8 packing density
  - » Even/odd firing has 19 mm spacing between actuator and 0.4 packing density
- Increased actuator spacing shows increase in lift similar to fully actuated cases although with reduced transient effects with each actuator pulse
  - » May allow for reduced infrastructure related to actuation



Even

$M = 0.3$, $\alpha = 10° \pm 9.5°$, $k = 0.07$, $F^+ = 0.4$

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Conclusions

- Low-speed (*M* ≈ 0.1) investigations of discrete COMPACT actuation programs using a VR-12 model (c = 0.38 m) during time-harmonic dynamic pitch.
  - » Significant control authority on the evolution of the dynamic stall vortex during upstroke and the timing of flow reattachment during downstroke
  - » Emphasis on control effectiveness during upstroke and downstroke using few actuation pulses.
  - » Improved cycle-averaged C_L and reduced hysteresis
  - » Increased pitch stability.
- VR-12 model tested at NASA Glenn IRT in collaboration with UTRC M ≤ 0.5
  - » Actuator effectiveness at actual rotorcraft flight speed was demonstrated by increase in instantaneous and cycle-averaged lift.
  - » Similar flow physics as demonstrated in low-speed testing expected to allow pulse actuation programs to be transitioned to high speed

Comments by Peretz Friedmann

- Current state of the art in understanding dynamic stall (DS)

  My interests are in development of high-fidelity codes to model and control aeroelastic response, vibration, noise and performance on current (advanced) rotorcraft. Accurate reduced order models (ROMs) of DS are required, for computational efficiency. Such models do not exist, and there is still a heavy reliance on semi-empirical DS (2D) models.

- Who is advancing the state of the art and how are they doing it?

  Field currently somewhat static

- What errors do you see the general community still making?

  High quality experiments on rotating blades and correlation with CFD needed but not available.

AFC

- Active flow control of DS has had significant funding in the past, but there are still no systems installed on current vehicles. Are there physics that can be exploited to make AFC viable?
- Elimination and control of DS on rotating blades has not been demonstrated. However, it has not prevented the design of pretty good flying rotorcraft.
- Flow control has potential that has not been realized, the effectiveness of other control approaches, such as on-blade control has had only very limited success.

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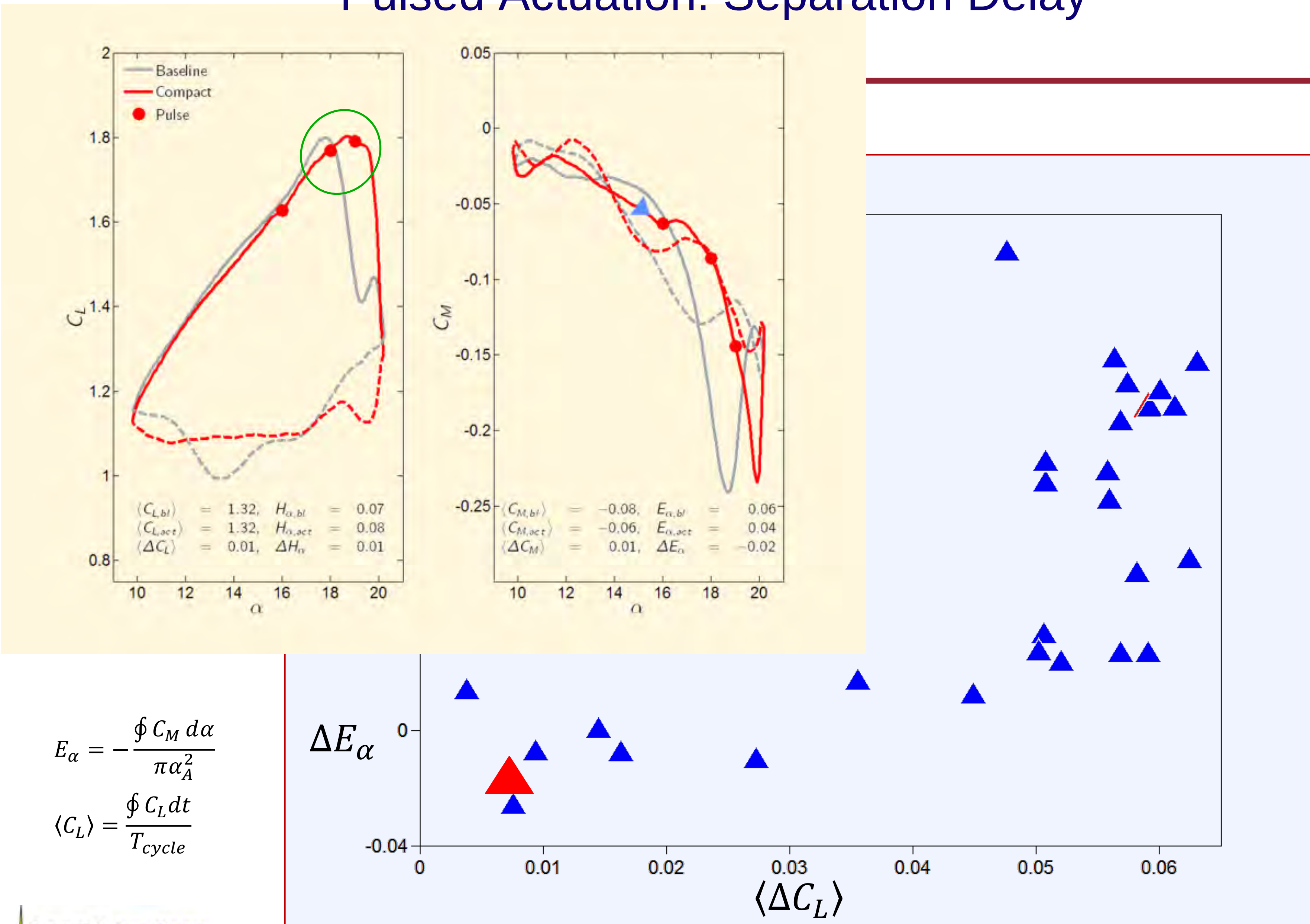
Pulsed Actuation: Separation Delay



$$E_\alpha = -\frac{\oint C_M \, d\alpha}{\pi \alpha_A^2}$$

$$\langle C_L \rangle = \frac{\oint C_L \, dt}{T_{cycle}}$$

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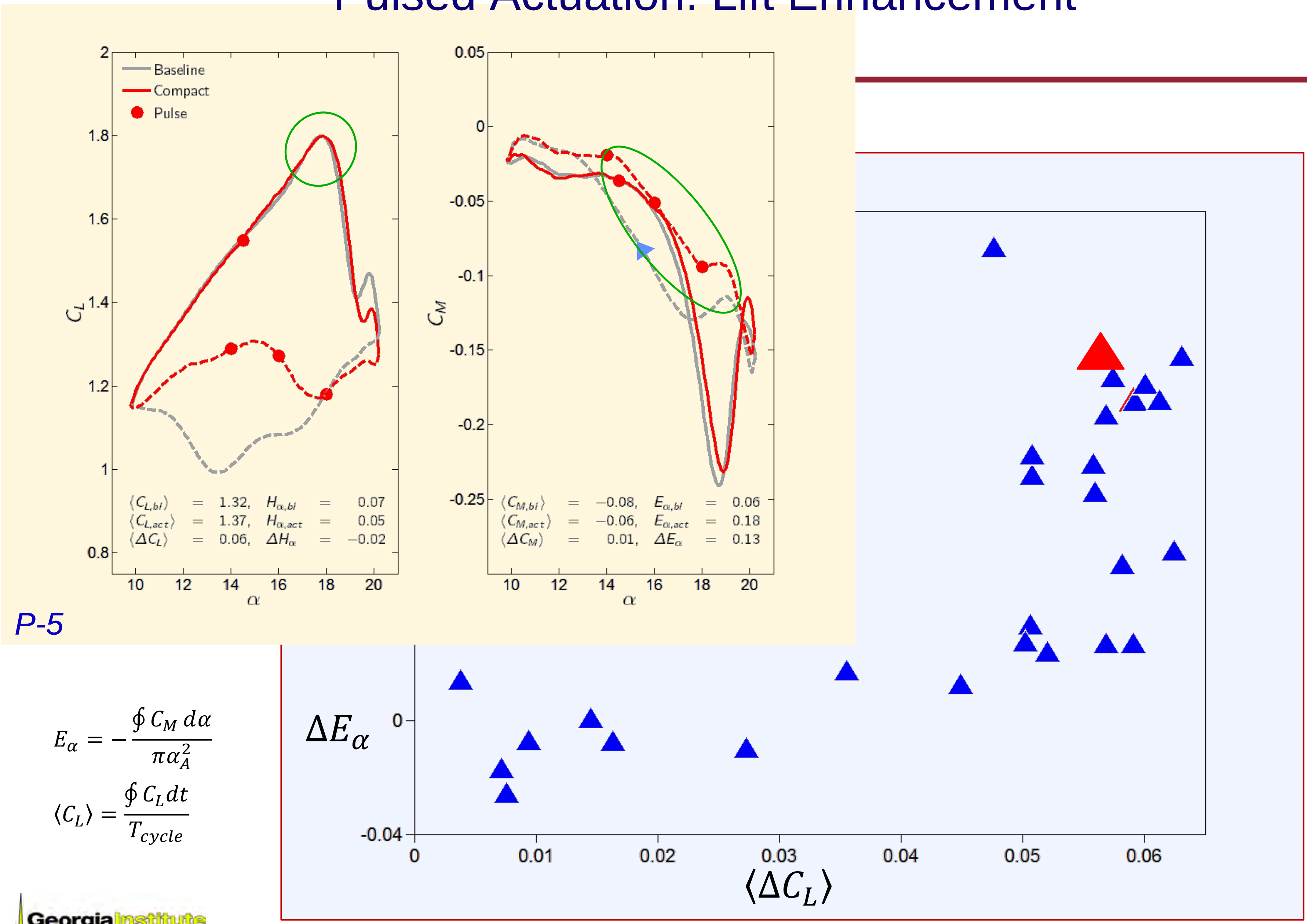
Pulsed Actuation: Lift Enhancement



$$E_\alpha = -\frac{\oint C_M \, d\alpha}{\pi \alpha_A^2}$$

$$\langle C_L \rangle = \frac{\oint C_L dt}{T_{cycle}}$$

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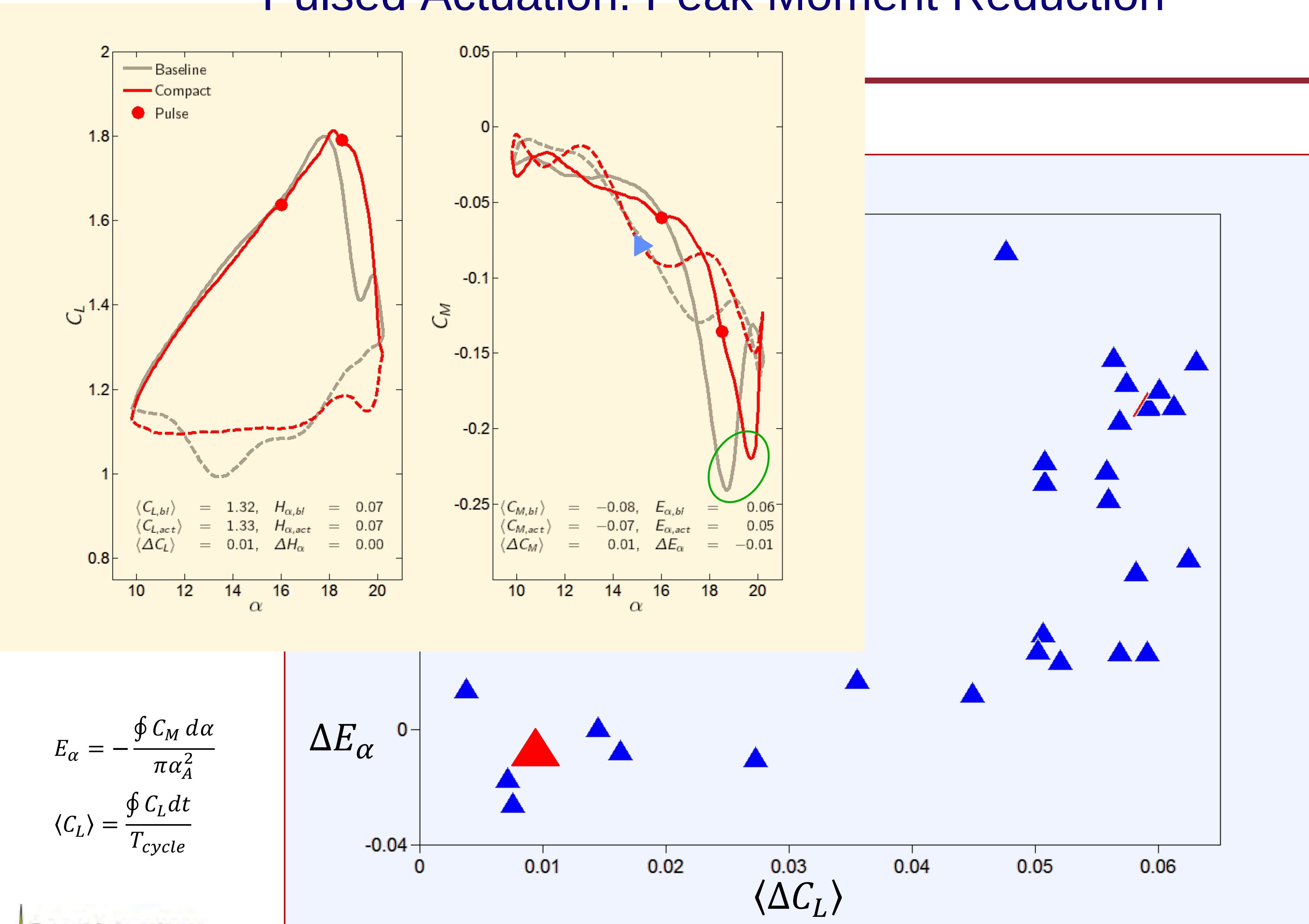
Pulsed Actuation: Peak Moment Reduction



$$E_\alpha = -\frac{\oint C_M \, d\alpha}{\pi \alpha_A^2}$$

$$\langle C_L \rangle = \frac{\oint C_L \, dt}{T_{cycle}}$$

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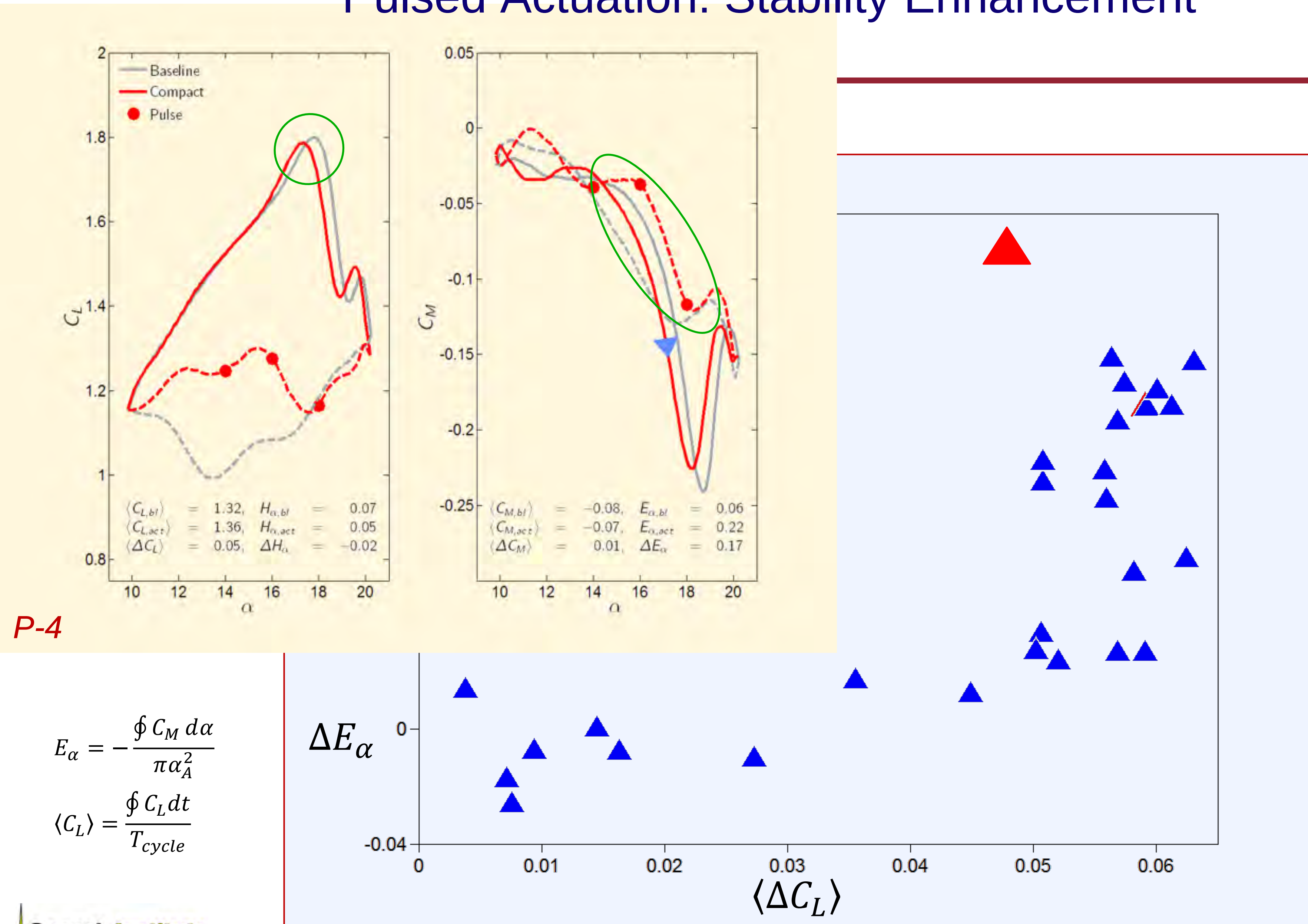
Pulsed Actuation: Stability Enhancement



$$E_\alpha = -\frac{\oint C_M \, d\alpha}{\pi \alpha_A^2}$$

$$\langle C_L \rangle = \frac{\oint C_L \, dt}{T_{cycle}}$$

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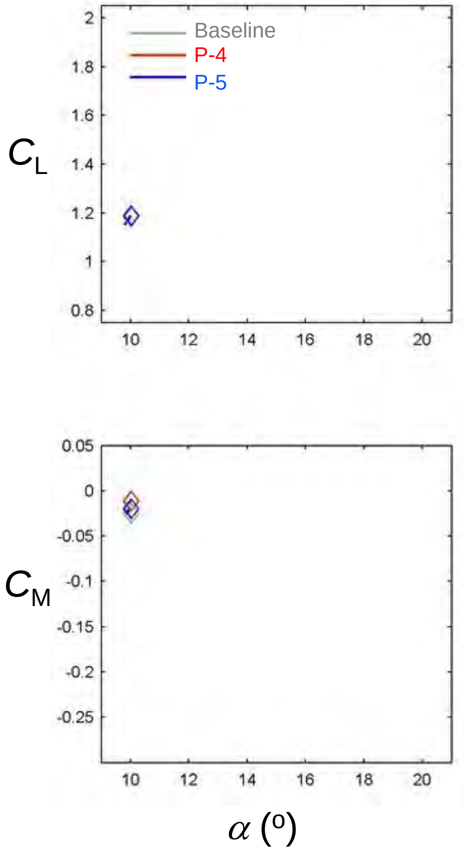
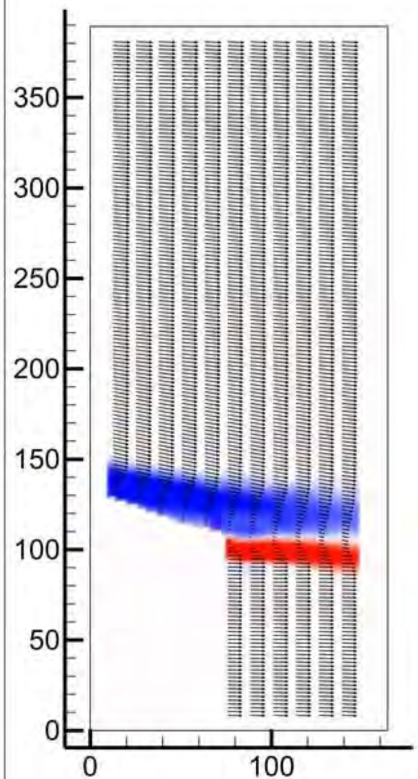
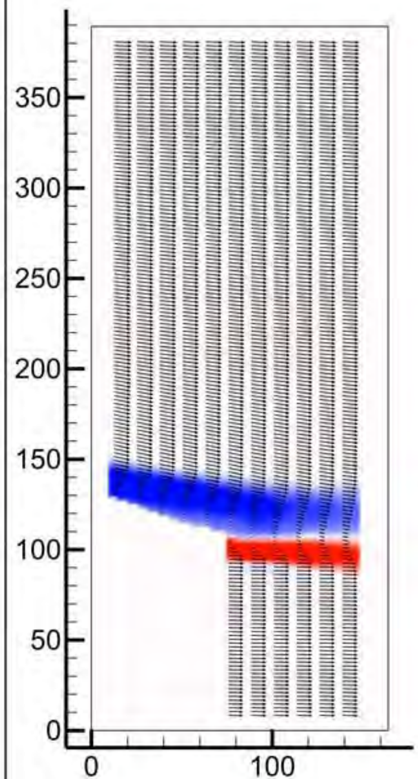
PIV: Selected Programs



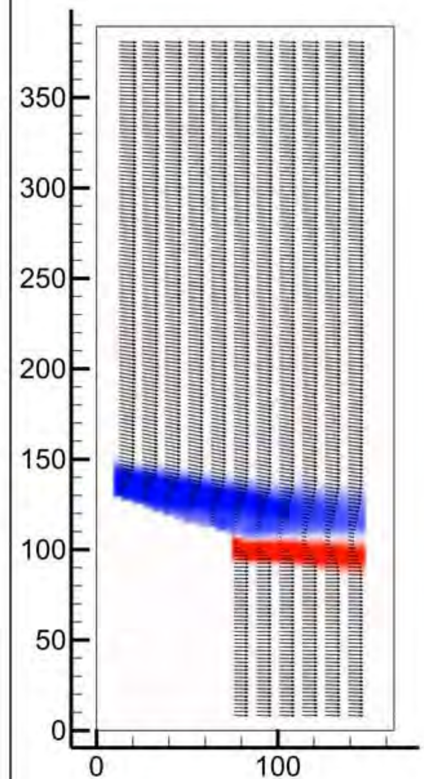
Baseline



Stability Enhancement



Lift Enhancement



Baseline

$\langle C_{L,bl} \rangle = 1.32$

$E_{\alpha,bl} = 0.06$

- Stall commences @ $\alpha \approx 17^o \uparrow$
- Reattachment @ $\alpha \approx 11^o \downarrow$
- Strong hysteresis and loss of lift during downstroke

P-4

$\langle C_{L,P\text{-}1} \rangle = 1.36$

$E_{\alpha,P\text{-}1} = 0.22$

- Baseline flow during upstroke
- 3 pulses during downstroke @ $\alpha = 18^o \downarrow$, $16^o \downarrow$, and $14^o \downarrow$

P-5

$\langle C_{L,P\text{-}2} \rangle = 1.37$

$E_{\alpha,P\text{-}2} = 0.18$

- One pulse during upstroke @ $\alpha = 14.5^o \uparrow$
- 3 pulses during downstroke @ $\alpha = 18^o \downarrow$, $16^o \downarrow$, and $14^o \downarrow$

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ON THE CONTROL OF SEPARATION AND REATTACHMENT OF TURBULENT BOUNDARY LAYER

