

Evaluation of a Physics-Based Unsteady RANS Method for Buffet Onset Prediction

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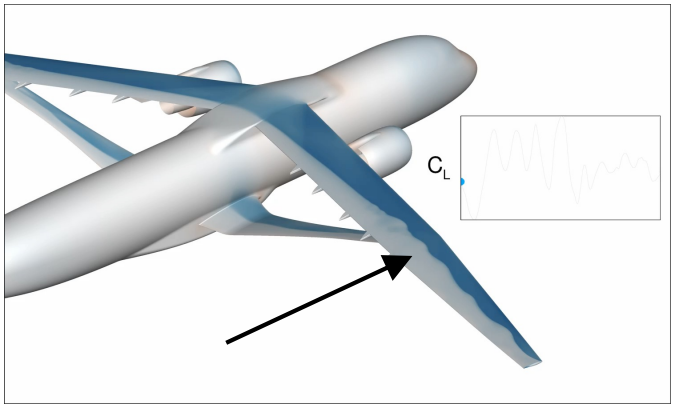
NASA Langley Research Center

Advanced Modeling & Simulation (AMS) Seminar Series

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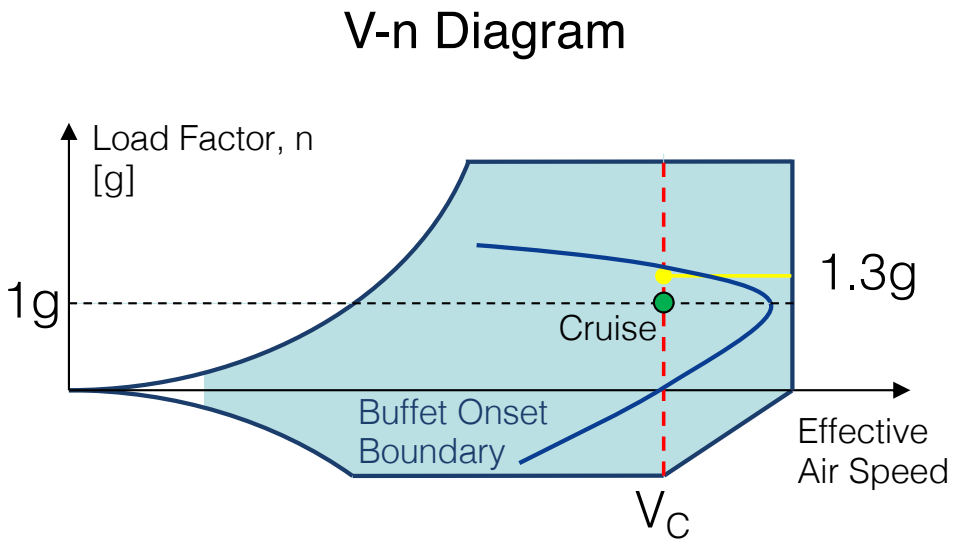
Outline

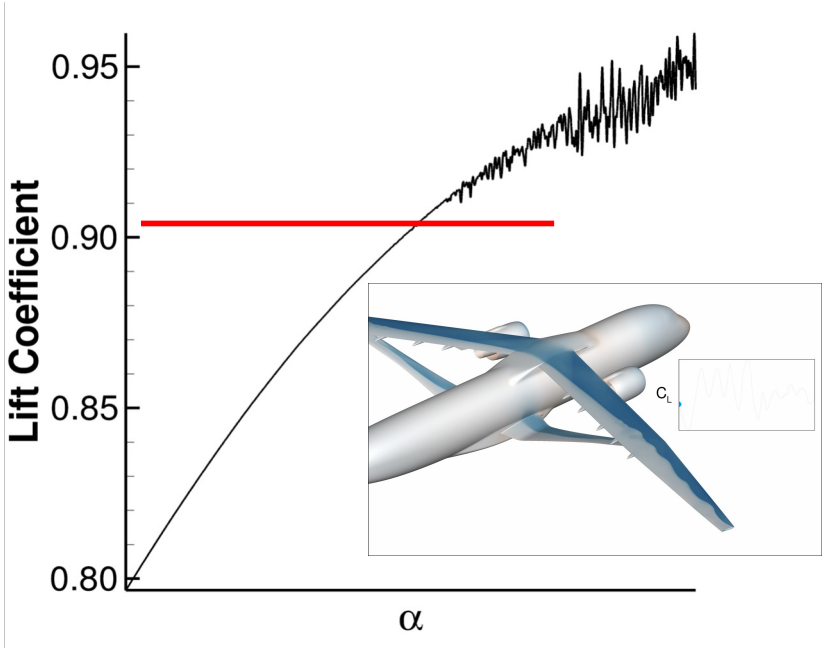
- Introduction to Transonic Buffet
- Computational Methodology
- Physics-Based Unsteady RANS Method for Buffet Onset Prediction
- Method Evaluation and Sensitivity Studies:
  - ONERA OAT15A Airfoil
  - NASA Common Research Model (CRM) Wing-Body
- Application to the Boeing SUGAR Transonic Truss Braced Wing (TTBW)
- Conclusion, Current Best Practices, and Future Work