Based on experiments of Darabi, Phyllips and Taubert

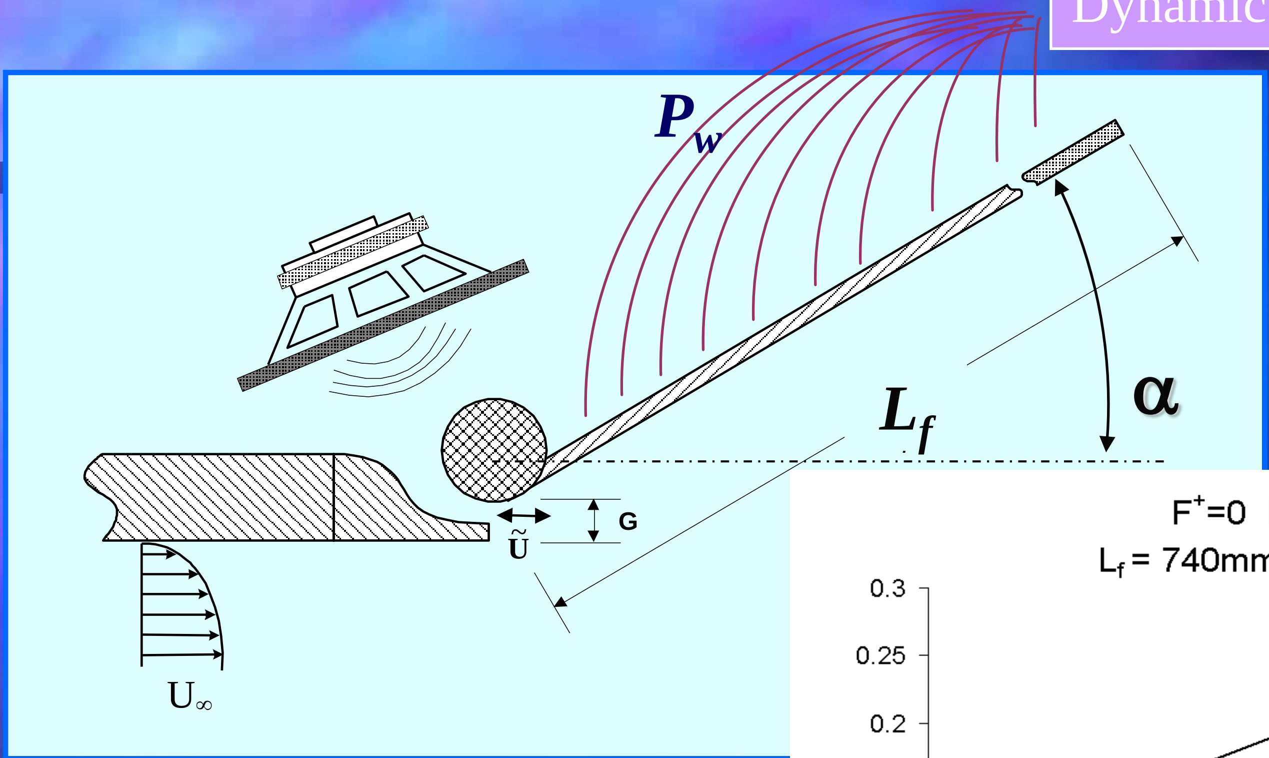
Presented by

Israel Wygnanski

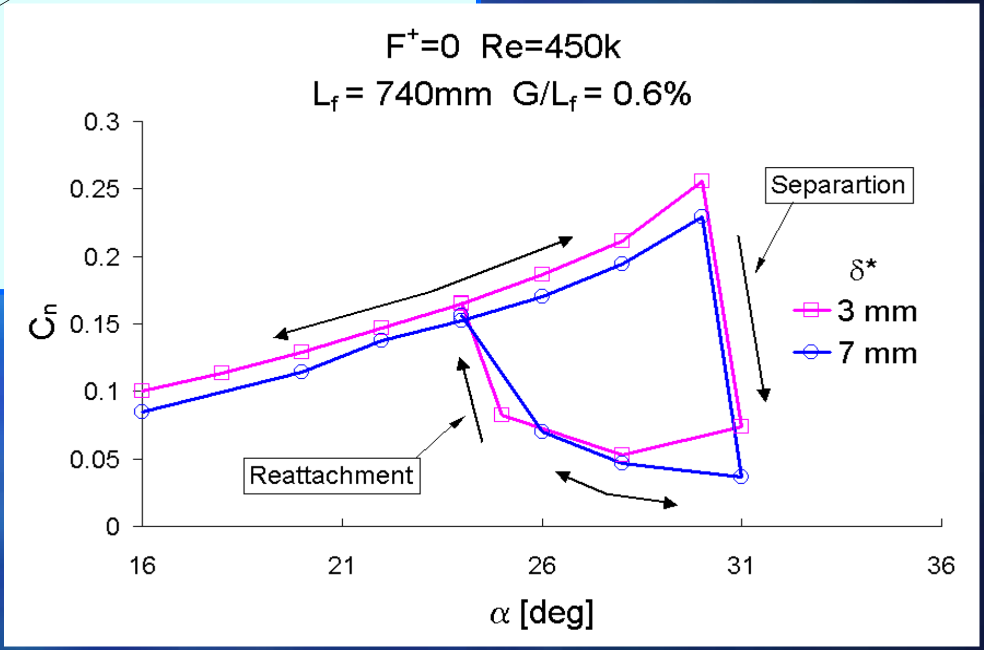
ARO-GT Dynamic Stall Workshop

September 2019

Dynamic Pressures



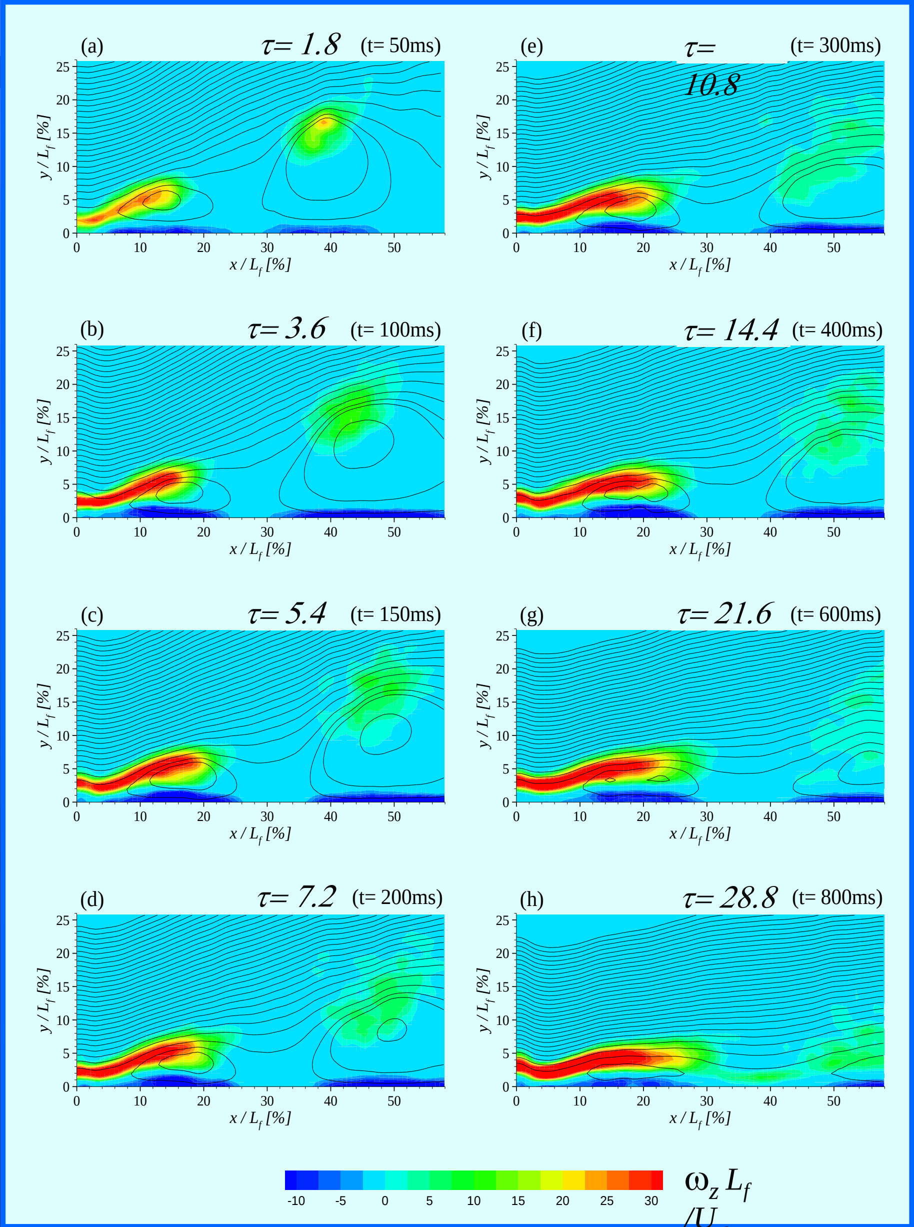
Hysteresis loop is observed when a flap is deflected beyond it natural separation deflection.

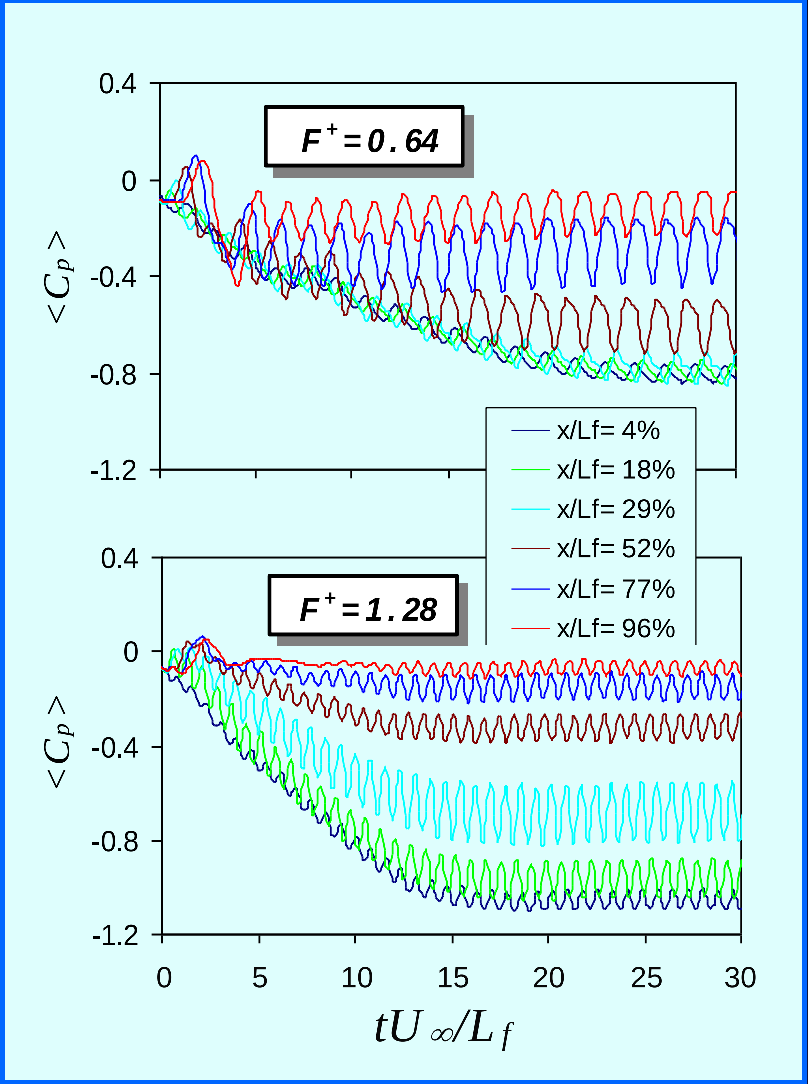


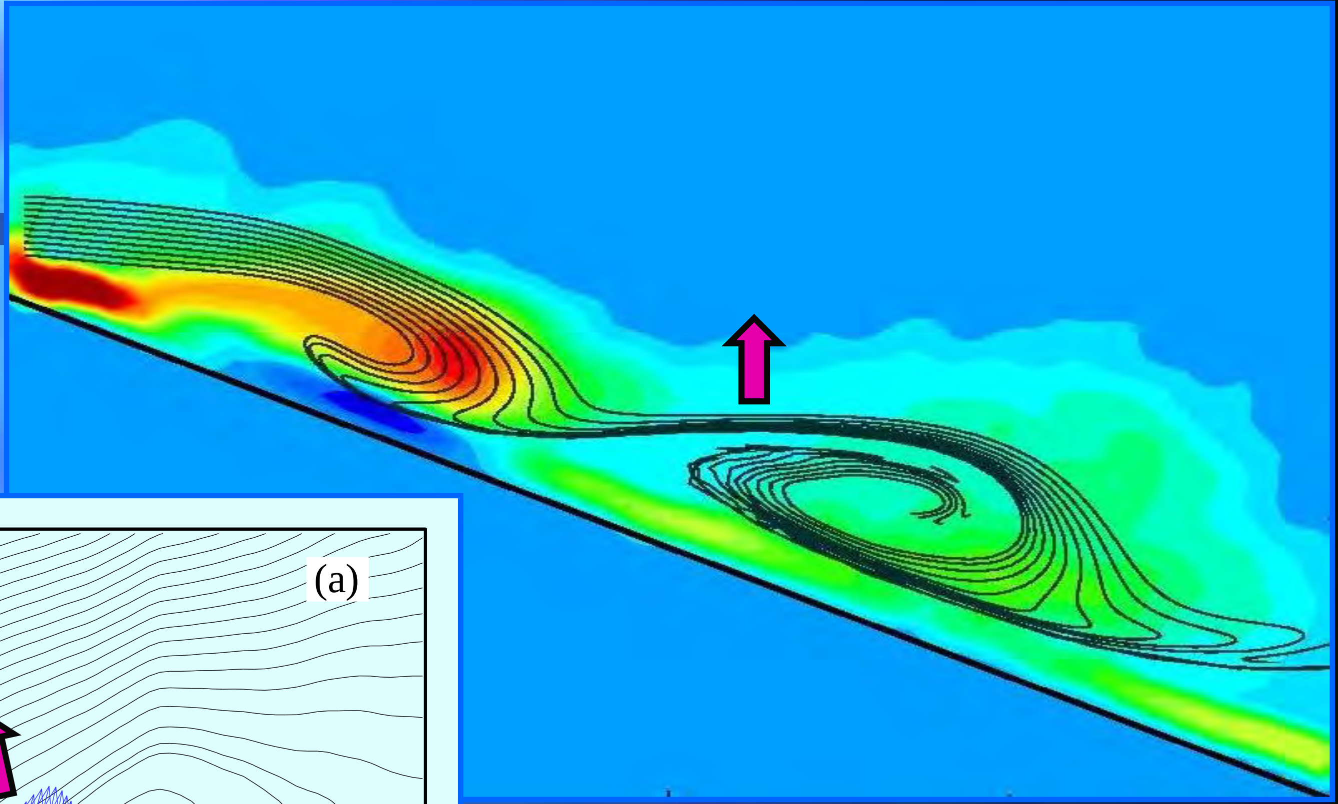
Reattachment due to AFC may be investigated by setting $a>a_{sep}$ & changing AFC input to force reattachment or starting with attached flow due to AFC and controlling the separation process by AFC

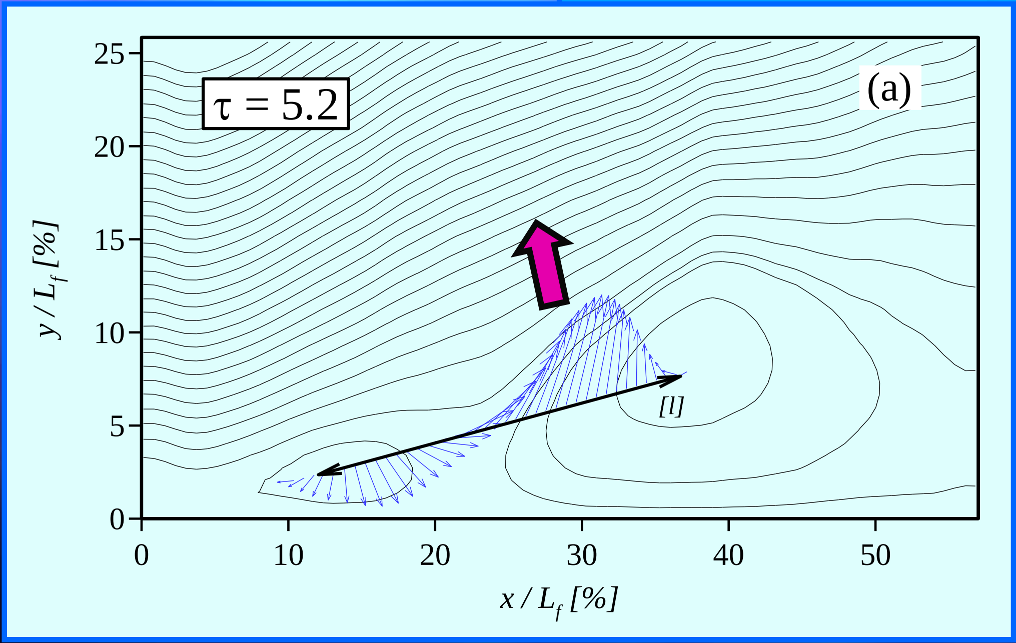
The reattachment process is tracked by surface pressures and by PIV. It takes some 20 cycles to reattach regrdless of F+, note spatial amplification of pressures and the slow bending of the separated mixing layer toward the surface.

<cμ>= 0.05% , Δα=6º





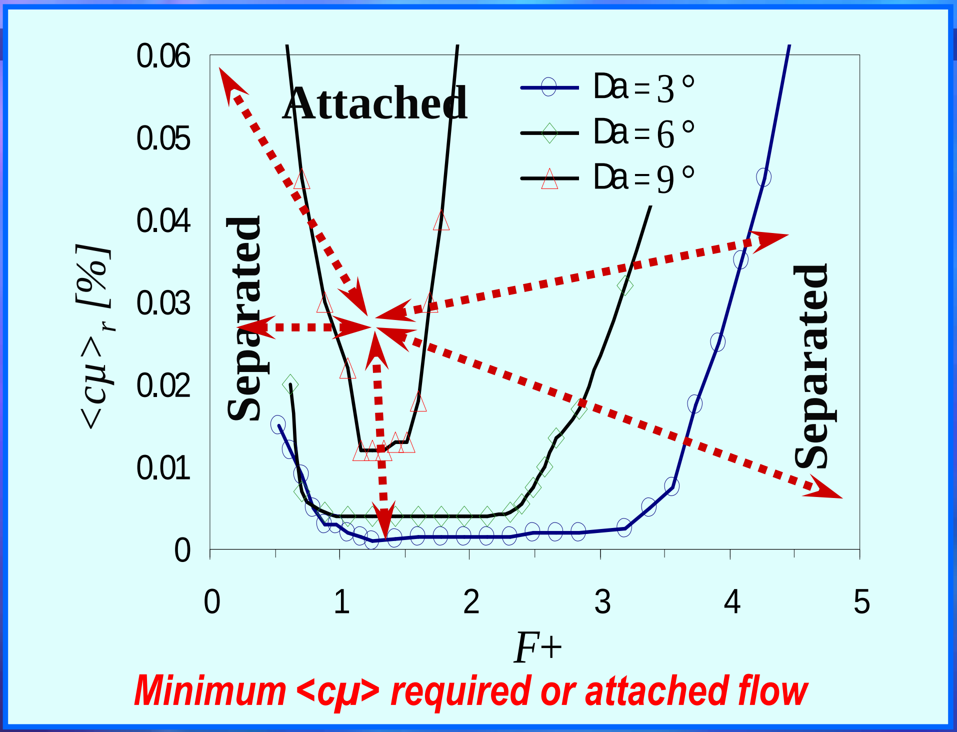


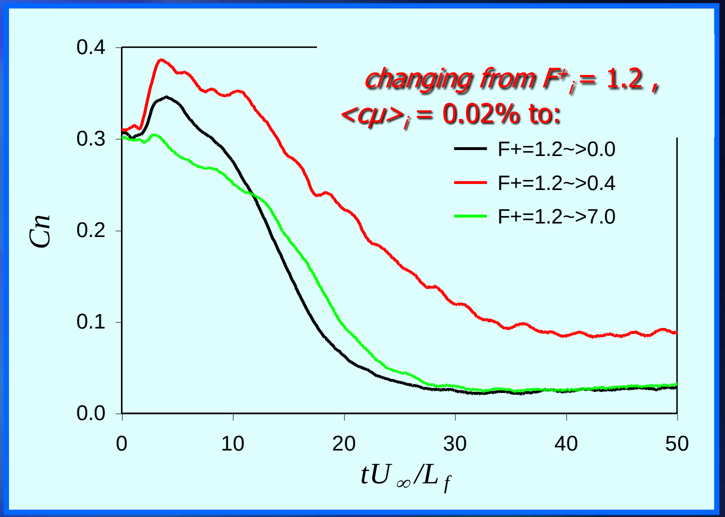


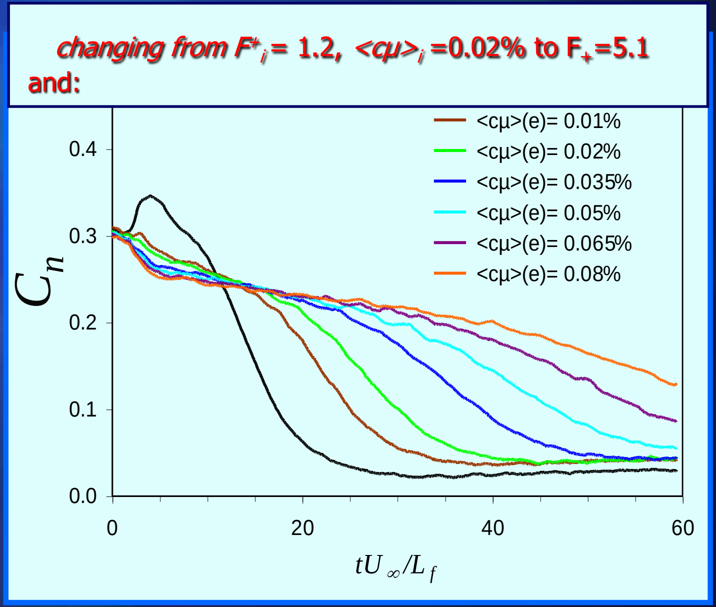
Reverse flow seeping in from the trailing edge is removed by the passing eddies away from the surface. Thus mass flow balance is maintained.

So, is it possible to control the separation process and avoid the generation of the Dynamic Stall Vortex (DSV)?

Various ways to transition from attached state (Cn=0.3) to separated state (Cn→0) involves changing all three variables: Δα, F+, <cμ> in any combination





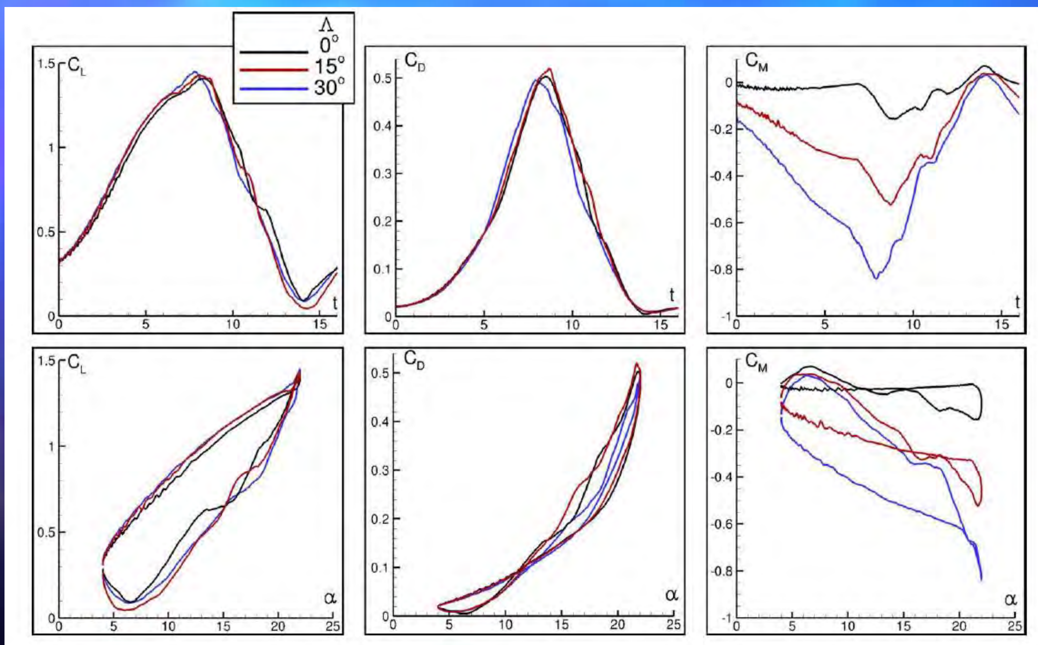


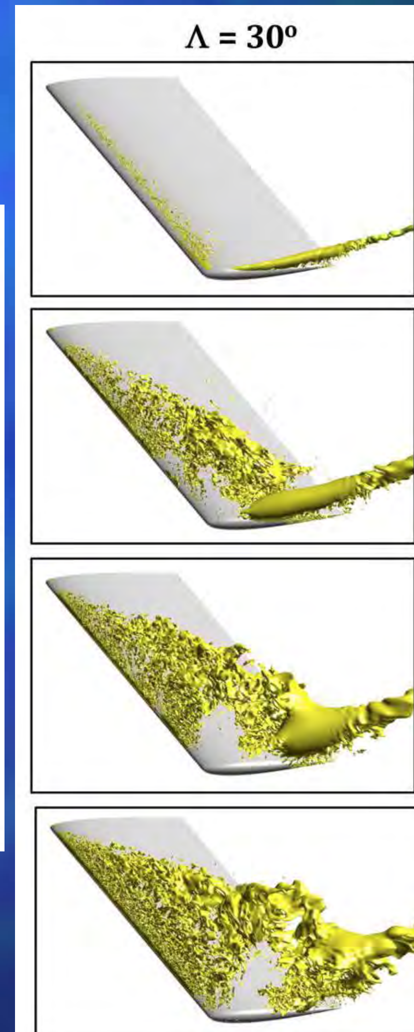
Increasing frequency eliminates the DSV, reducing it enhances the DSV

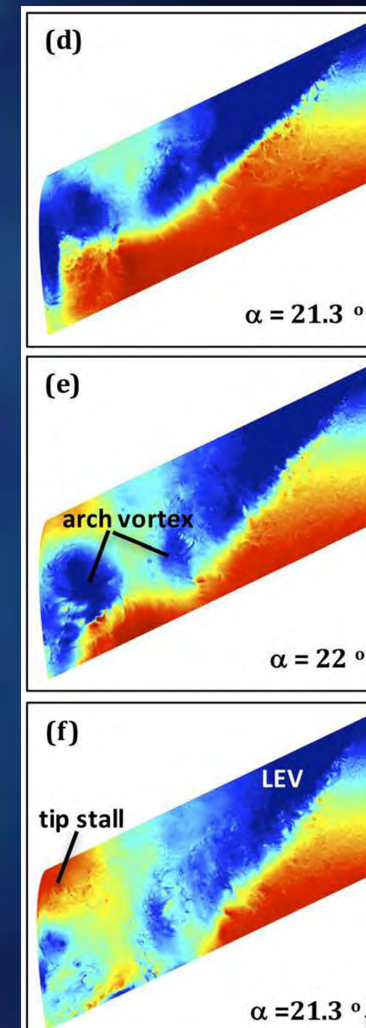
The pace of separation is easily controlled by changing <cμ>

One may change course during transition and recover (e.g. create a DSV and then reduce α before it is shed-Cobra maneuver)

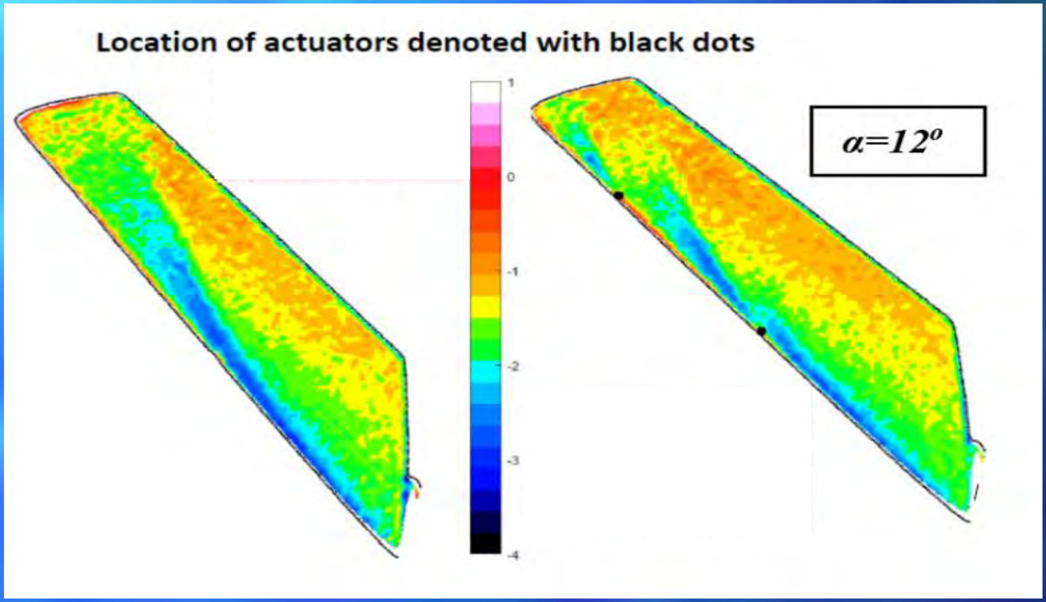
Visbal & Garmann (2018) computed the effects of sweep on the DSV & on the ensuing forces and moments acting on a swept back wing of AR=4 suggesting that Λ has a large effect on C_m. Their wing was based on NACA-0012 airfoil.

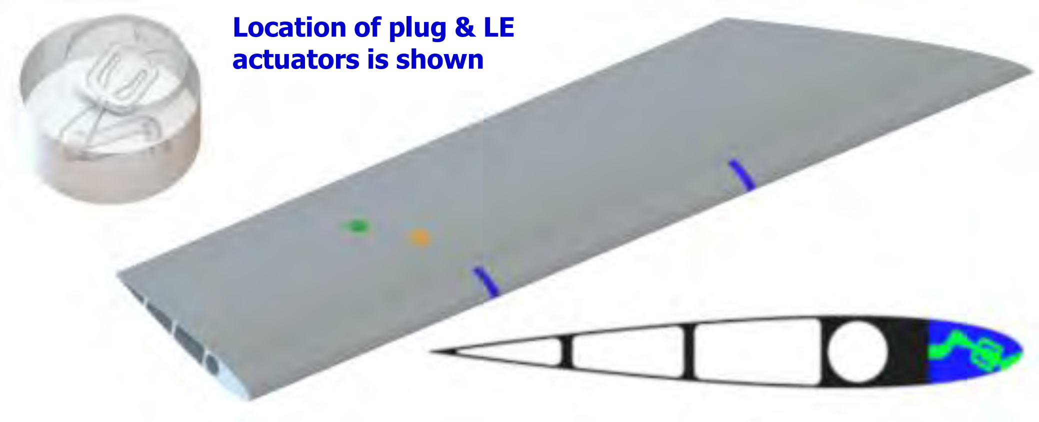






We are currently converting our steady AFC wing experiment that is also based on the NACA-0012 airfoil at a sweep back of 45º to a pitching wing experiment to verify Visbal's observations and provide the means of controlling the DSV,





Conclusions

- Oscillatory excitation effectively controls the flow during the fundamental state transitions in 2D.
  - ***<c$_\mu$> and F^+ can be used to regulate the rate-of-change, and hence the total time of occurrence, for these transitions.***
  - ***There is an upper limit to the rate at which state transitions can be forced, its time scale is an order of magnitude larger than the periodic excitation.***
  - ***Sweeping jet actuators are effective in controlling the DSV on a flap although the control mechanism is different***
  - ***An experiment was initiated to control the DSV by sweeping jets on a swept back wing at $\Lambda=45^o$***

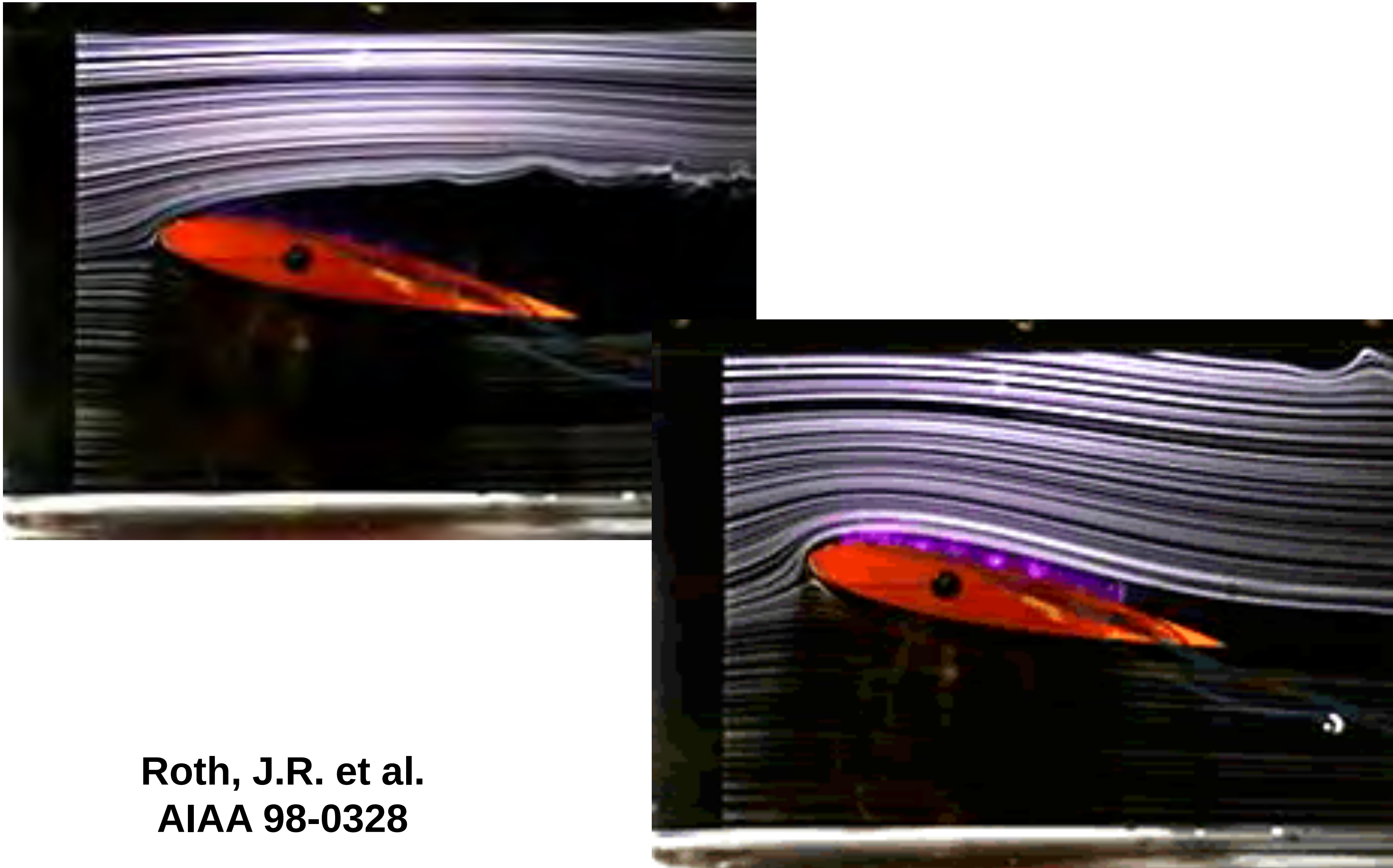
Dynamic Stall Control by NS SDBD Plasma Actuators

Andrey Yu. Starikovskiy

Department of Mechanical and Aerospace Engineering

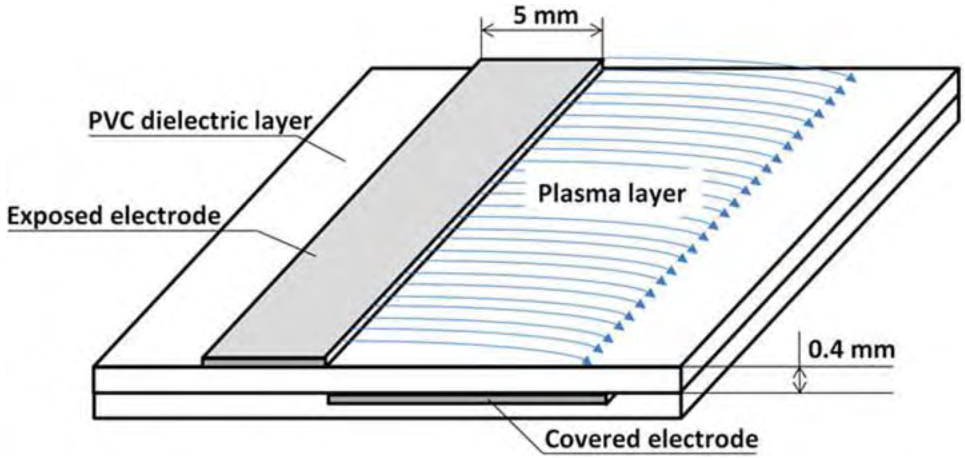
PRINCETON
University

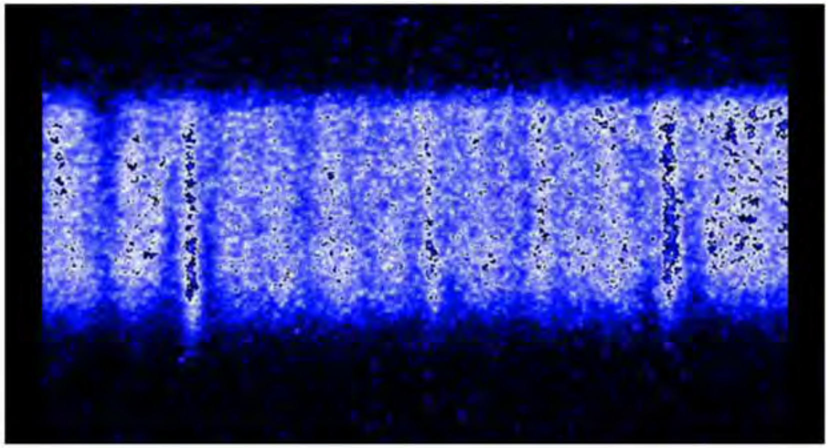
Plasma Aerodynamics: Flow Control by AC-SDBD plasma actuators

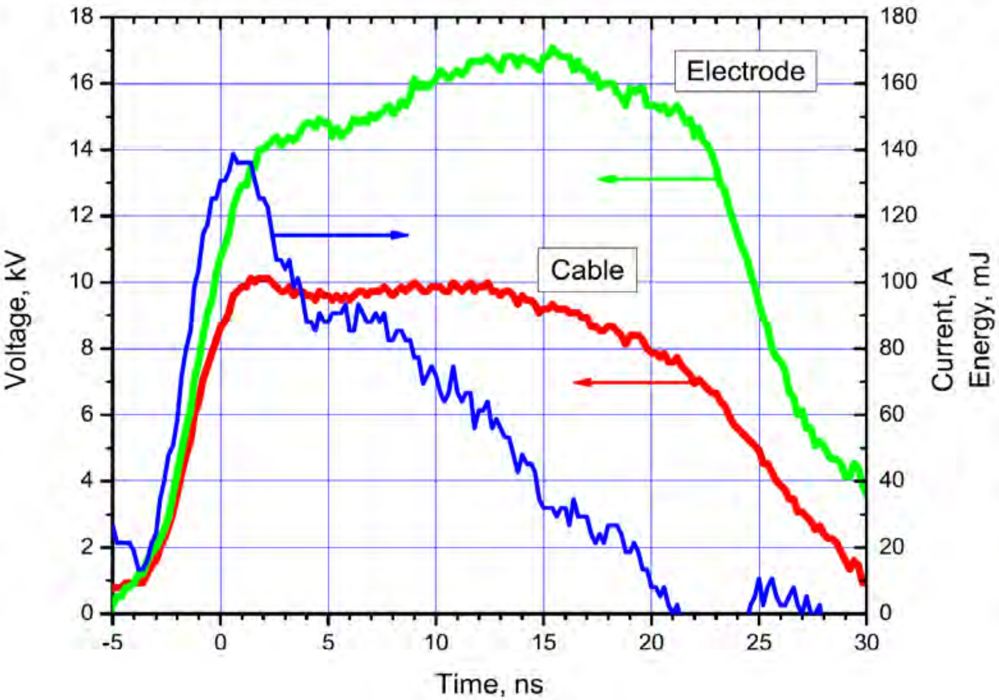


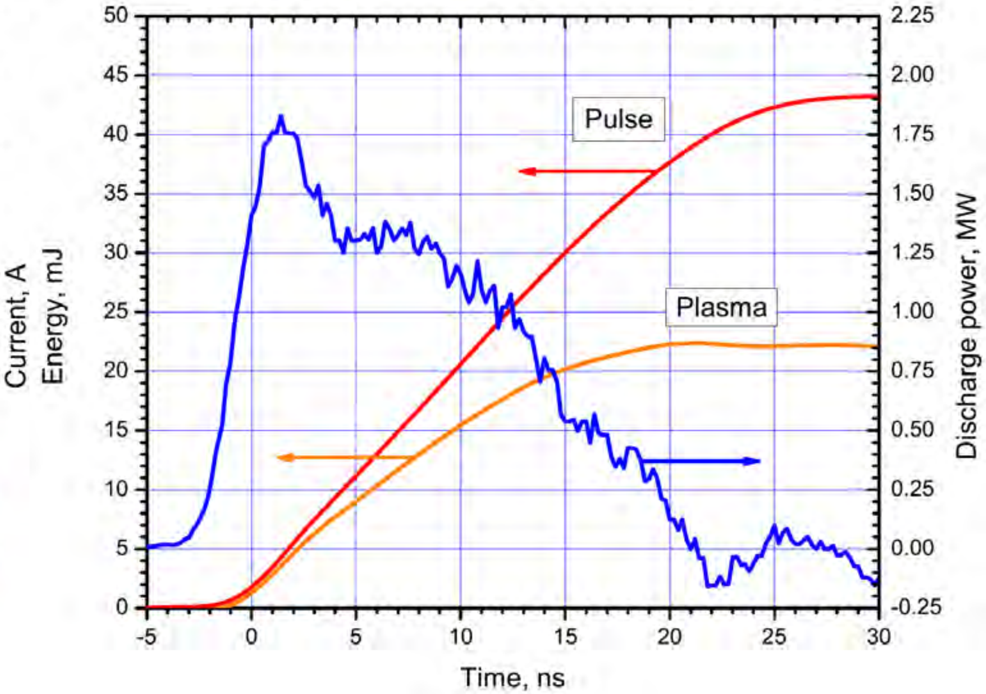
Roth, J.R. et al.
AIAA 98-0328

Schematic of the dielectric barrier discharge actuator (left) and image of the NS SDBD development (right). Air, 1 atm, time after NS SDBD start is 5 ns, ICCD camera gate is 1 ns.









NS SDBD Flow Separation Control

G. Correale, I.B. Popov, A.E. Rakitin, A.Yu. Starikovskii, S.J. Hulshoff, L.L.M. Veldhuis *Flow Separation Control on Airfoil with Pulsed Nanosecond Discharge Actuator.* 49th AIAA Aerospace Sciences Meeting. Orlando, Florida. Jan 2011. Paper AIAA-2011-1079

Flow Velocity =30m/s

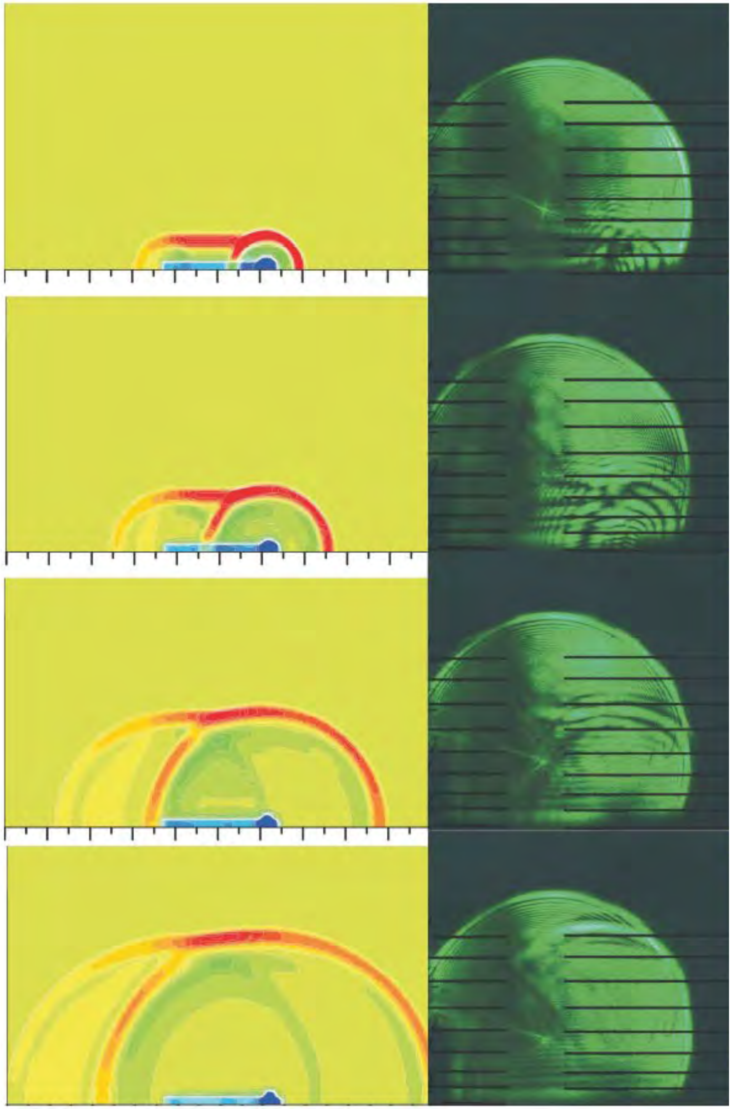
Model: NACA 63-618

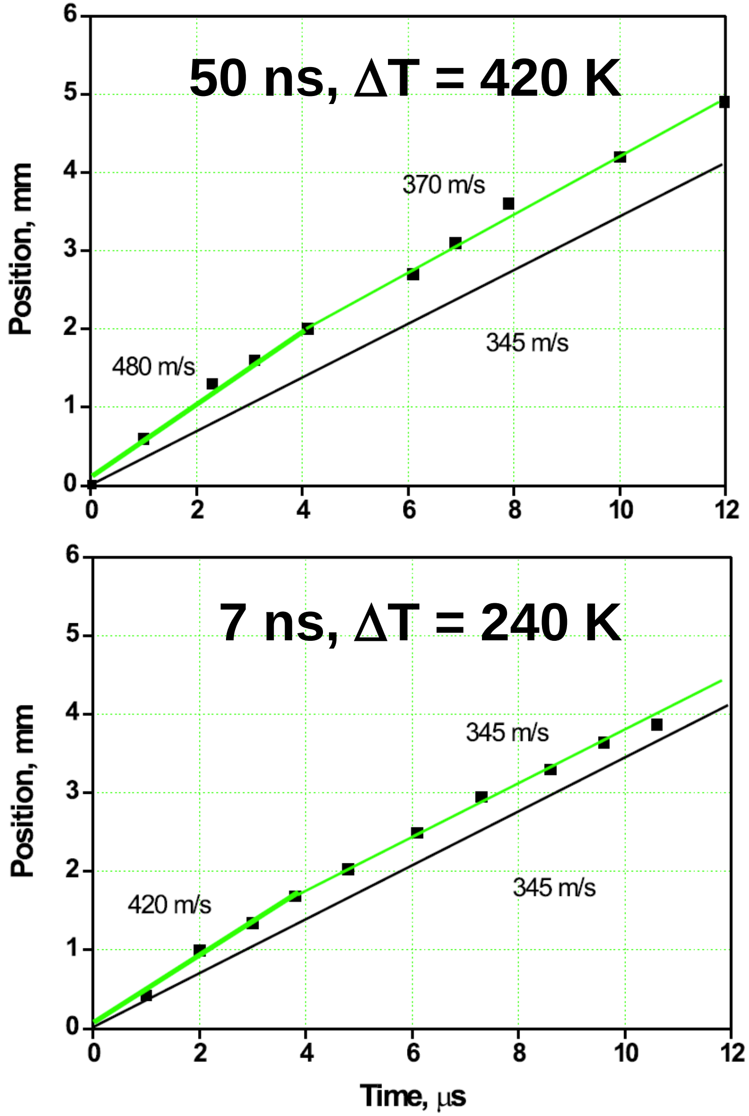
AoA=26

f = 200 Hz

Single Pulse

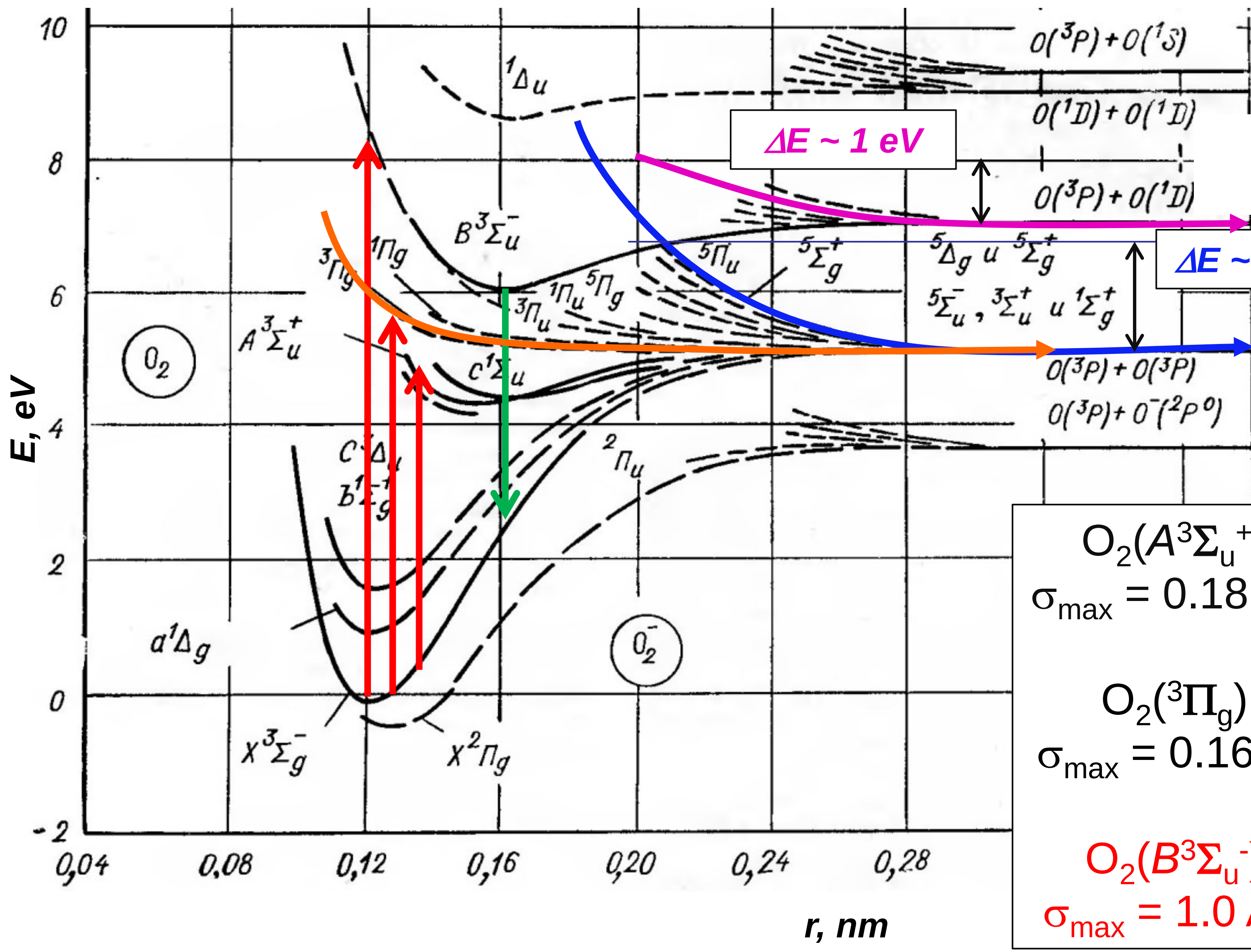
Shock Wave and Hot Spot Formation by NS-SDBD





A.Nikipelov, M.Nudnova, D.Roupassov, A.Starikovskiy. *Acoustic Noise and Flow Separation Control by Plasma Actuator.* AIAA-2009-695. 47th AIAA Aerospace Sciences Meeting including The New Horizons Forum and Aerospace Exposition, Orlando, Florida, Jan. 5-8, 2009

Potential Energy Curves of Molecular Oxygen



$O_2(A^3\Sigma_u^+)$, 4.5 eV

σ_{max} = 0.18 A^2 (6.6 eV)

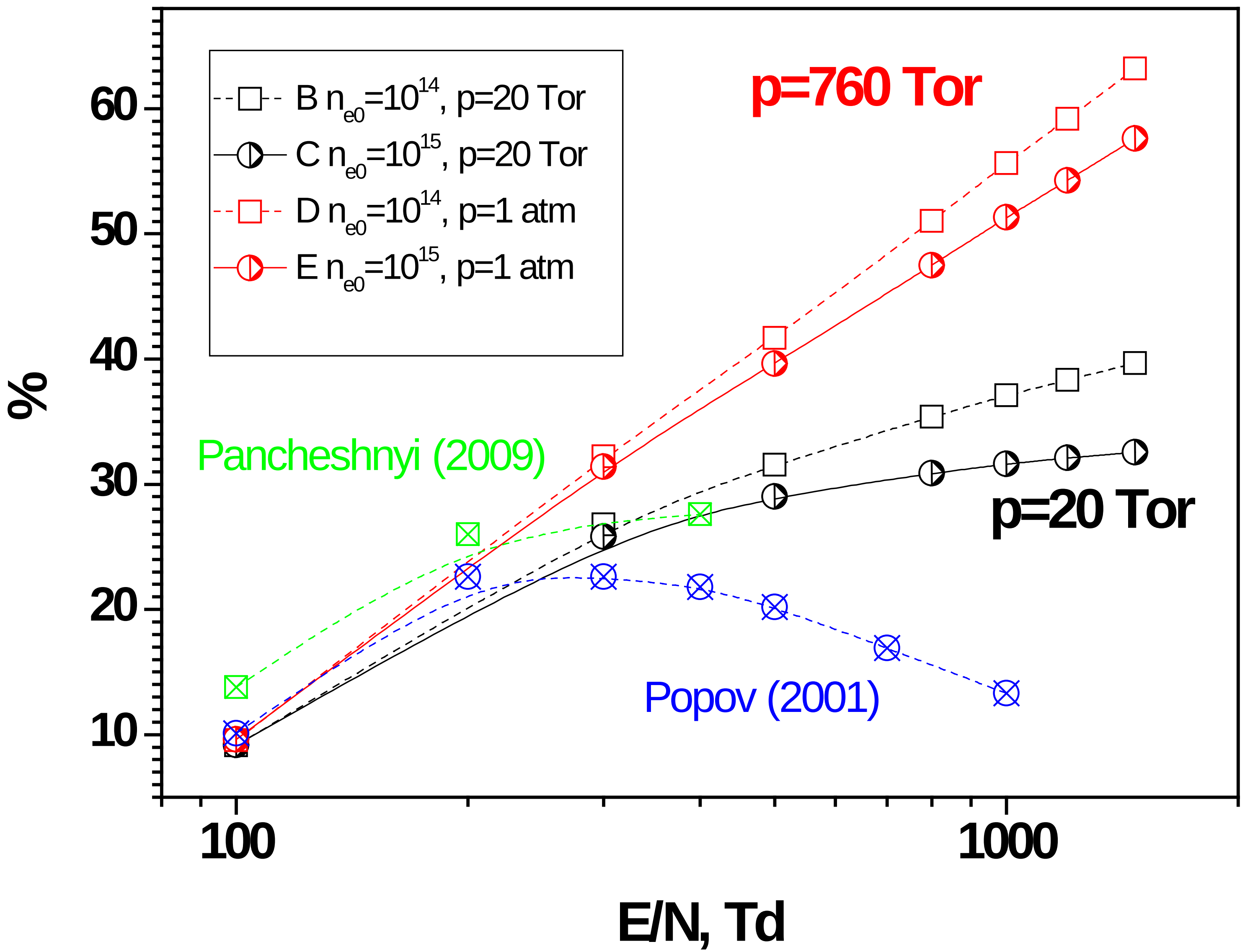
$O_2(^3\Pi_g)$, 5.6 eV

σ_{max} = 0.16 A^2 (12 eV)

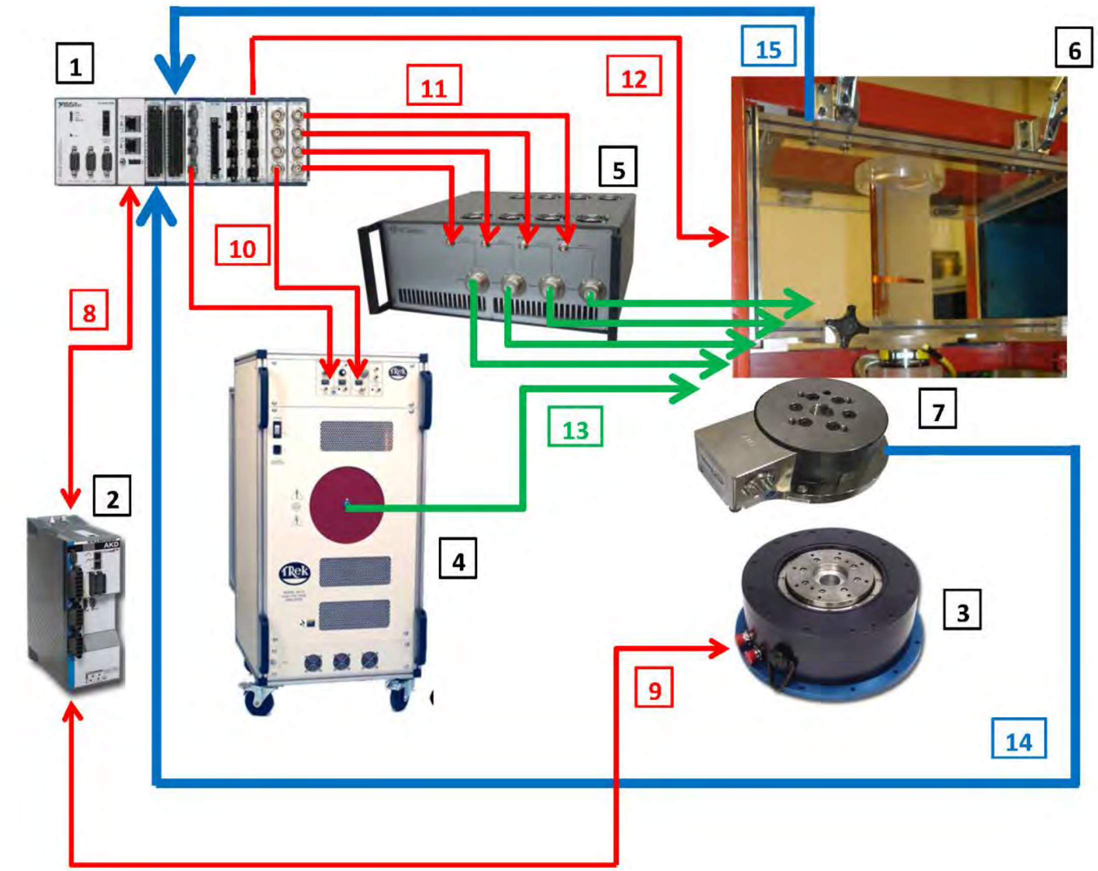
$O_2(B^3\Sigma_u^-)$, 8.4 eV

σ_{max} = 1.0 A^2 (9.4 eV)