Unsteady surface pressure and time-history of lift on TTBW at post-buffet condition

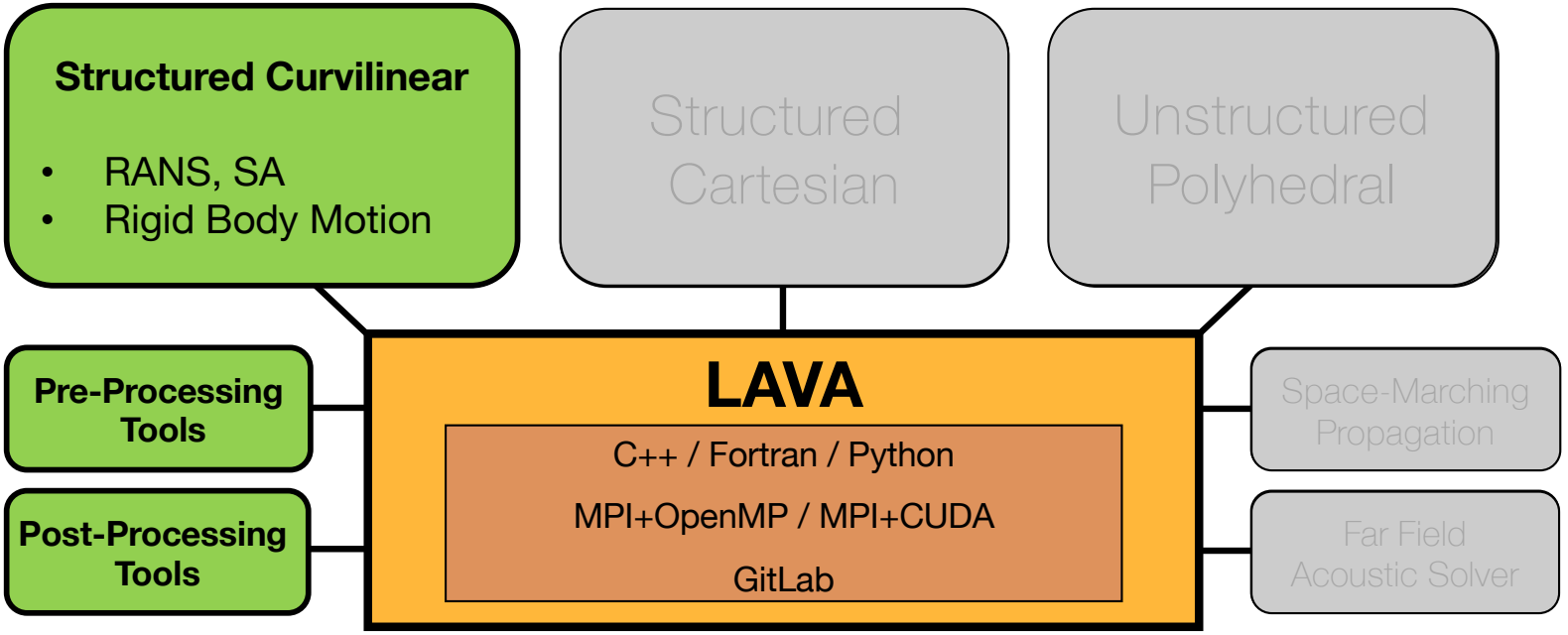
Introduction to Transonic Buffet





A step towards "***Certification By Analysis***"

Computational Methodology



- Chimera Grid Tools (CGT) and LAVA based tools* (C. Ashby) for grid generation
- Structured overset grid connectivity module and panel-weights* (J. Koch)
- Structured overset grid solver
- FFT post-processing module for surface and volume-based output

*** These tools/modules will be presented in the upcoming Overset Grid Symposium**

Structured Overset Grid Solver Options



- Reynolds Averaged Navier-Stokes equations for generalized curvilinear coordinates in strong conservation form
- Spalart-Allmaras turbulence model (negative form) with the following corrections considered
  - Rotation curvature (RC)
  - Compressibility correction (CC)
  - Low Reynolds number (LRe)
  - Quadradic Constitutive Relation, 2000 version (QCR2000)
- Second-order finite-difference convective flux discretization
  - Modified Roe numerical flux with blended centered/upwind left/right state reconstructions limited with the Koren limiter
  - KEEP applied to non-dissipative portion plus artificial dissipation from modified Roe scheme
- Centered/upwind blending function based on vorticity and strain-rate magnitude sensor combined with a wiggle sensor
- Second-order midpoint-and-node viscous flux discretization
- Second-order backward differencing in time