Mechanism of Fast Heating in Discharge Plasmas (High E/N)

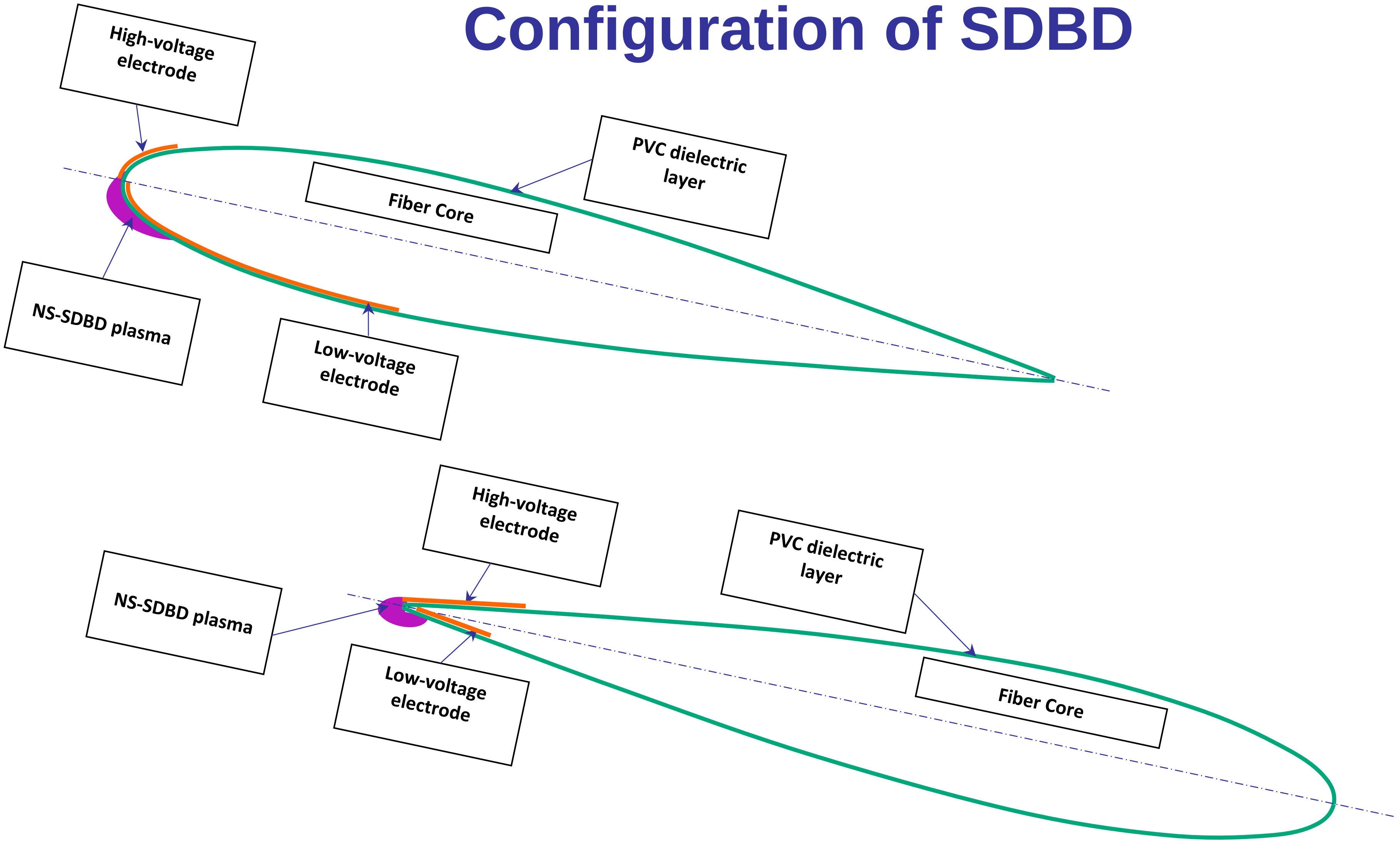


Subsonic Variable Speed Plasma (SVSP) Wind Tunnel schematics and instrumentation.

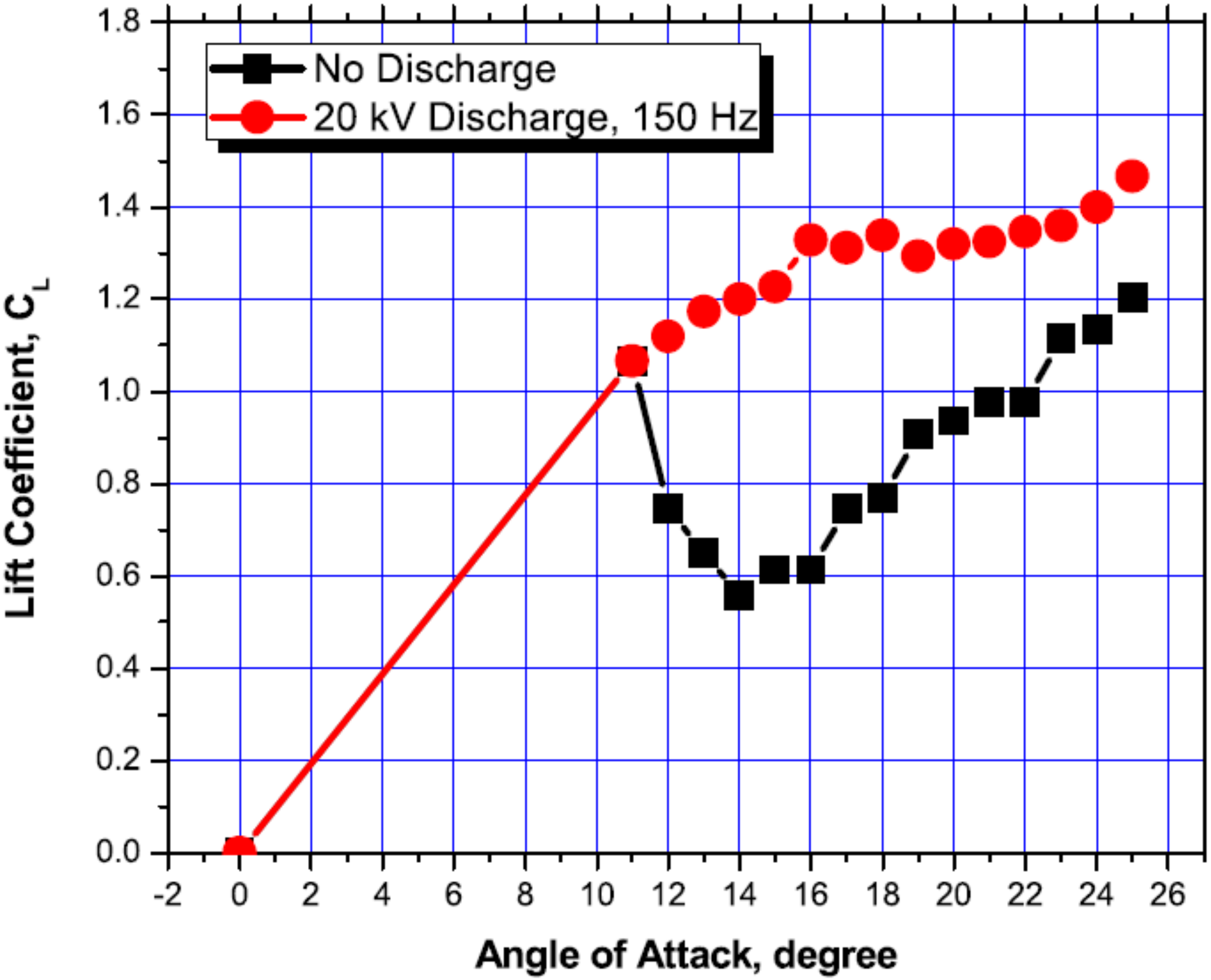


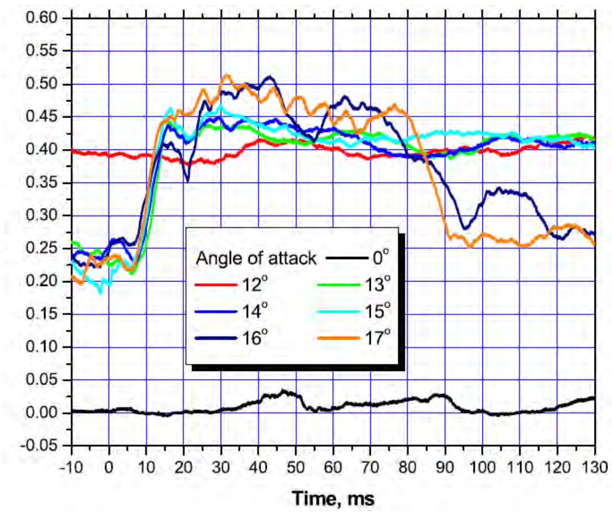
1 – NI cRIO 9068 control module, including programmable voltage and current sources; 32-ch differential 16-bit analog input modules; 8-ch TTL input/output modules; EtherCAT interface for servomotor control. 2 – servomotor drive. 3 – direct drive Kollmorgen servomotor. 4 – TREK high-voltage amplifier for bias/AC supply. 5 – FID 4-ch pulser. Maximal voltage 36 kV, frequency 20 kHz, pulse duration 15 ns, interchannel jitter less than 100 ps. 6 – wind tunnel. Maximal speed is 180 m/s for small chord models; 100 m/s for large models. 4 screens; 1:16 contraction ratio. 250×360 mm² cross-section. 7 – ATI-IA DAQ F/T 6-component transducer. 8 – EtherCAT interface. 9 – servomotor interface. 10 – amplifier control. 11 – FID pulser synchronization. 12 – dynamic control of wind tunnel speed. 13 – high-voltage lines to actuators. 14 – DAQ transducer cable. 15 – Pitot tube and hot wire sensors free-stream velocity data.

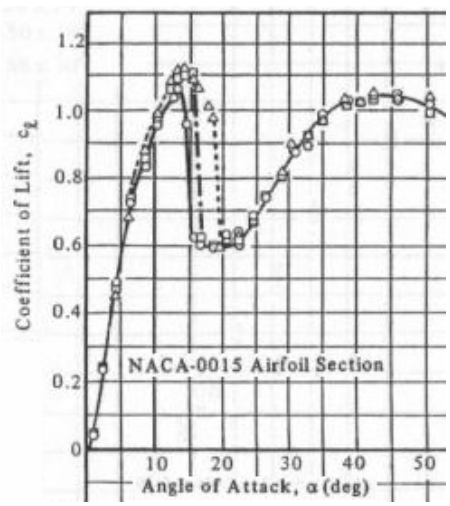
Leading Edge Actuation Configuration of SDBD



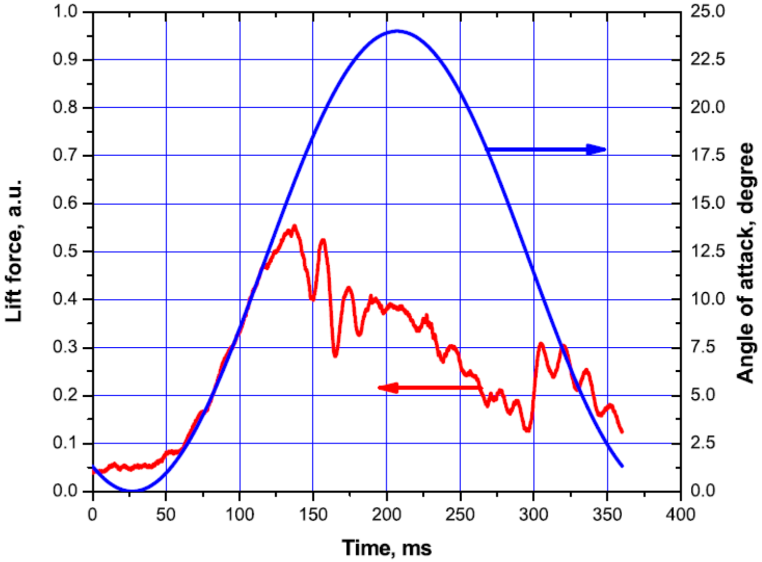
Lift force as a function of time and AoA.
P = 2 W, f = 150 Hz, Q = 15 mJ/pulse.
V = 31 m/s, NACA0015 airfoil.

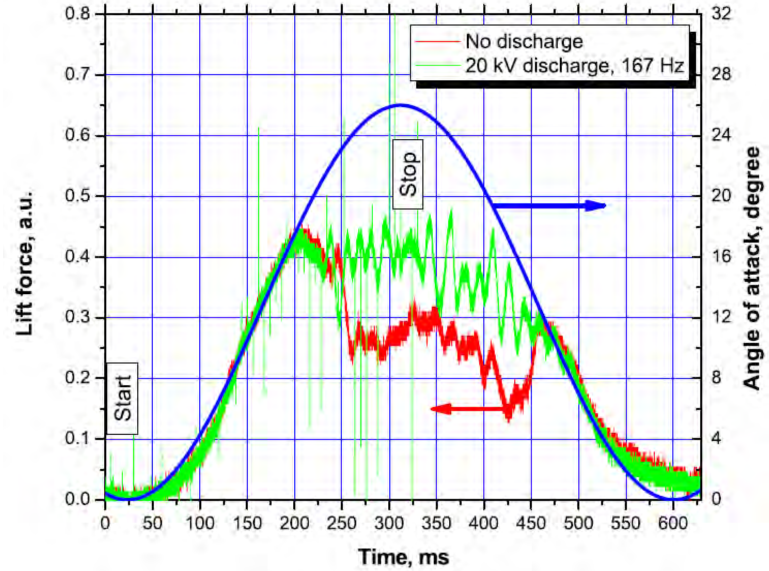


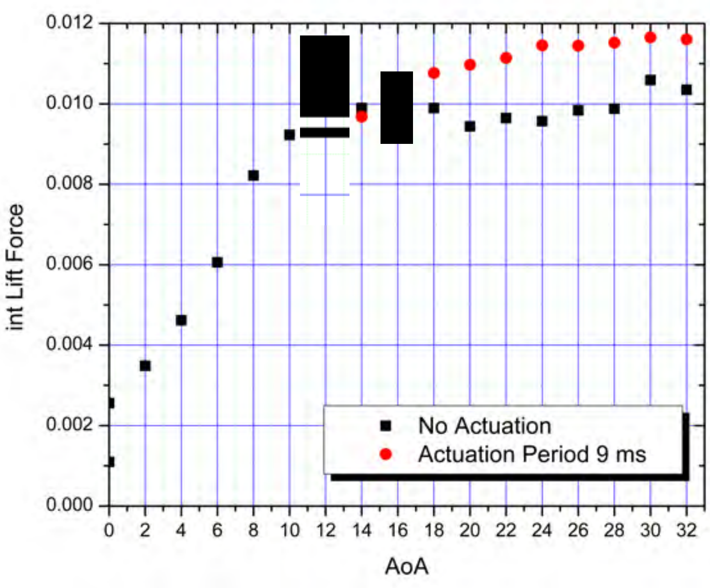


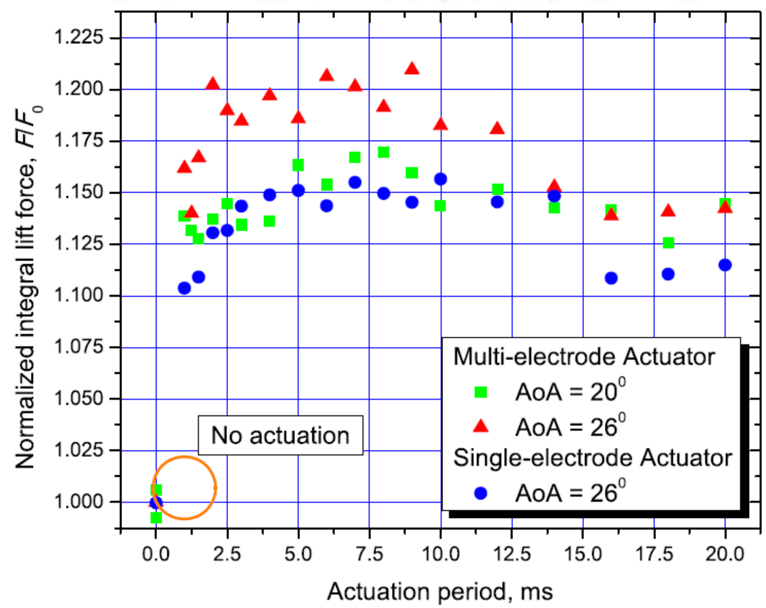


Dynamics of the lift force over the pitching cycle. Normal Flow. Flow speed 31 m/s

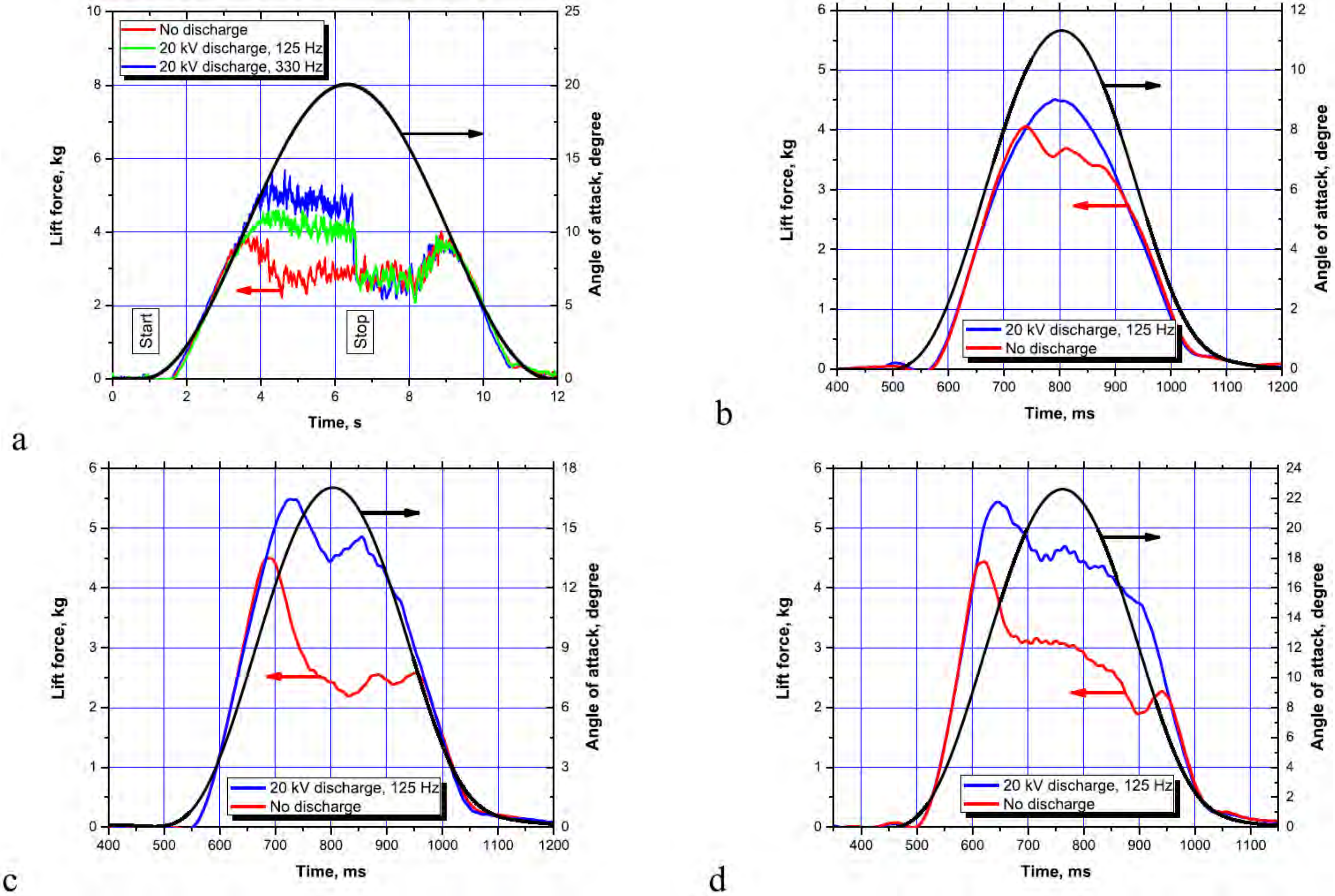




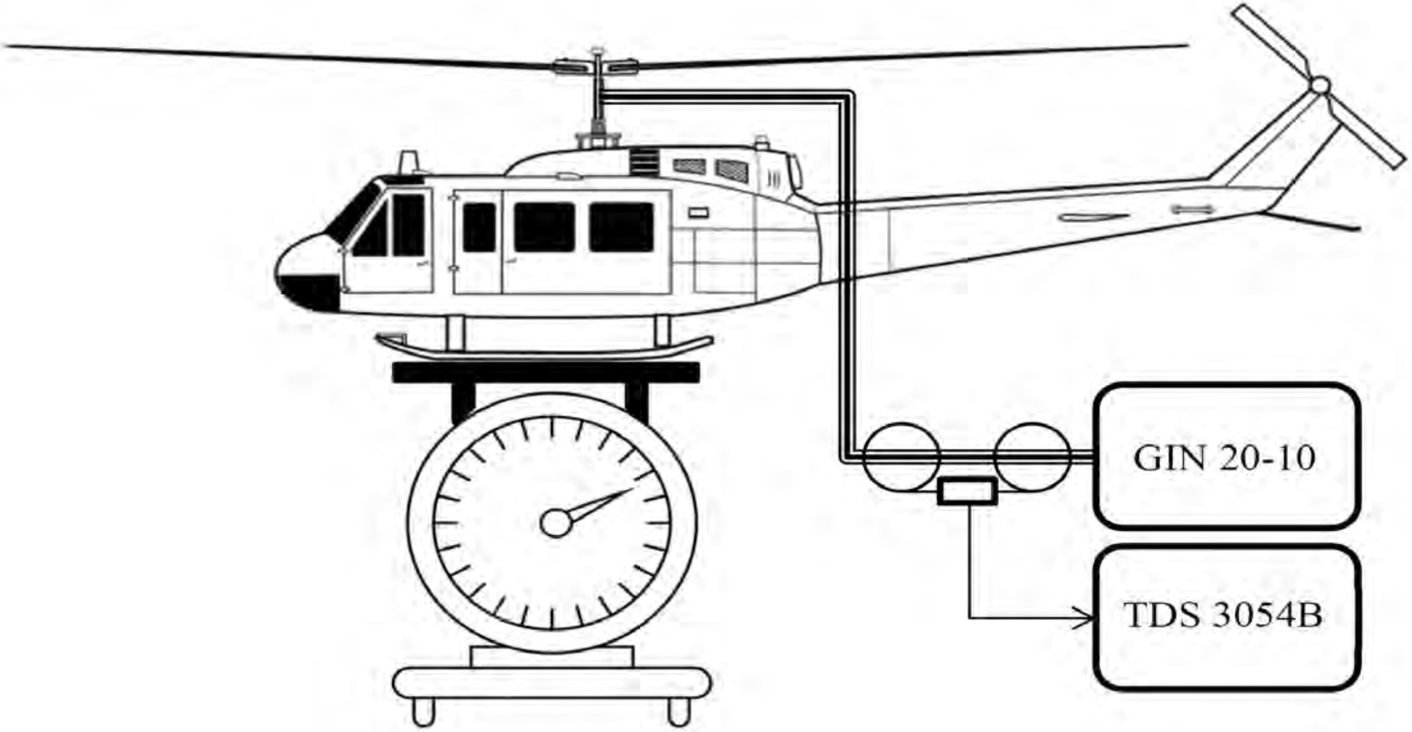


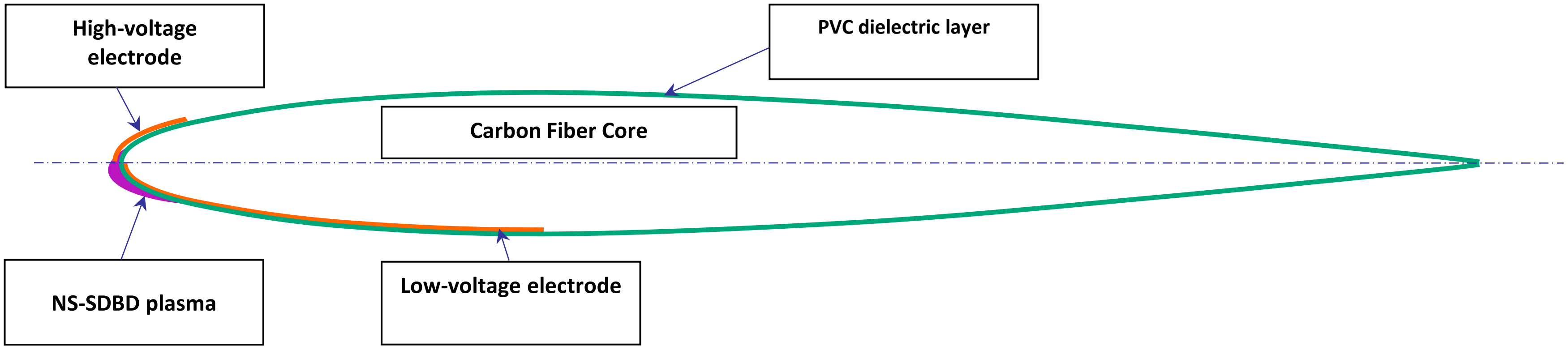


Dynamics of the lift force over the pitching cycle. Reverse Flow. Flow speed 31 m/s

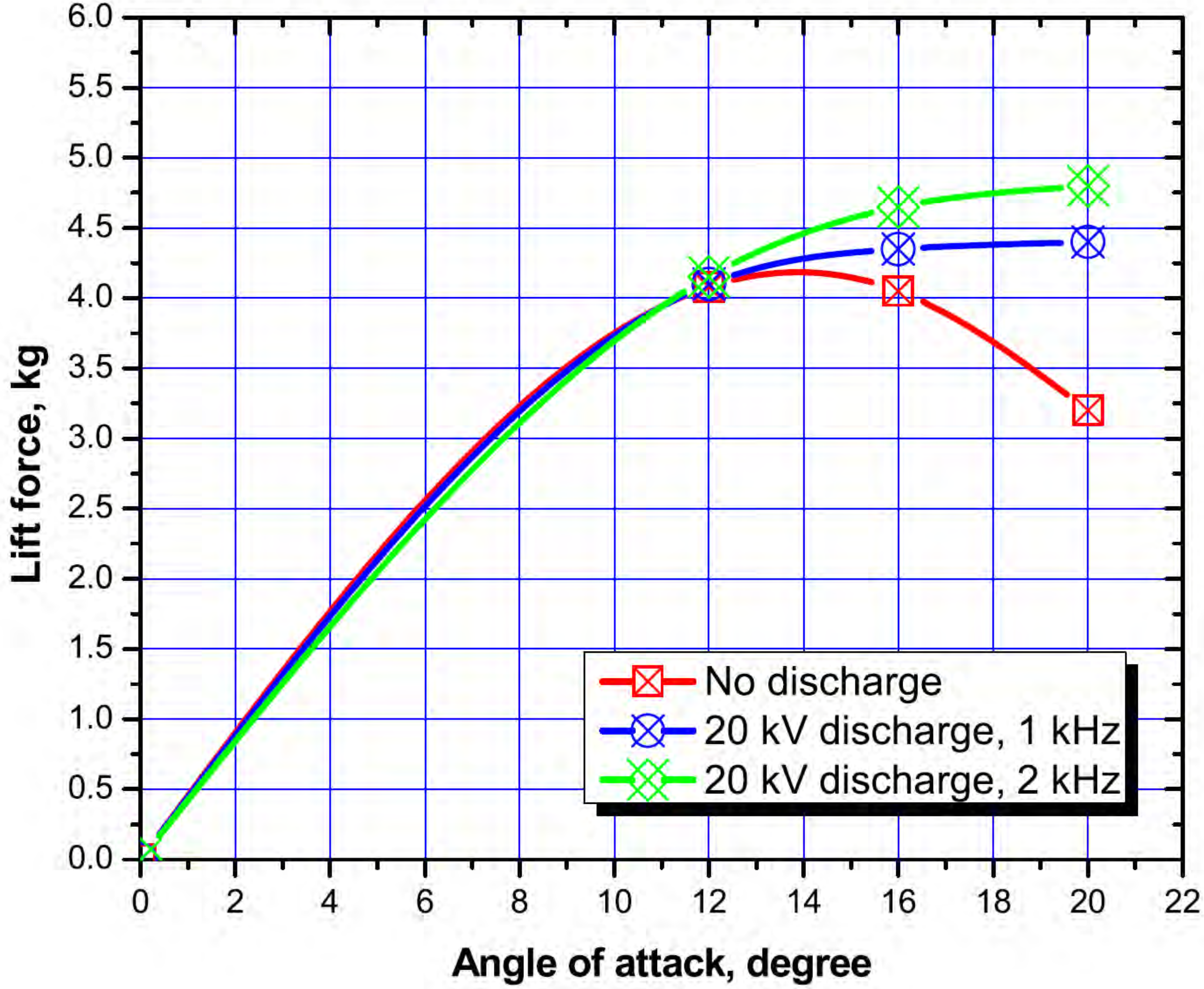


Hover Lift Force Increase

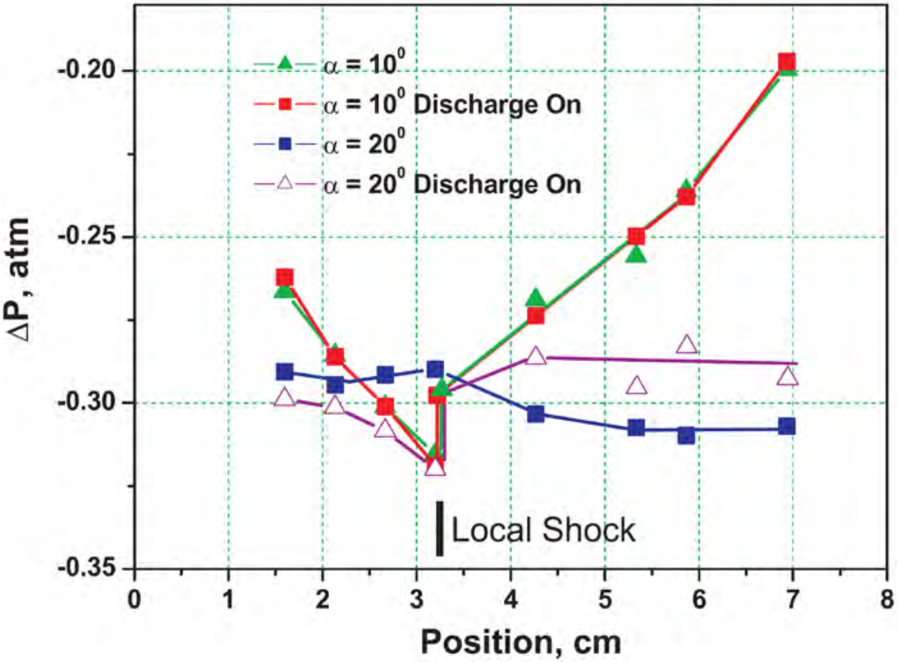


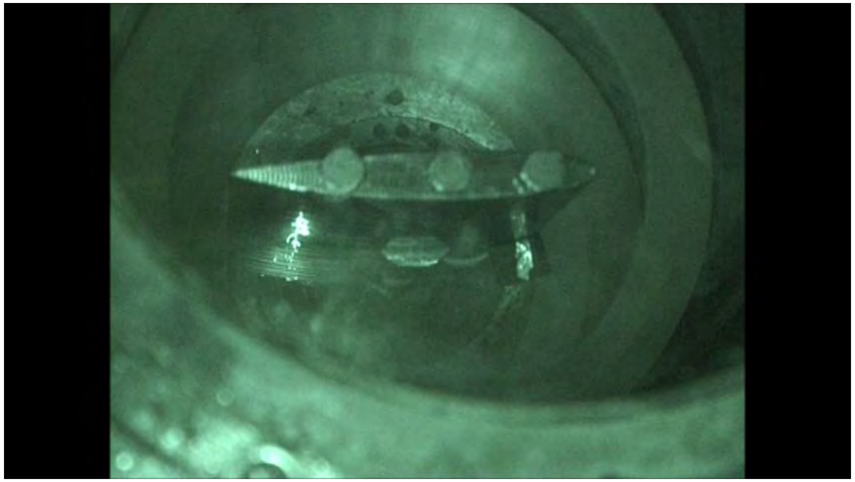


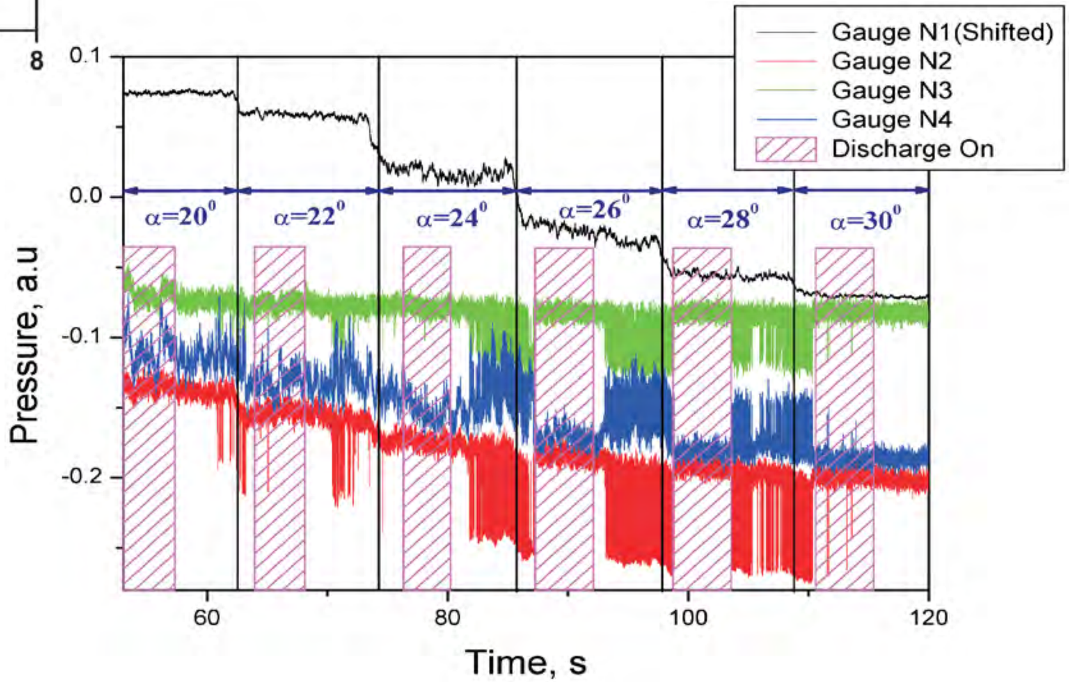
Lift Force Dependence on Angle of Attack P(motor) = 1500 W, P(plasma) = 50 W



Boundary Layer Separation Control.
M = 0.74

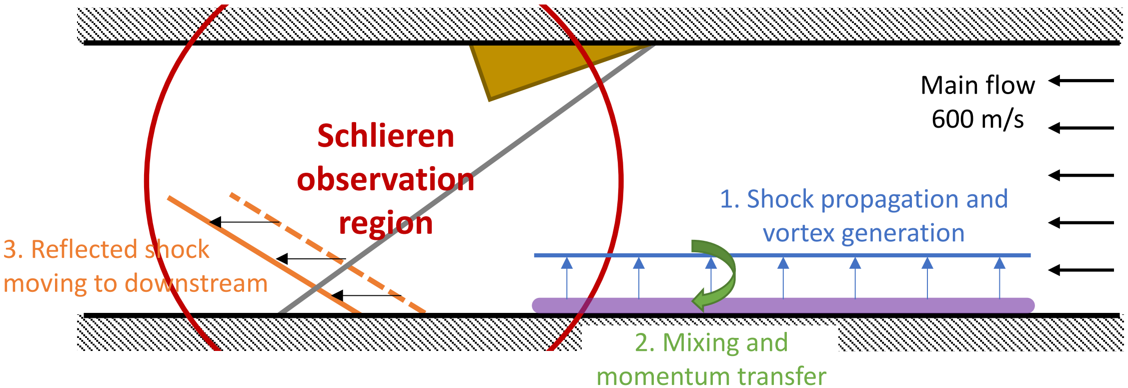




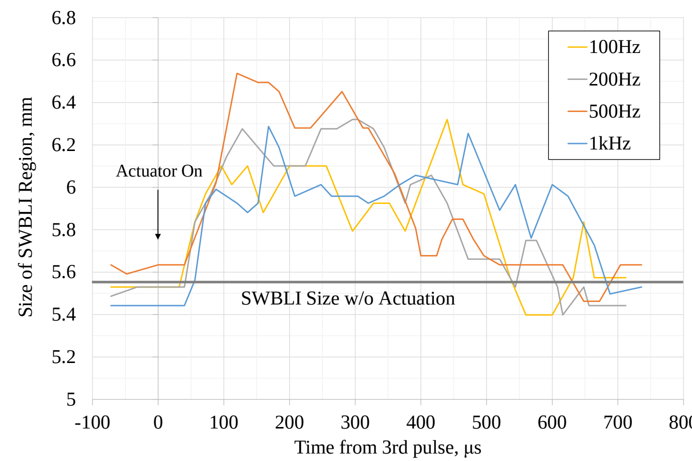


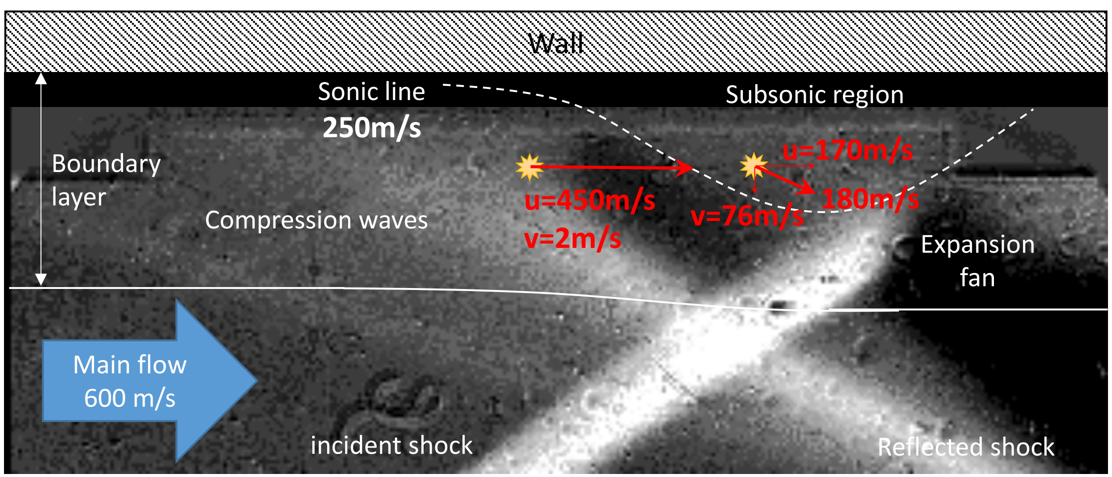
- Airfoil: CAST 10-2/DOA 2
- Model Dimensions: 12x8 cm

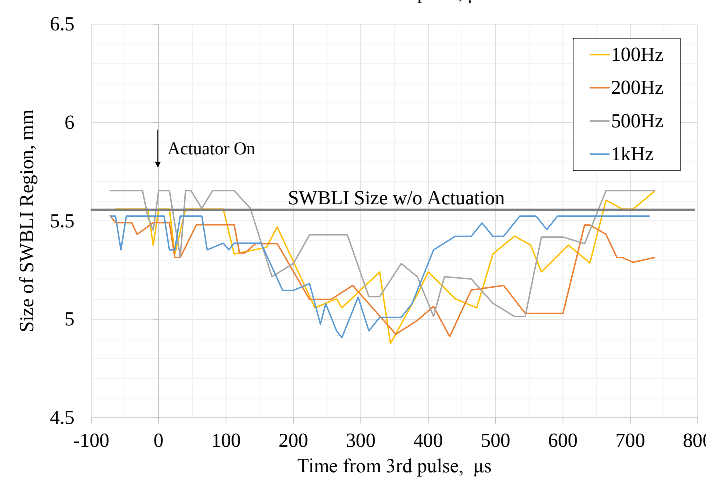
Boundary Layer – Shock Wave Interaction Control



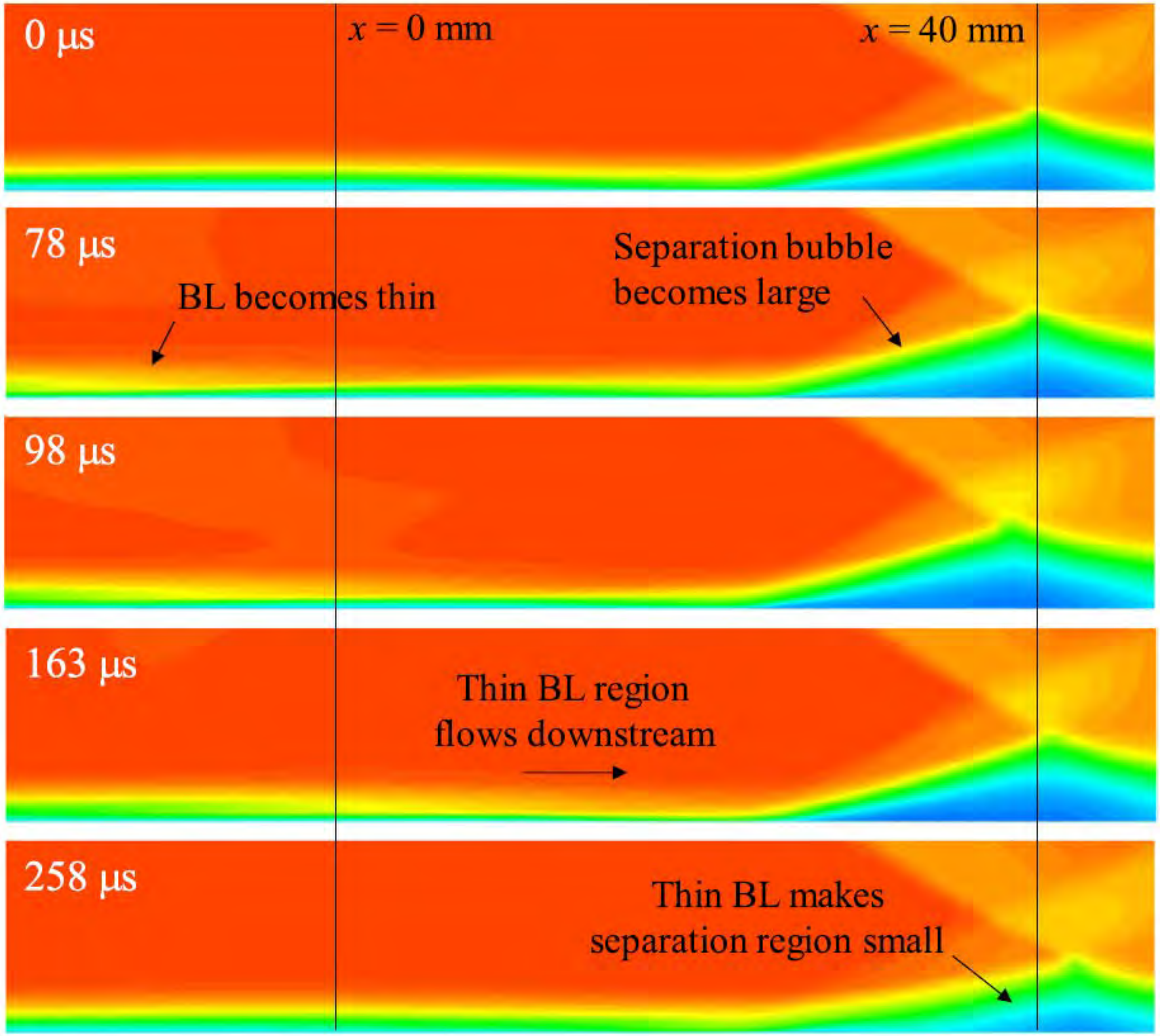
M = 2.8



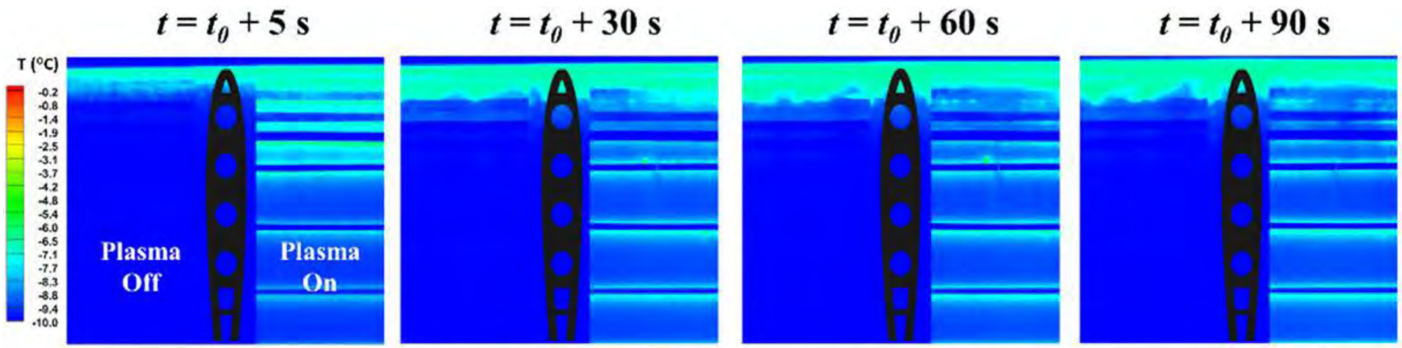




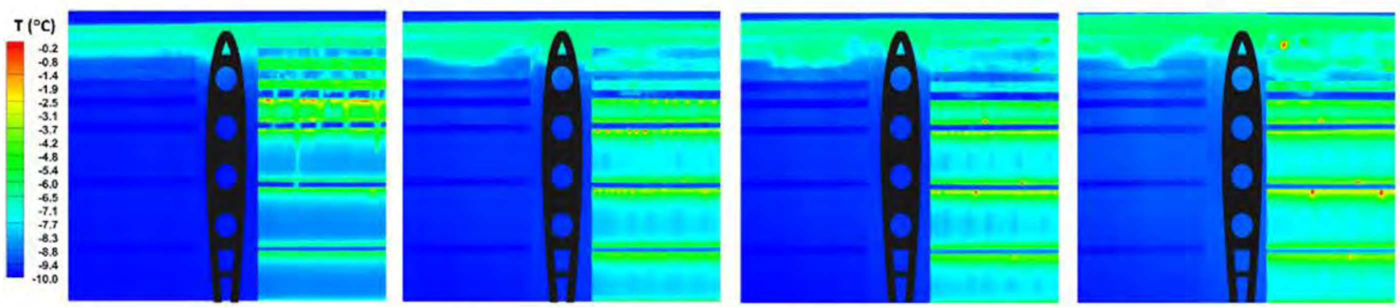
x-direction velocity evolution at the spanwise center



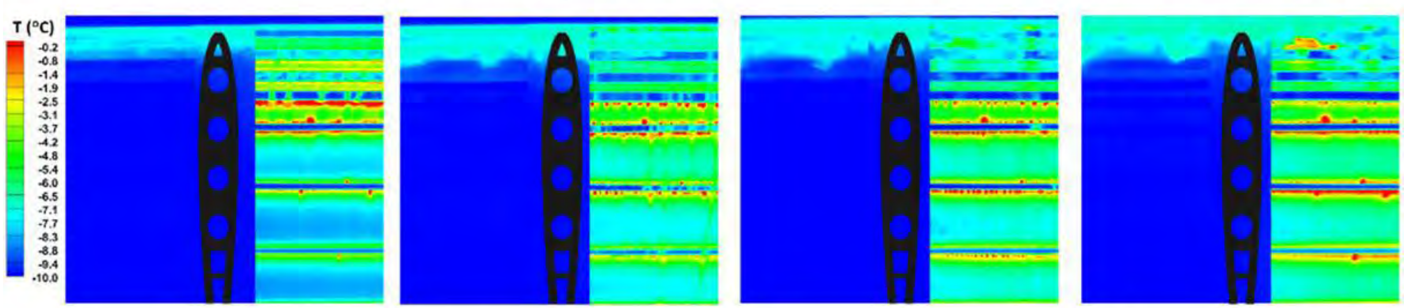
Icing conditions: U_∞ = 40 m/s, LWC = 1.0 g/m^3, and T_∞ = −10 °C



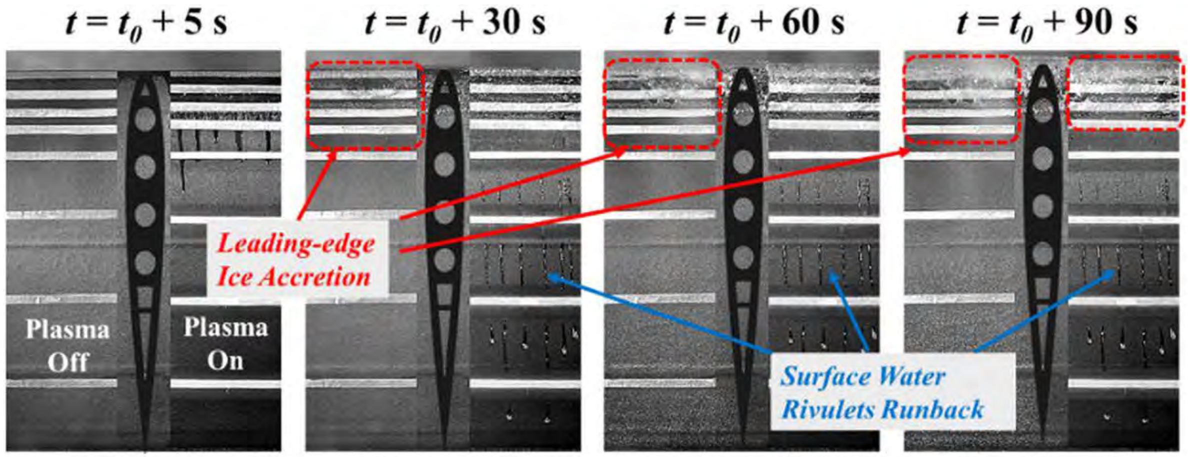
(a) Time-evolution of surface temperature distribution during the icing process at f = 2 kHz



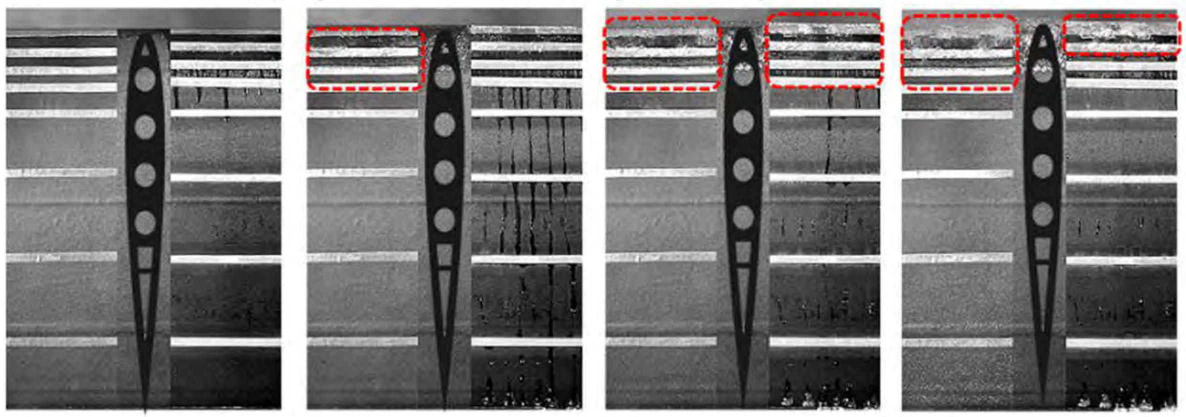
(b) Time-evolution of surface temperature distribution during the icing process at f = 4 kHz



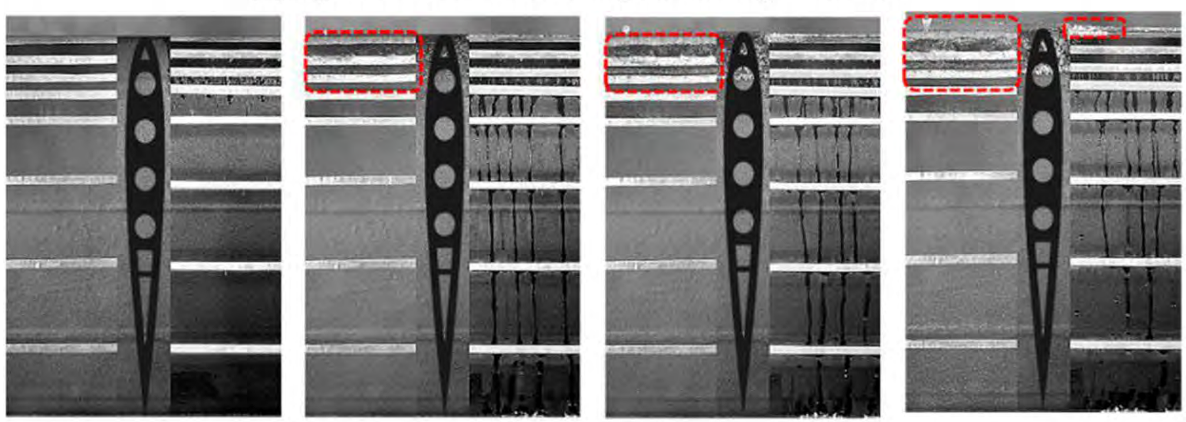
(c) Time-evolution of surface temperature distribution during the icing process at f = 6 kHz



(a) Dynamic ice accretion process at $f = 2$ kHz



(b) Dynamic ice accretion process at $f = 4$ kHz



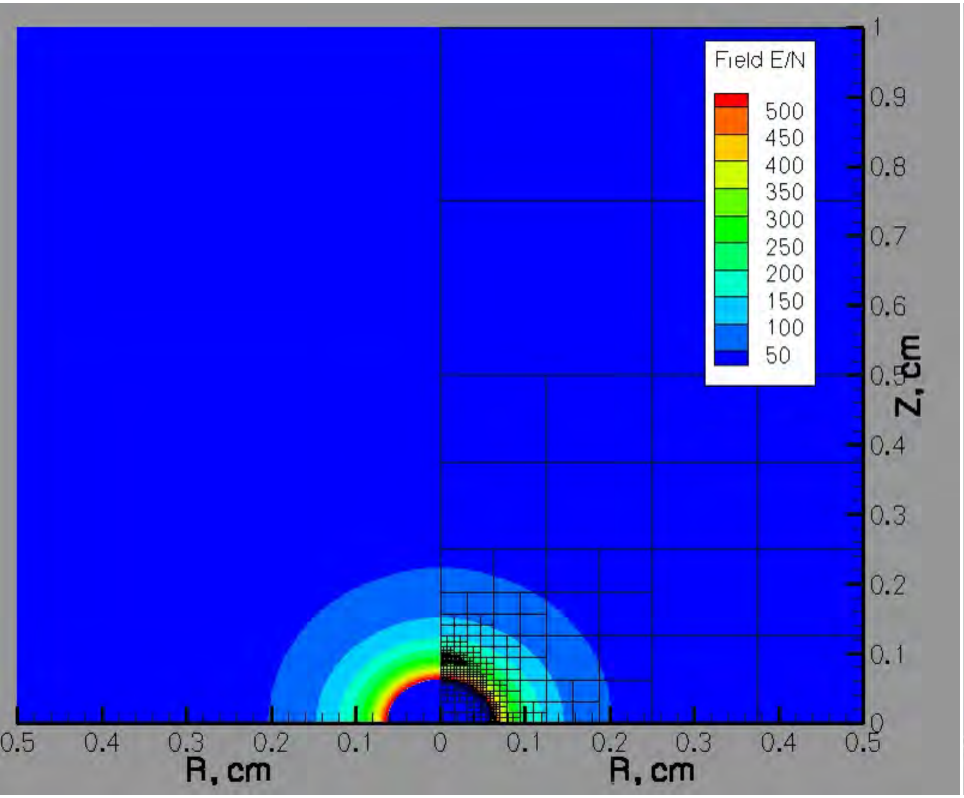
(c) Dynamic ice accretion process at $f = 6$ kHz

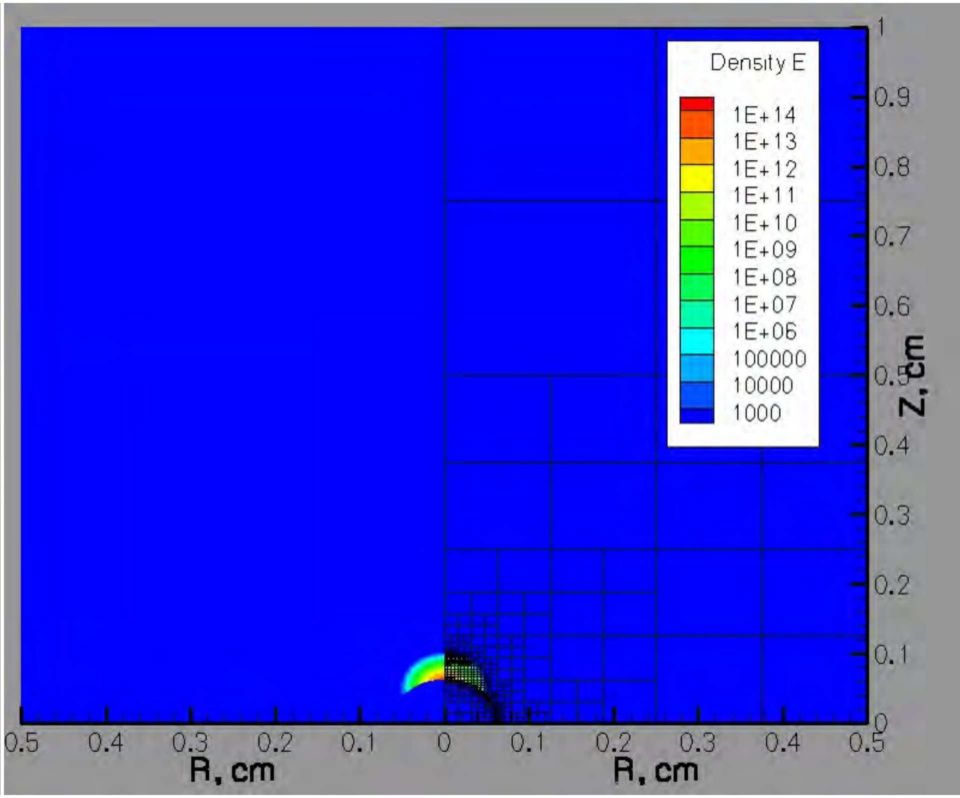
FUTURE RESEARCH

Flight Demonstrator

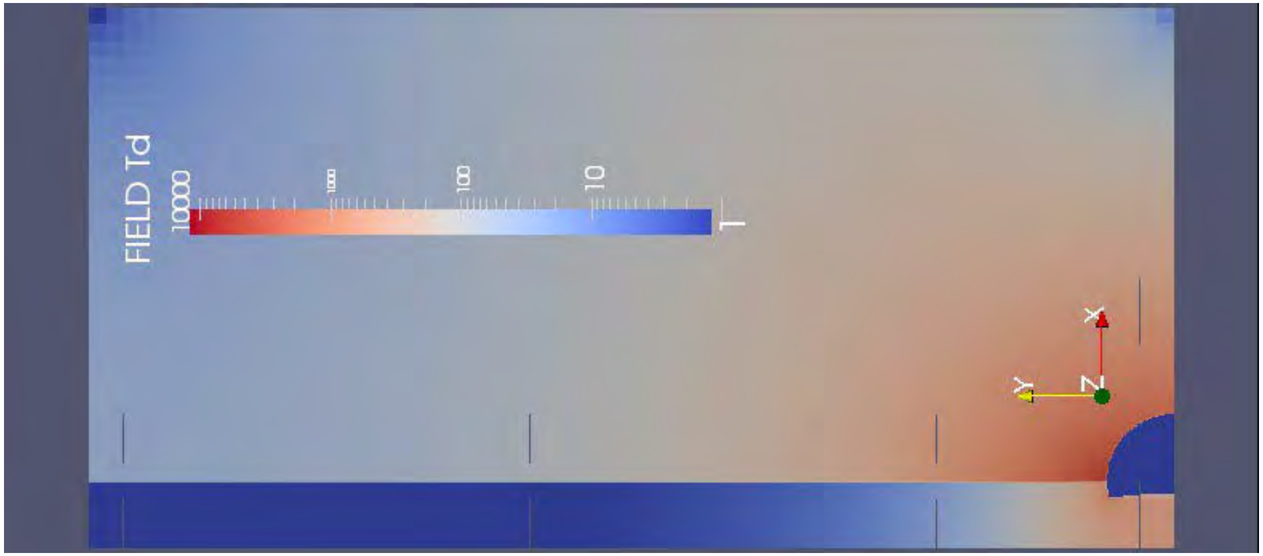
Predictive Modeling

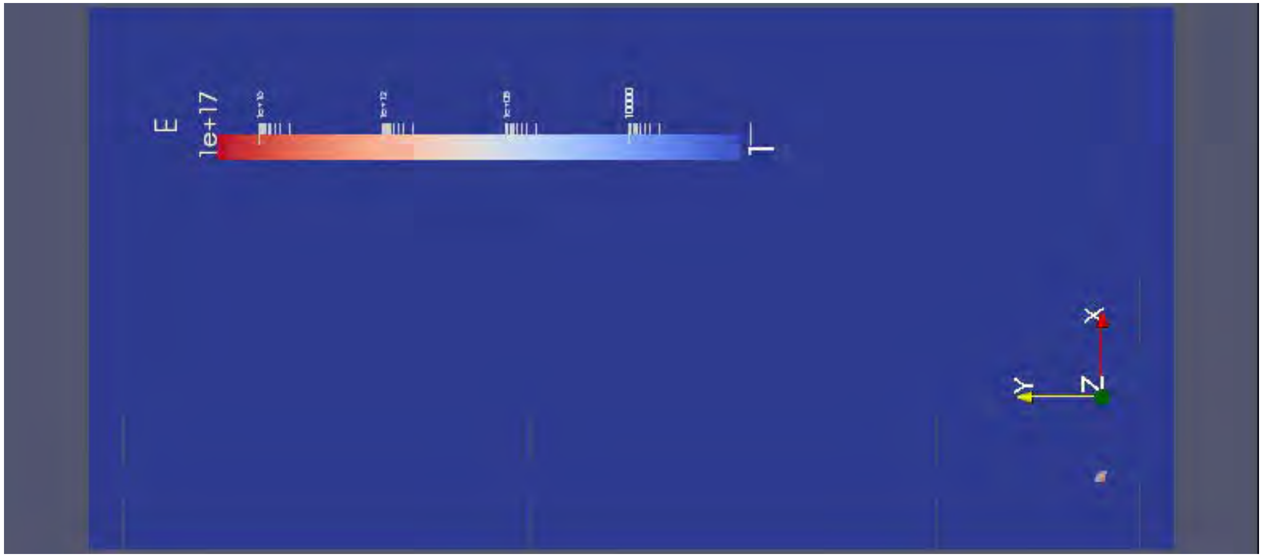
Streamer discharge propagation.
10 kV. Air, p = 1 atm



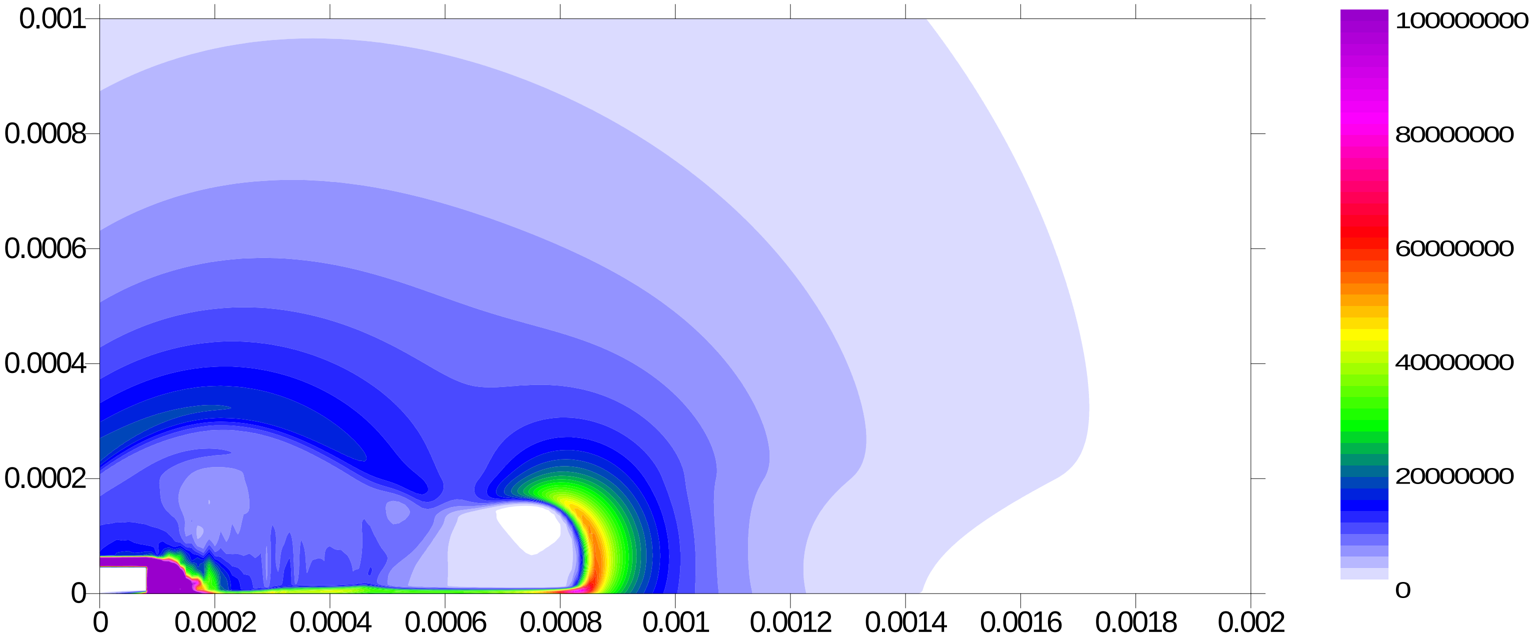


NS SDBD 12 kV. Air, p = 1 atm

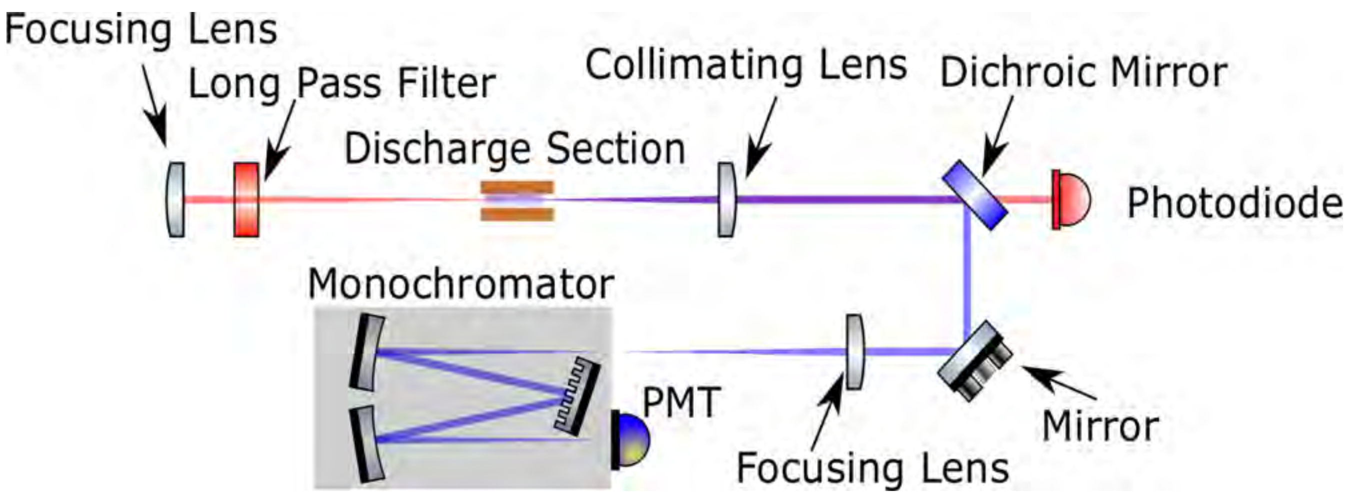


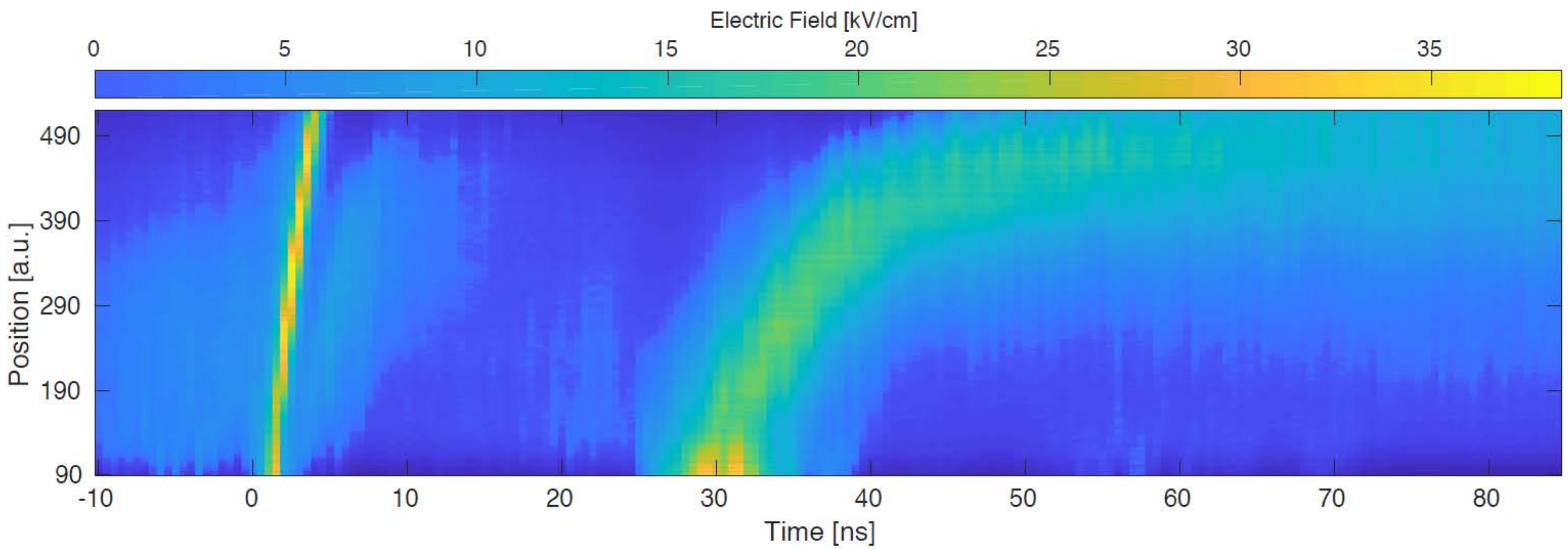


Electric Field distribution. X-Y plane.



ns-SDBD Electric Field Measurements by E-FISH





Plasma Sources Science and Technology

Special issue on nonequilibrium nanosecond plasma aerodynamics

Guest Editor: Andrey Starikovskiy, Princeton University, USA

- **Static and dynamic stall control by NS SDBD actuators.** Andrey Starikovskiy *et al* 2018 *Plasma Sources Sci. Technol.* **27** 124001
- **Electric field distribution in a surface plasma flow actuator powered by ns discharge pulse trains.** M Simeni Simeni *et al* 2018 *Plasma Sources Sci. Technol.* **27** 104001
- **Gas-heating phenomenon in a nanosecond pulse discharge in atmospheric-pressure air and its application for high-speed flow control.** Atsushi Komuro *et al* 2018 *Plasma Sources Sci. Technol.* **27** 104005
- **Numerical modelling of nanosecond surface dielectric barrier discharge evolution in atmospheric air.** Victor R Soloviev and Vladimir M Krivtsov 2018 *Plasma Sources Sci. Technol.* **27** 114001
- **Modeling non-equilibrium discharge and validating transient plasma characteristics at above-atmospheric pressure.** Riccardo Scarcelli *et al* 2018 *Plasma Sources Sci. Technol.* **27** 124006
- **Fast gas heating of nanosecond pulsed surface dielectric barrier discharge: spatial distribution and fractional contribution from kinetics.** Yifei Zhu and Svetlana Starikovskaia 2018 *Plasma Sources Sci. Technol.* **27** 124007
- **An experimental study on the thermal characteristics of NS-DBD plasma actuation and application for aircraft icing mitigation.** Yang Liu *et al* 2019 *Plasma Sources Sci. Technol.* **28** 014001
- **Post-stall flow control using nanosecond pulse driven dielectric barrier discharge plasma actuators.** Jesse Little *et al* 2019 *Plasma Sources Sci. Technol.* **28** 014002

Acknowledgments

This work was supported by the Army Research Office (ARO) Grant W911NF-15-1-0236 ‘Control of Static and Dynamic Stall in a Wide Range of Mach Numbers by Plasma Actuators with Combined Energy/Momentum Action’ under Grant Officer Representative Dr Matthew J Munson.

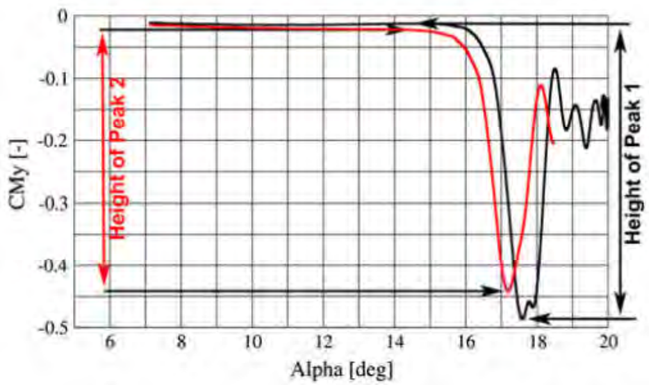
DLR activities in flow control to mitigate dynamic stall

Tony Gardner, Christian Wolf
DLR Göttingen

DLR

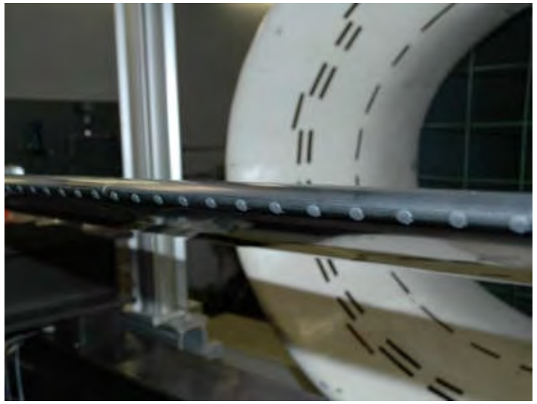
History and approach

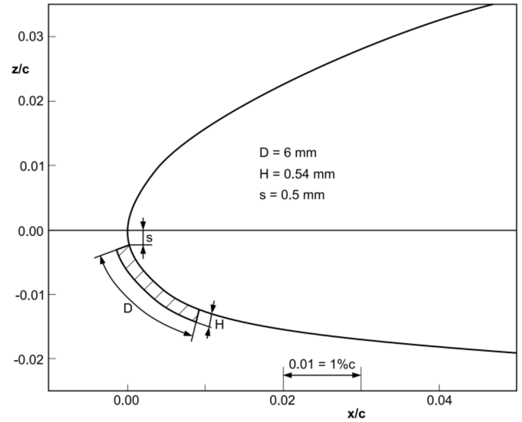
- We work with the following assumptions:
  - Flow control is the most useful method of understanding the aerodynamics of a flow phenomenon. Designing a flow control device is only a secondary consideration
    - Older experiments using droop-nose and active flaps had stiffness problems and only shifted the stall to higher angles
  - For series production for dynamic stall control have to be significantly better than a rotor redesign
  - In general, flow control will not exceed the performance of a point-optimized airfoil
    - Investigating flow control on older, symmetric, nontabbed airfoils may result in erroneous conclusions
  - Dynamic stall occurs only during transient manoeuvres with reingesttion and high blade elasticity. The aerodynamic angle of attack on the rotor blade is only controllable with an accuracy ±5° in the **best case**
    - Moving the stall angle by 1-2° is not useful
    - Deep stall will always occur
    - Dynamic stall control is measured by the reduction in pitching moment peak height

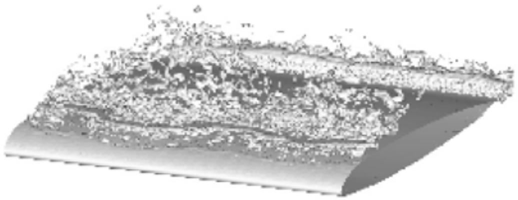


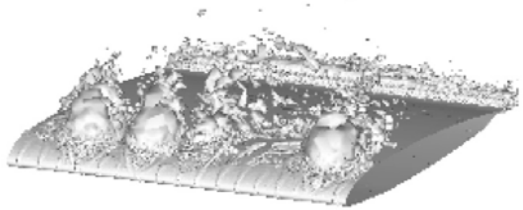
Leading edge vortex generators

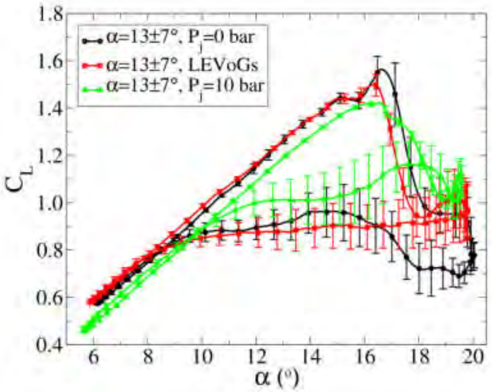
- Passive flow control method with stick-on discs
- Easy to apply, tested up to LBA “right to fly” approval as retrofit
- Wind tunnel on multiple pitching airfoils (OA209, EDI-M109, EDI-M112, DSA-9A) and wind tunnels (TWG, 1MG, Onera F2), with CFD and flight testing
- Pitching moment reduction ~25% in deep stall
- Drag increase 5-30 drag counts depending on angle of attack and flow condition



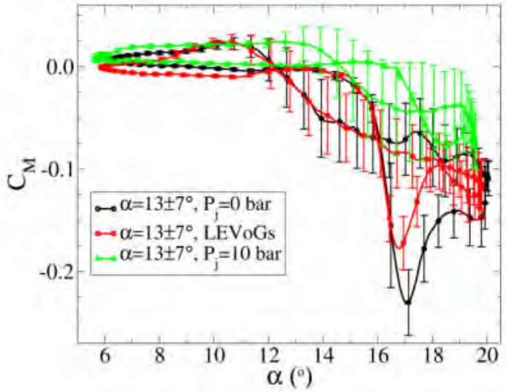








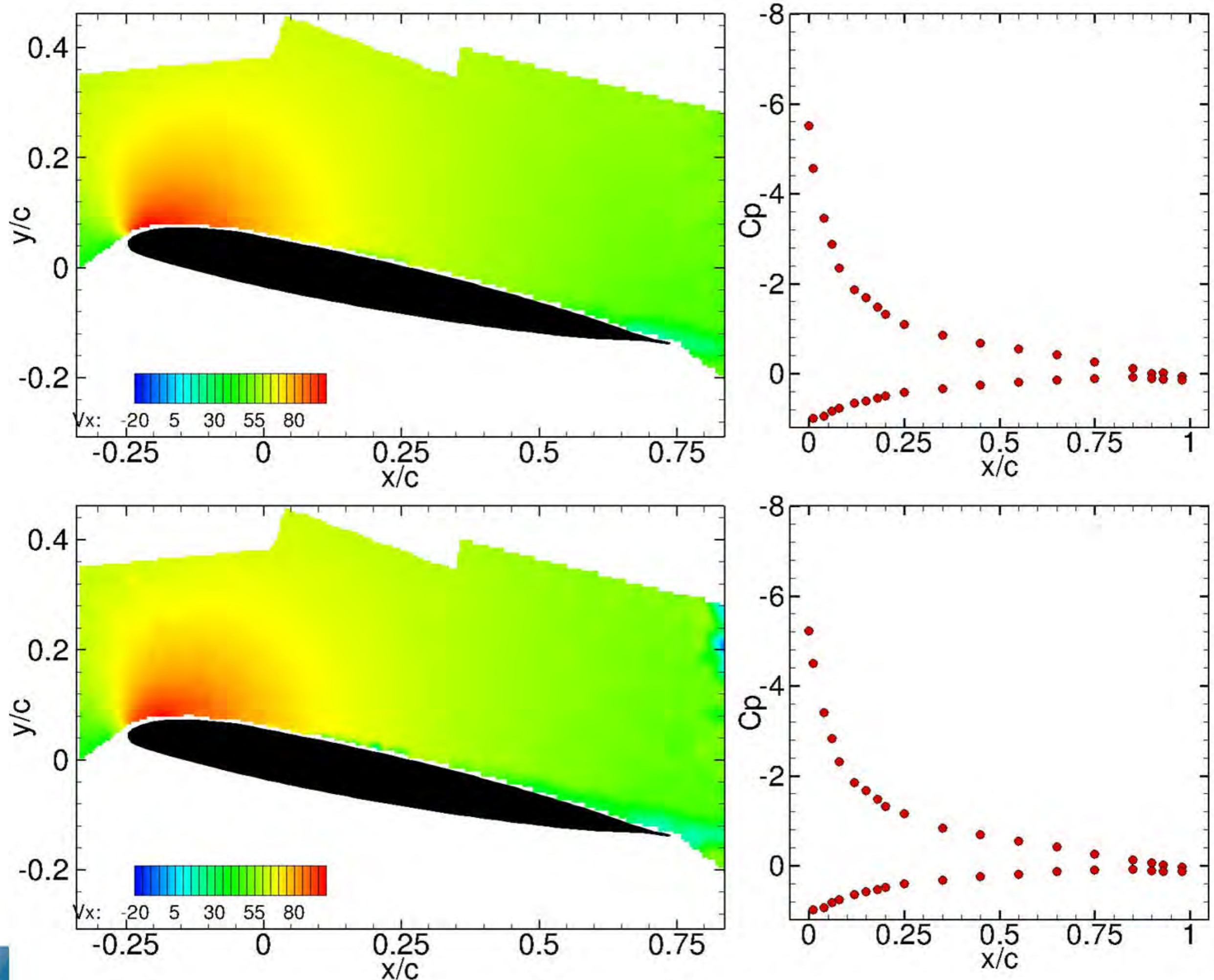
(a) C_L vs α



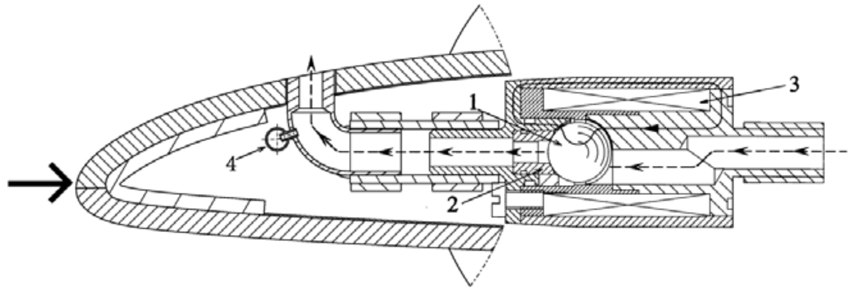
(b) C_M vs α

Leading edge vortex generators – PIV comparison

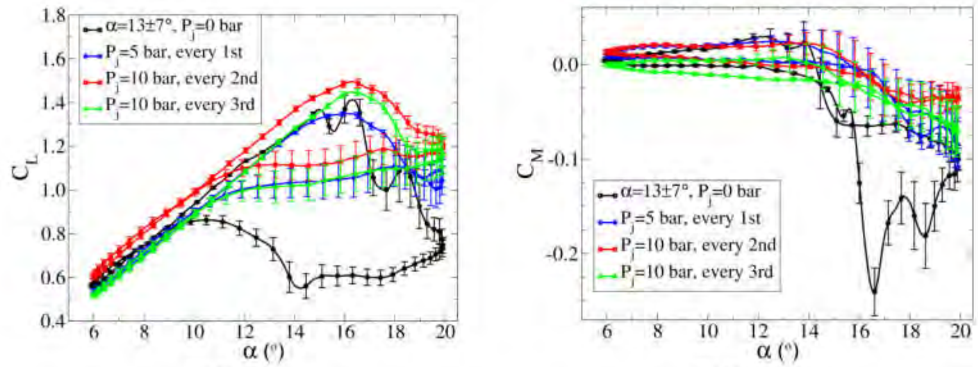
- Data taken in the Onera-F2 by Karen Mulleners and Benjamin Heine
- Simultaneous high-repetition-rate PIV and pressure measurements



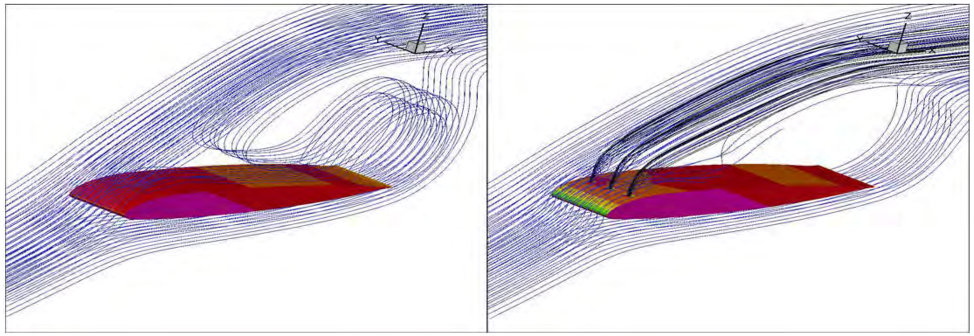
Fluidic control devices



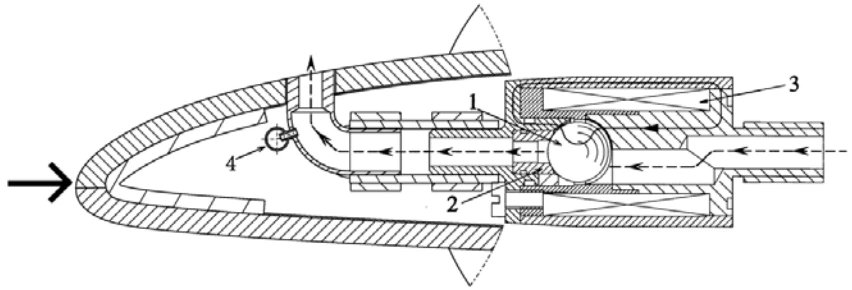
- Active flow control method using cold air jets
- Would require new blades with internal tubing and a high-pressure air buffer (a fireman's 10L SCBA tank would offer 1-10 seconds of operation)
- Wind tunnel testing of constant and pulsed blowing on an OA209 airfoil up to Mach 0.5 and CFD
- Pitching moment reduction 80-90% in deep stall
- Instantaneous power on the order of main rotor power (but probably only needed intermittently)
- No drag increase when turned off.



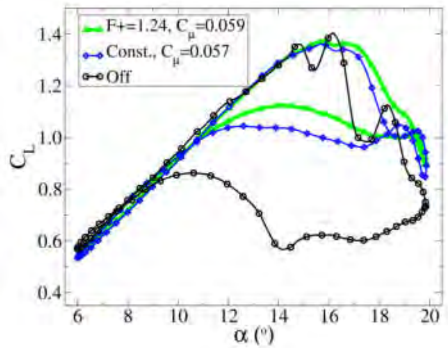
(a) C_L vs α (b) C_M vs α

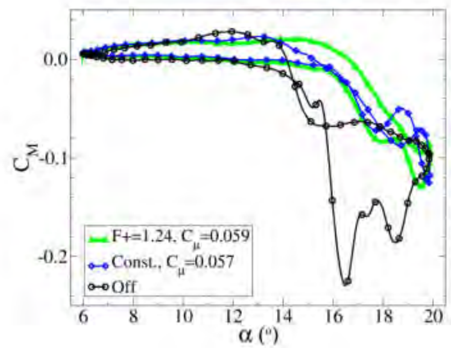


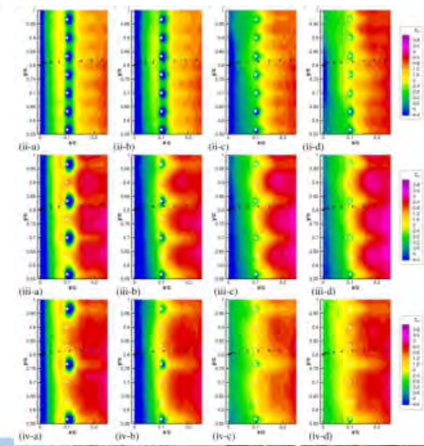
Fluidic control devices



- Pulsed operation showed that no increased effect compared to continuous blowing could be achieved. The flow control effect was only a function of the introduced momentum.
- Experimental difficulties:
  - Pressure integration of the strongly 3D flow from pressure taps needed to be carefully validated
  - Pulsed high-pressure flow was difficult to achieve
  - Force-balance measurements were affected by the presence of the pressure-lines
  - PSP was affected by the strong temperature differences between freestream and injected gases

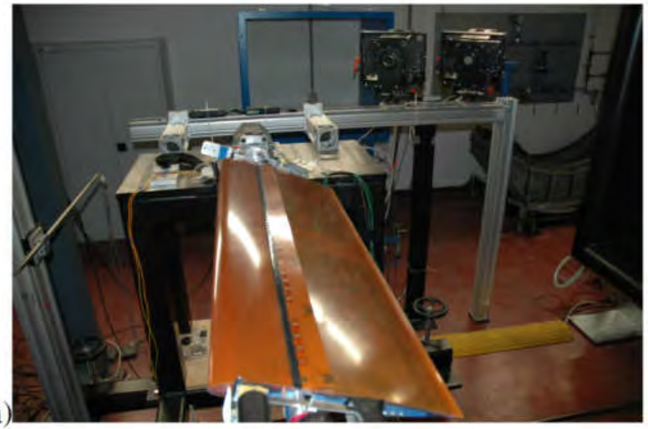






Back-flow flap

- Passive actuation requiring flap integration
- Production demonstrator showing single-cure EPDM/Carbon-fibre structure
- Single wind tunnel test (1MG), OA209 airfoil
- Automatic opening on stall
- No drag penalty when closed
- Wind tunnel model included active actuation, but could show that it never reached the performance of the passive actuation
- Pitching moment reduction of 20-25% in deep stall



a)

Back-flow flap

- For the “Light Stall” case care must be taken with active opening of the flap or it can make the dynamic stall worse
  - The passive flap completely suppresses light dynamic stall using small opening angles
- For deep stall the stall peaks are reduced by 20-25%, by splitting the single stall vortex into smaller vortices, moving it away from the surface and slowing the flow speed

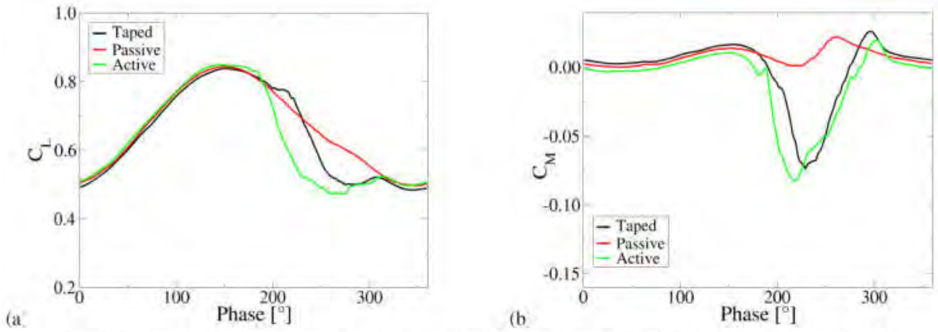
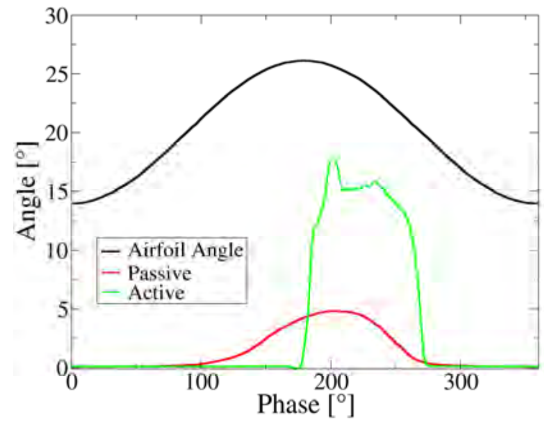
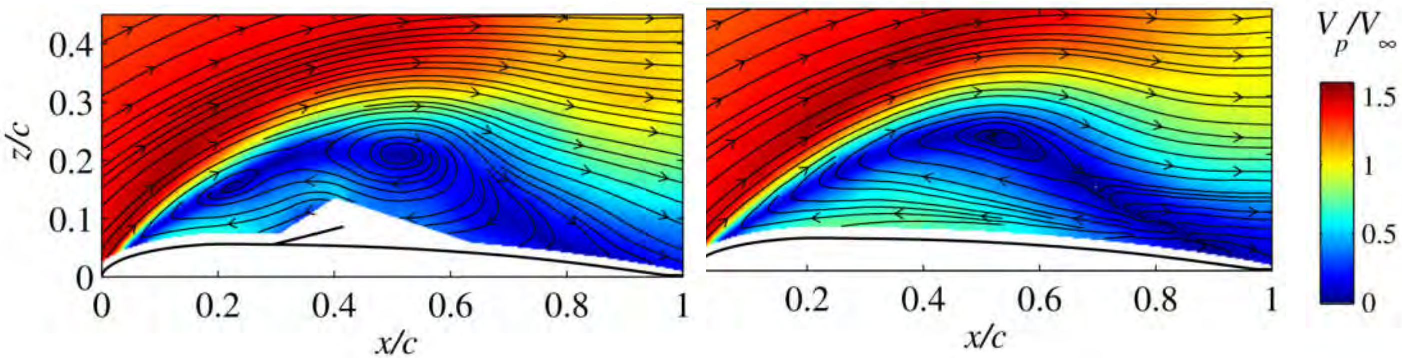


Fig. 19. Effect of the flap for α=20±6° at 2.5 Hz (a) Lift coefficient (b) Pitching moment coefficient





Summary

- Flow control has been used to understand the aerodynamics of a flow phenomenon.
- Up to now a tradeoff between effectiveness and cost has been noted
- Currently (since 2018) we have no flow control activities, and currently we do not have activities planned
- The accuracy and quality of the flow control data tends to be less than without, for instance air jet pressure, flow rate and temperature have additional error bars.
- Data and geometries are available for all test cases with the pitching airfoil which we have published with the OA209 or DSA-9A airfoils.

- We note that it is difficult to make generalisations due to a lot of details about the implementation

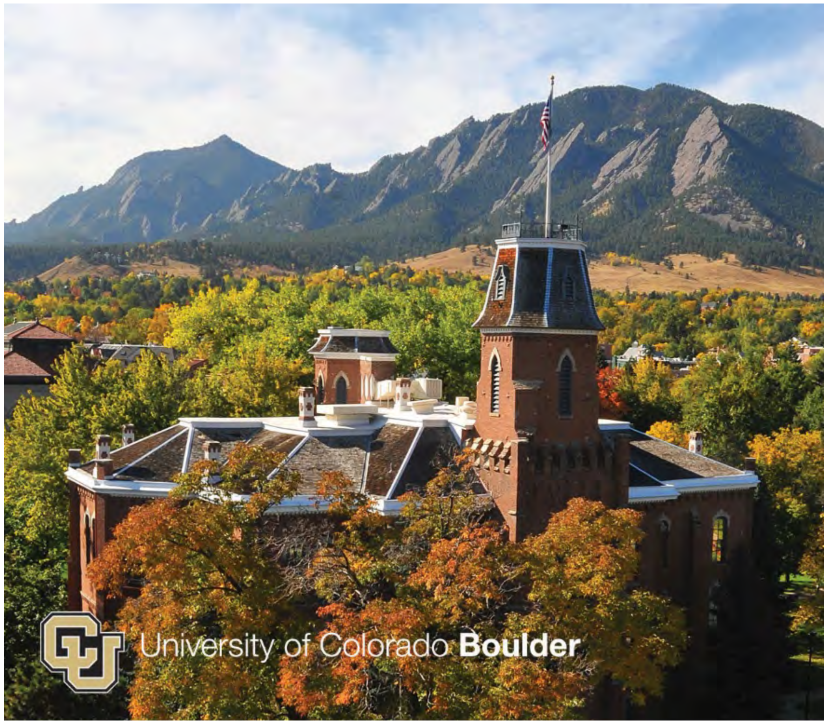
Pitch Rate Induced Separation Delay Modeling of Dynamic Stall and Stall Flutter

Ethan C. Culler and John A. N. Farnsworth

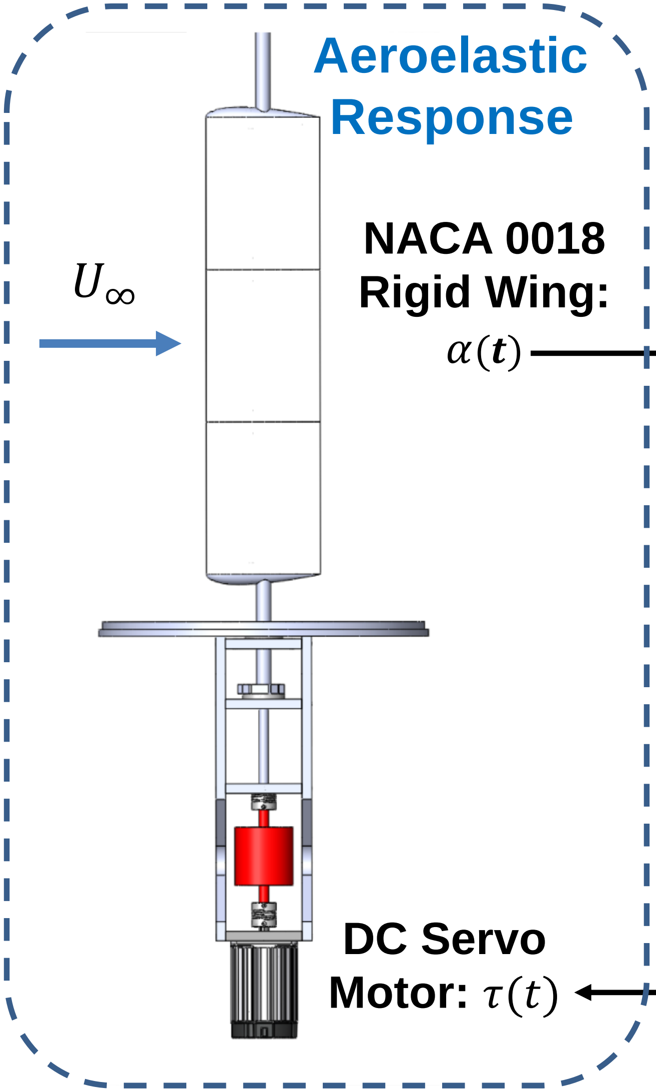
Ann and H.J. Smead Aerospace Engineering Sciences Department
University of Colorado **Boulder**

ARO/GT Dynamic Stall Workshop

September 10-11, 2019

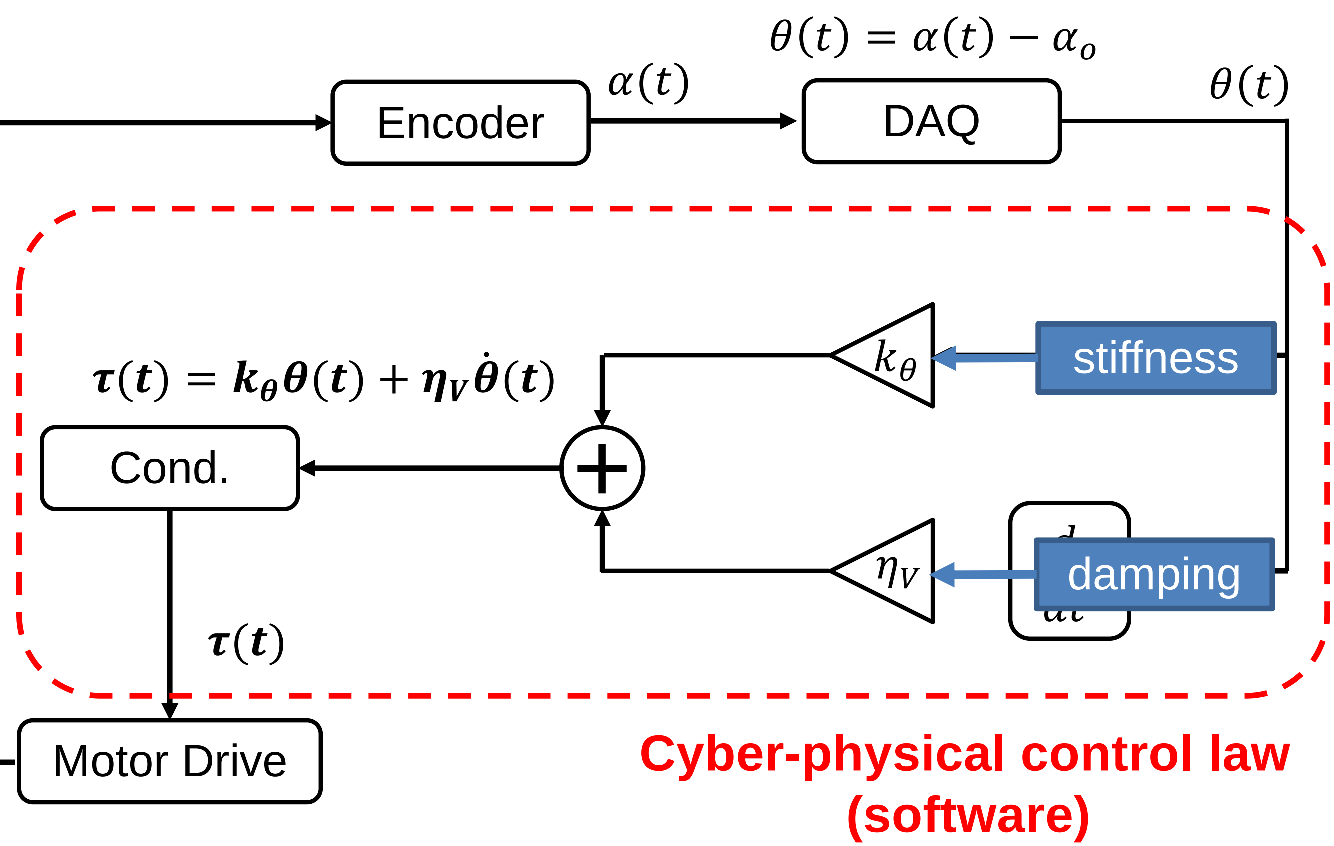


Research Approach: Cyber-Physical



Utilized a position feedback cyber-physical approach:

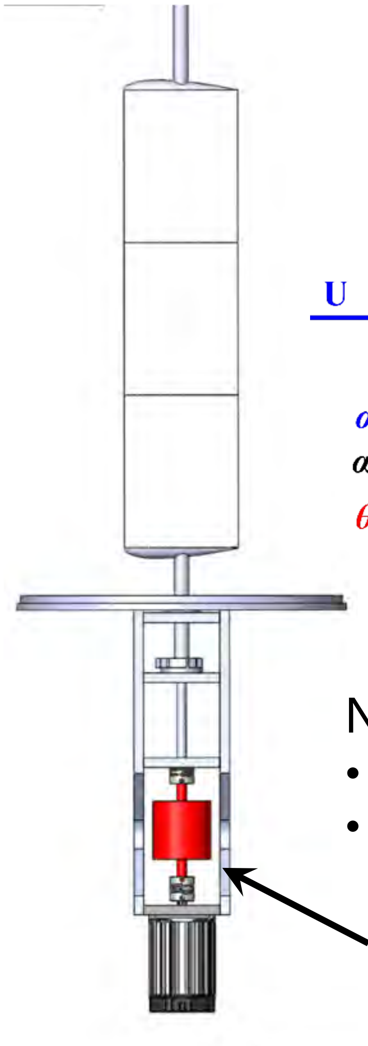
(Onoue et al., J. Fluid Struct., 2015; *Fagley et al., J. Fluid Struct. 2016, Culler et al. J. Fluid Struct. 2017*)

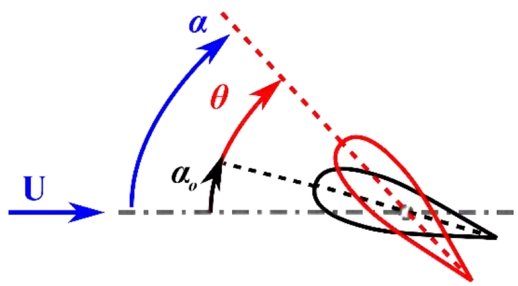


Culler and Farnsworth, J. Fluid Struct., 2019

Research Approach: One Model, Two Motions

Two approaches for generating dynamic stall motions were used:





α → angle of attack
α_o → geometric angle of attack
θ → twist angle

NACA 0018 Rigid Wing
- Aspect Ratio, AR = 4
- Chord, c = 15cm

Futek Tss400 Torque Cell

(1) Cyber-physical Stall flutter

- Torsion Spring

$$\tau = \underline{k_\theta}\theta + \underline{\eta_V}\dot{\theta}$$

k_θ → Stiffness
η_v → Virtual Damping
(Note: $\theta(t) = \alpha(t) - \alpha_o$)

(2) Driven Motion

- Prescribed Motion

$$\alpha(t) = \bar{\alpha} + \sum_{j=1}^{N} \underline{A_j} sin\left(j\omega t + \underline{\widehat{\Phi_j}}\right)$$

A_j → Amplitude
$\widehat{\Phi_j}$ → Phase

Culler and Farnsworth, J. Fluid Struct., 2019

Research Approach: Setup & Parameters

xAero Lab
CU Experimental Aerodynamics Laboratory

Tunnel Facility

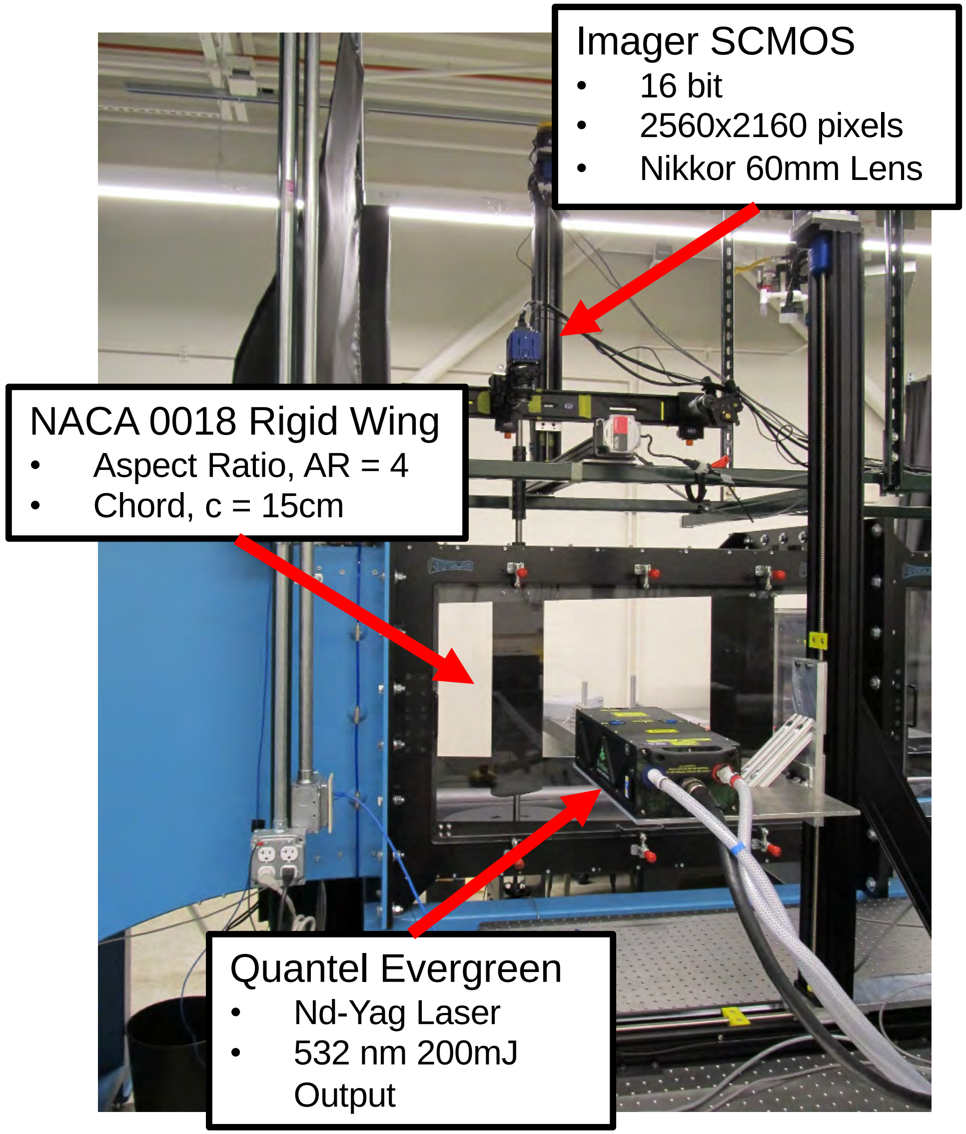
- CU low-speed research wind tunnel
- $15\,\frac{m}{s} \leq U_\infty \leq 20\,\frac{m}{s}$
- $1.3 \cdot 10^5 \leq \text{ Re} \leq 1.7 \cdot 10^5$
- $\boldsymbol{k^* = \frac{\omega c}{2U_\infty} = 0.11}$

Moment Measurements

- Futek Tss400 torque cell (1000 oz-in)
- $f_s = 1000$ samples/s; $T_s = 30s$
- Low-pass Butterworth filter at 25 Hz

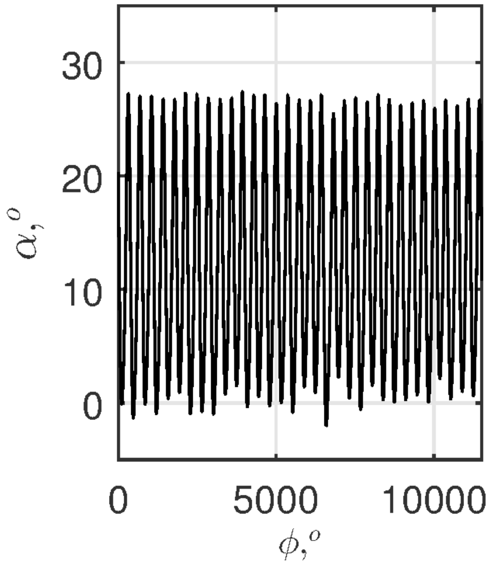
Planar PIV Measurements

- 64 phases ($\Delta\emptyset = 6^o$)
- $\Delta t = 60\mu s$; $\text{M} = 10.2\,\frac{Pix}{mm}$
- 100 images per phase

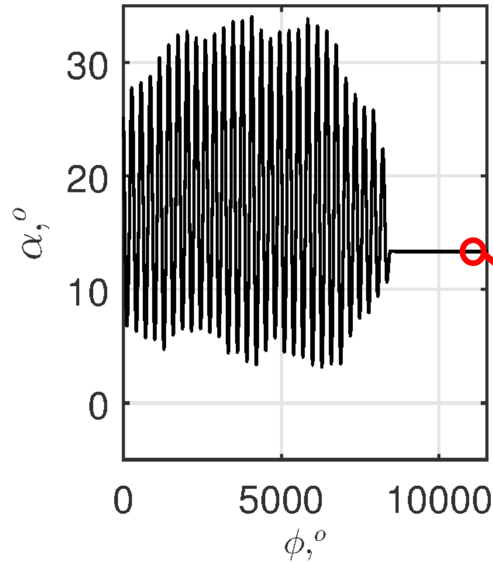


Stall Flutter: Kinematics

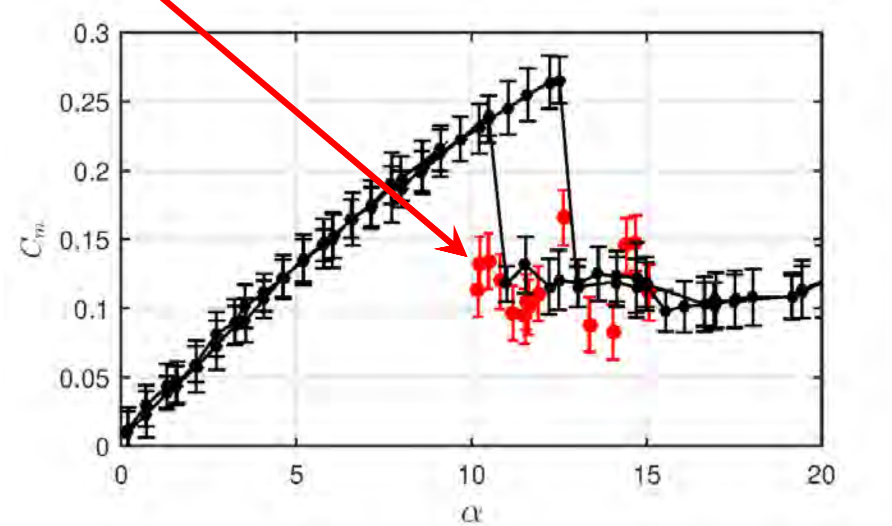
Stable Limit-Cycle Oscillation (LCO)



Unstable (Convergent) LCO



- Focused on stable LCOs
- LCO motion is similar to driven "sinusoidal" motion *(discussed later)*

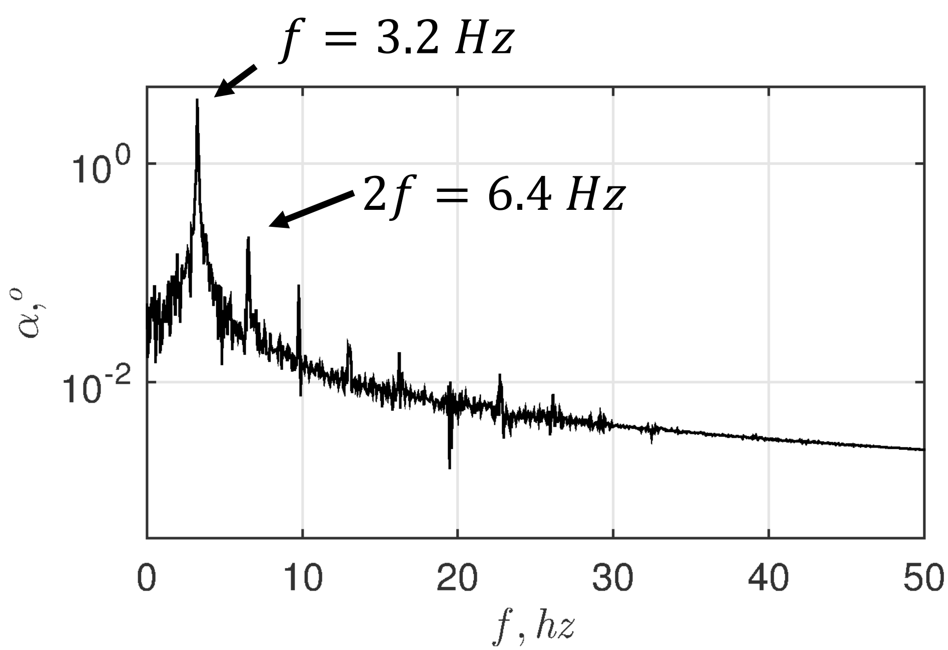


— Static C_m

● Dynamically Diverged $\{C_m, \alpha\}$

Unstable (Convergent) LCOs settle to a stalled aerodynamic state.

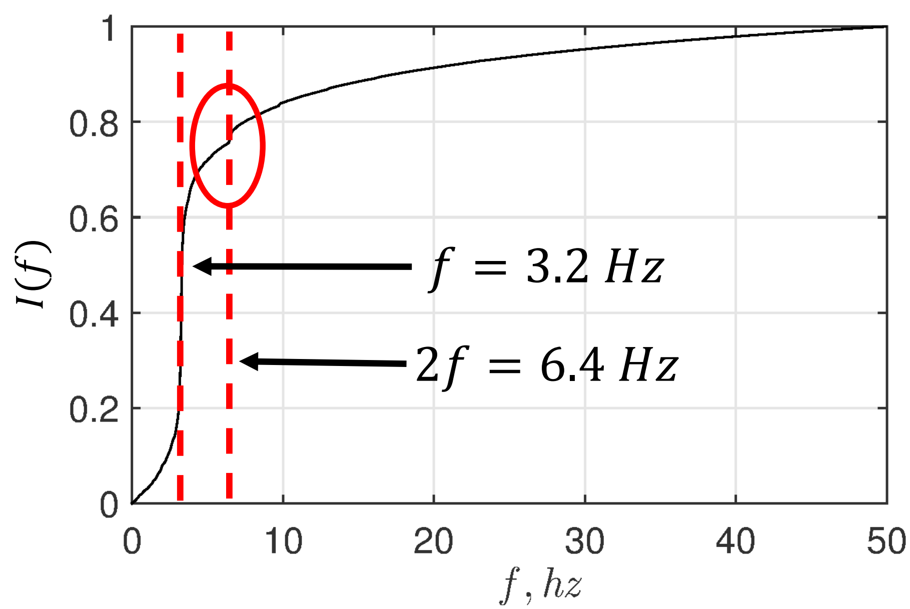
Stall Flutter: Kinematics



- $f = 3.2Hz$ is dominant
- Cascade of higher harmonics $(1f \rightarrow 7f)$
- *Are harmonics significant?*

$$I(f) = \int_0^{f_o} \alpha(f)df \,/\, \int_0^{50} \alpha(f)df$$

- $1f \rightarrow 70\%$ energy
- $2f \rightarrow 5\%$ energy
- $3f \geq$ negligible



1st and 2nd harmonics appear significant in pitch motion trajectory.

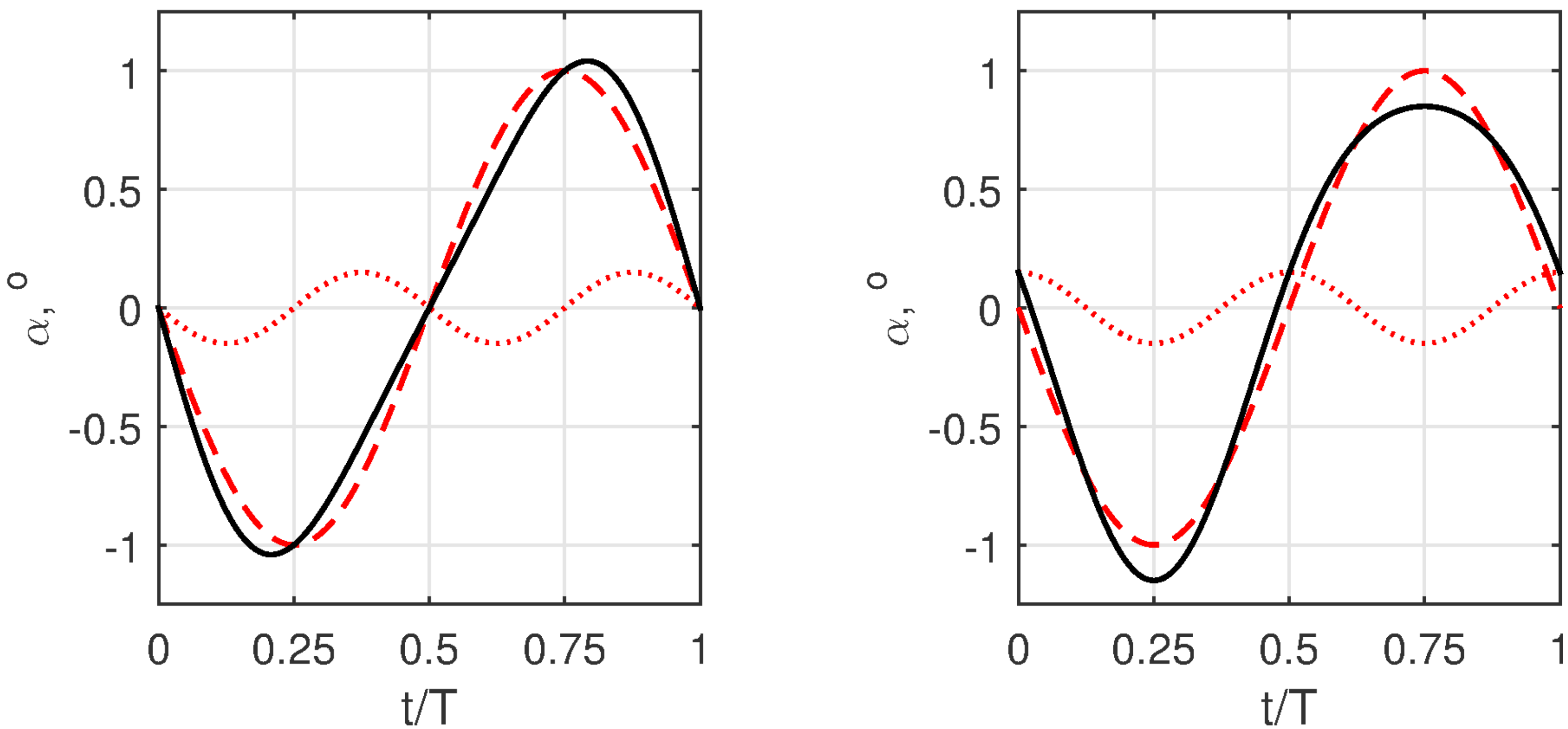
Driven Motion: Variation of Second Harmonic

$$\alpha(t) = \bar{\alpha} + \sum_{j=1}^{2} A_j sin\left(j\omega t + \hat{\phi}_j\right) \longrightarrow$$

$\widehat{\Phi_2}$ alters waveform shape

A_j scales this effect

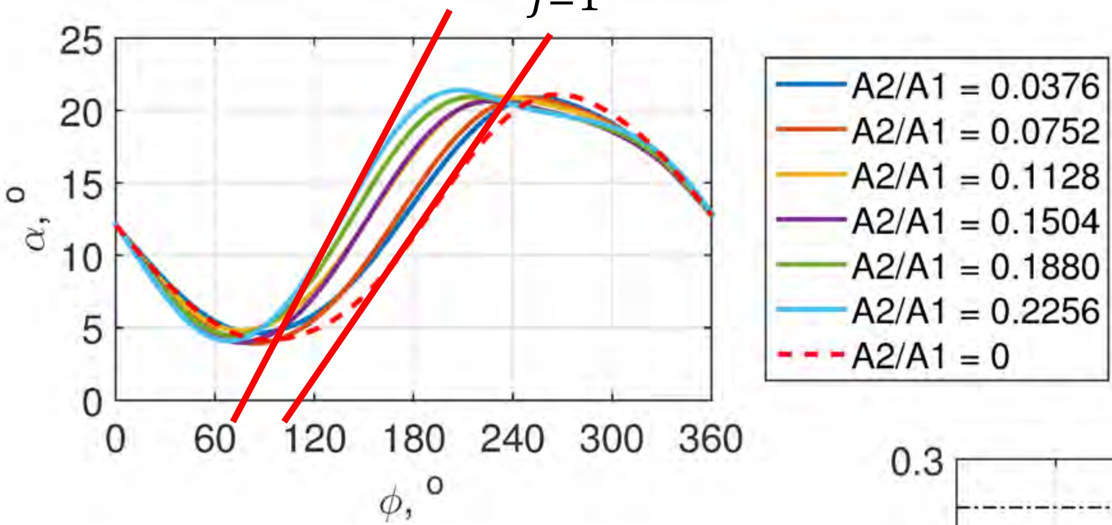
$\widehat{\Phi_2} = 0^o$ **(Sawtooth)** $\widehat{\Phi_2} = 90^o$ **(Peaked)**



Driven Motion: Response for $\widehat{\Phi}_2 = -90^o$

$$\alpha(t) = \bar{\alpha} + \sum_{j=1}^{N} A_j sin\left(j\omega t + \widehat{\Phi}_j\right)$$

$A_j \rightarrow$ Amplitude $\widehat{\Phi}_j \rightarrow$ Phase

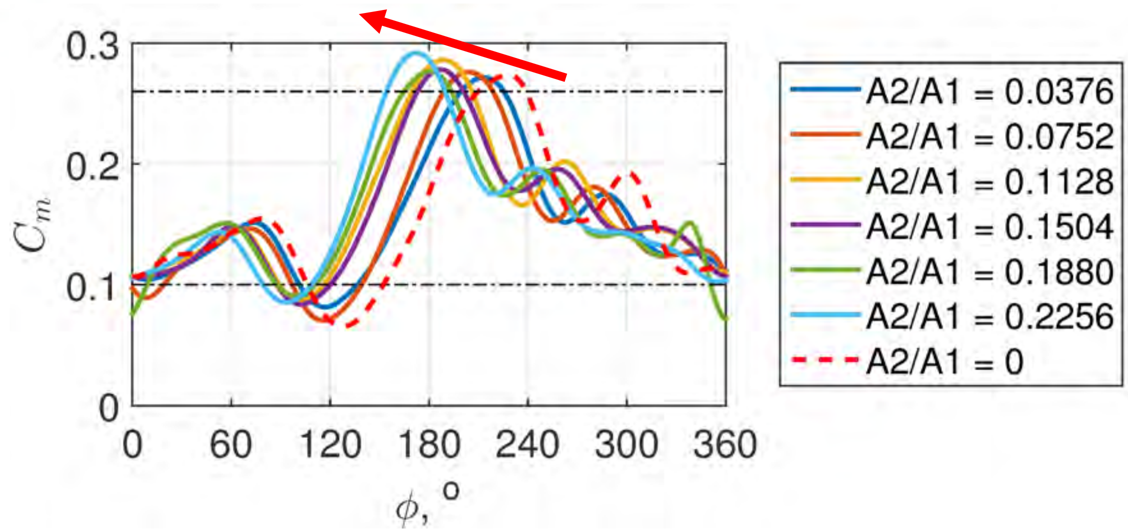


Kinematic Alteration:

$\uparrow \dot{\alpha}$ as $\uparrow \frac{A_2}{A1}$

Moment Response:

$\uparrow C_m$ as $\uparrow \dot{\alpha}$



For $\widehat{\Phi}_2 = -90^o$ increases in $A2/A1$ increase C_m.

Dynamic Stall: Peak Pitching Moment Scaling

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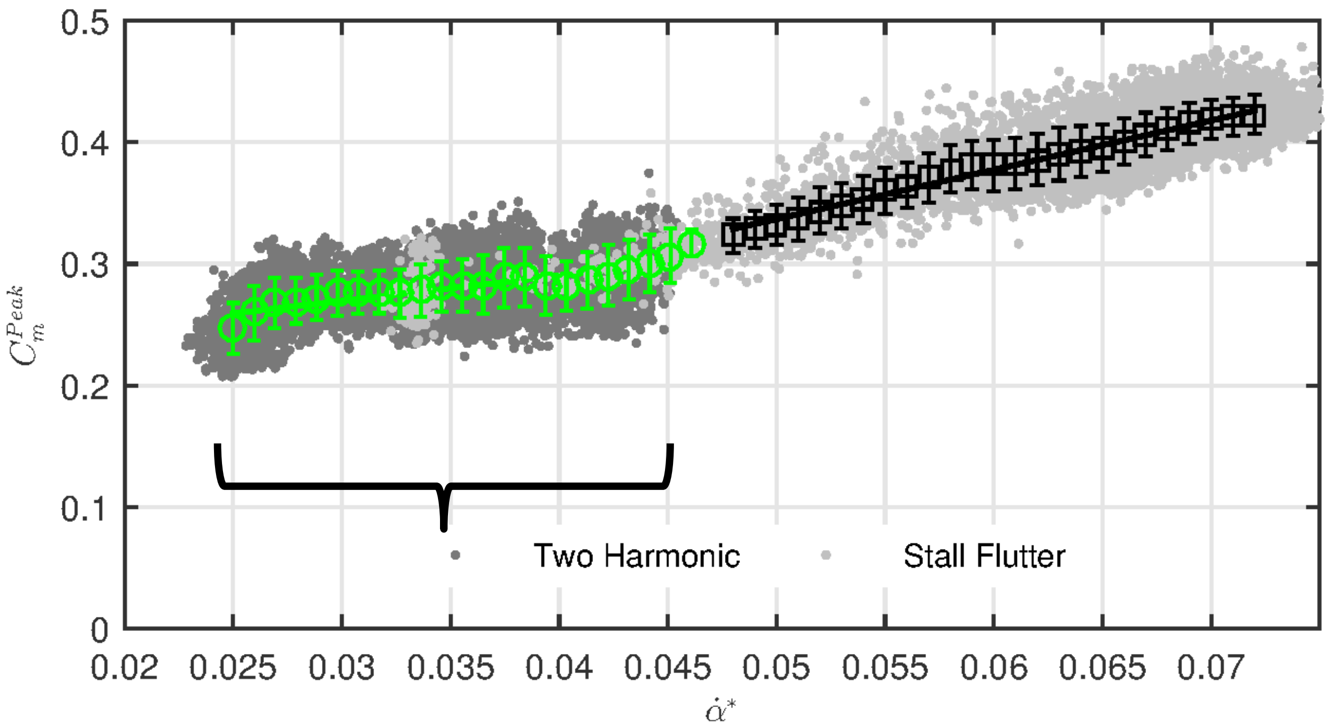
A linear scaling exists between $\dot{\alpha}^*$ and C_m^{Peak} consistent among all motion profiles tested. ($R^2 = 0.9$)

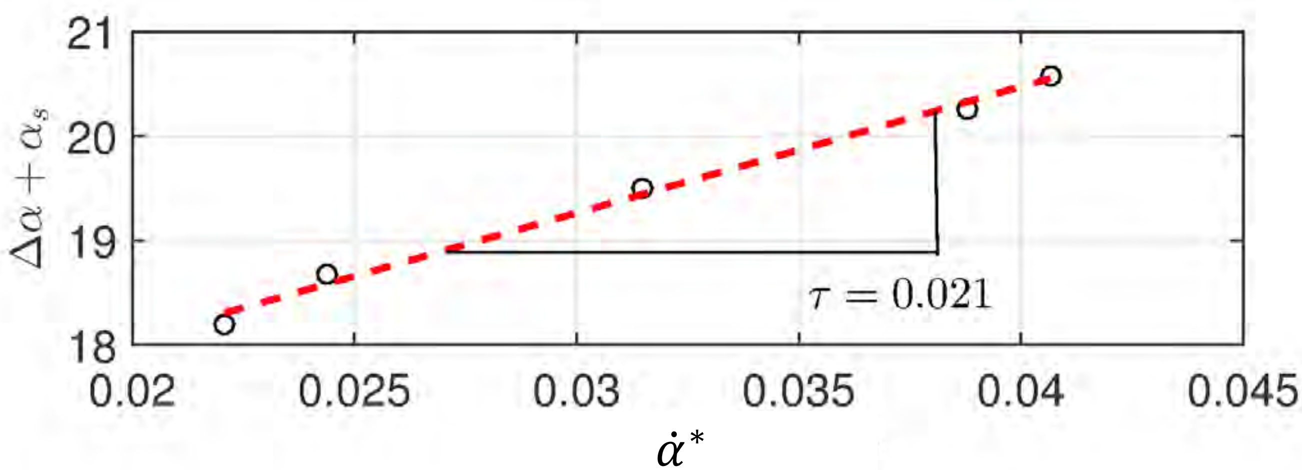


Where $\dot{\alpha}^* = \dot{\alpha}|_{max} \frac{c}{U_\infty}$

The higher harmonics distort $\dot{\alpha}$ and therefore scale C_m.

Dynamic Stall: Separation Delay

A linear scaling ***ALSO*** exists between $\dot{\alpha}^*$ and $\Delta\alpha + \alpha_s$



Where $\dot{\alpha}^* = \dot{\alpha}|_{max} \frac{c}{U_\infty}$

- Fit shown for a reduced set of five cyber-physical stall flutter cases.
- The slope of the fit, τ, represents a time delay constant for this wing section.

Increased pitch rate linearly delays flow separation and increases C_m^{Peak}.

Modeling: Modified Goman-Khrabrov

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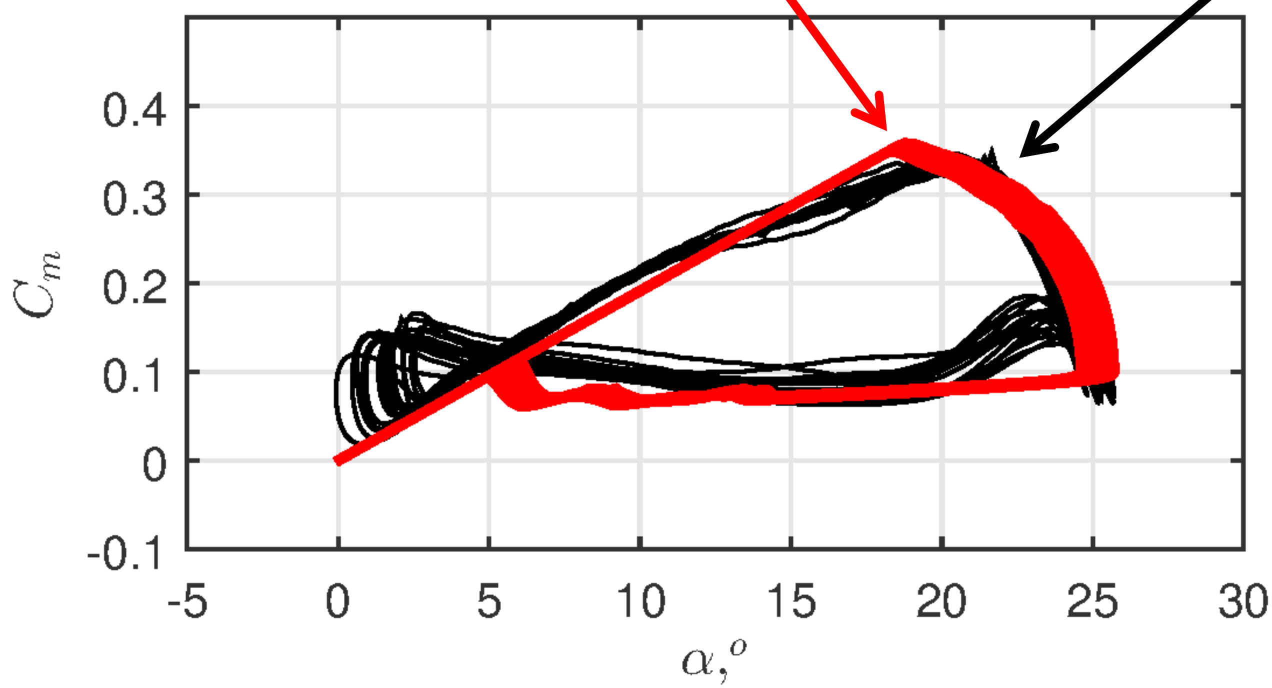
$$C_m = \left(\frac{\partial C_m}{\partial \alpha}\right)\Bigg|_{\dot{\alpha}=0} \alpha(t) X_0\big(\alpha(t) - \underbrace{\tau_2 \dot{\alpha}(t)}_{\textbf{Pitch Rate Delay}}\big) + \underbrace{f(t)}_{\textbf{LEV Advection Function}} \left(\frac{\partial C_m}{\partial \alpha}\right)\Bigg|_{\dot{\alpha}=0} \alpha(t)\big(1 - \underbrace{X(t)}_{\textbf{Flow Separation State}}\big)$$



Note: τ_2 is found from separation delay found earlier ($\tau_2 = \tau = 0.21$).

Note: $f(t) = 1 - t/0.043$

Stall Flutter: $k_\theta = 1.83 \frac{Nm}{rad}$, $\eta = 2.2(10^{-2})$

Provides a model with low computational requirements and moderate accuracy based upon *only* pitch rate variations.

Summary & Future Work

Summary:

- Higher harmonics distort the pitch motion trajectory and C_m time-history.
- There is a linear pitch rate dependence of peak C_m and α_{stall}
- Separation delay model characterized hysteresis loop with moderate accuracy. (Similar to Goman-Khrabrov Model)
  - Accounts for pitch rate delay in stall
  - Accounts for time-rate of change from flow state through LEV advection
  - Low computational power required, needs just current state and static airfoil behavior

Limitations and Future Work:

- Modified Goman-Khrabrov Model doesn't capture second secondary LEV
- Reattachment can be modeled, purely empirically (more work required)
- Need to expand implementation for other airfoils and broader range of dynamic stall cases (i.e. reduce frequencies, α ranges)
- Need to expand implementation to lift response.

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Questions?

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