Physics-Based URANS Method for Buffet Onset Prediction

Assumptions and Credits

Basic Assumptions

- Underlying physical mechanism of transonic buffet is a global instability
  - Accepted in the literature and the foundation for global instability analysis approaches (see Crouch *et. al.*, Timme, as well as Sansica and Hashimoto)
- The instability can be captured using unsteady RANS based analysis

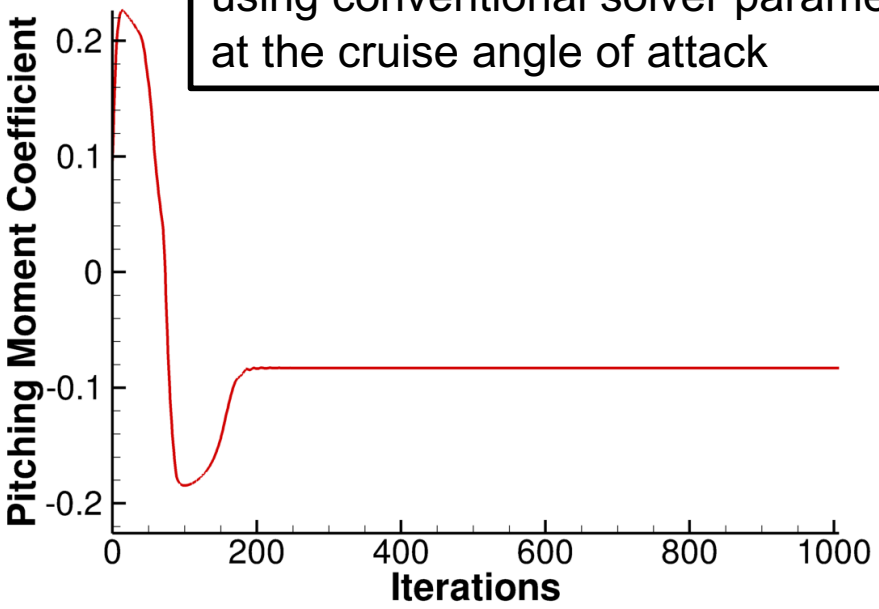
Credits

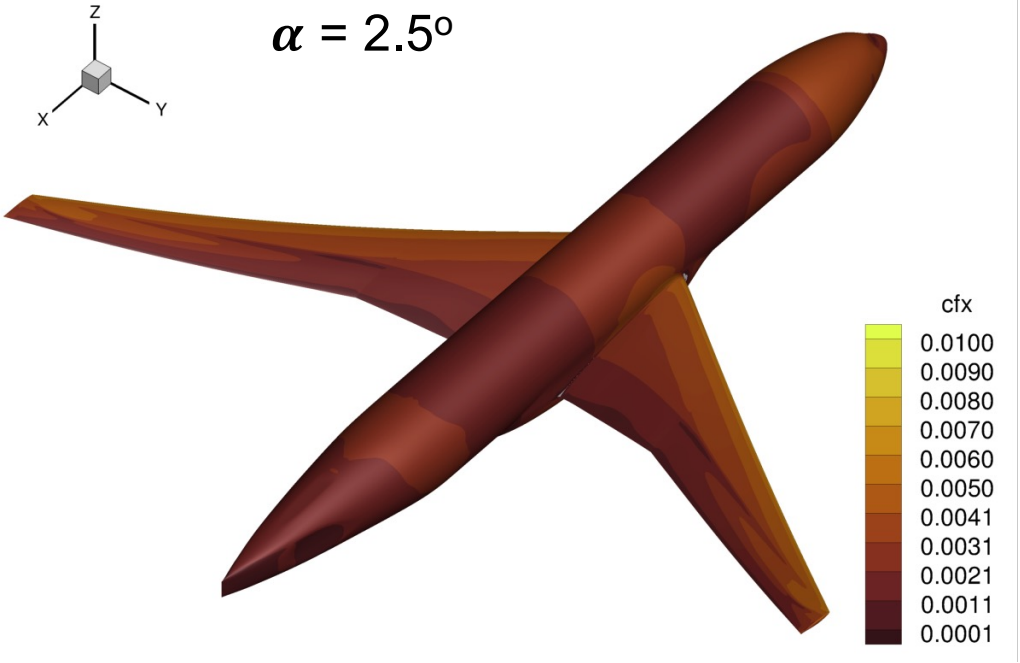
- The method of continuously pitching an aircraft model is commonly utilized in experimental wind-tunnel tests (see McDevitt and Okuno and Harrison *et. al.*)
- Present work was inspired by Jeffrey Crouch's (Boeing) recent Stanford Fluid Mechanics seminar and was explored in the context of WMLES for the NACA0012 (see Goc *et. al.*)

Step 1

Steady-state RANS

Perform steady-state RANS analysis using conventional solver parameters at the cruise angle of attack

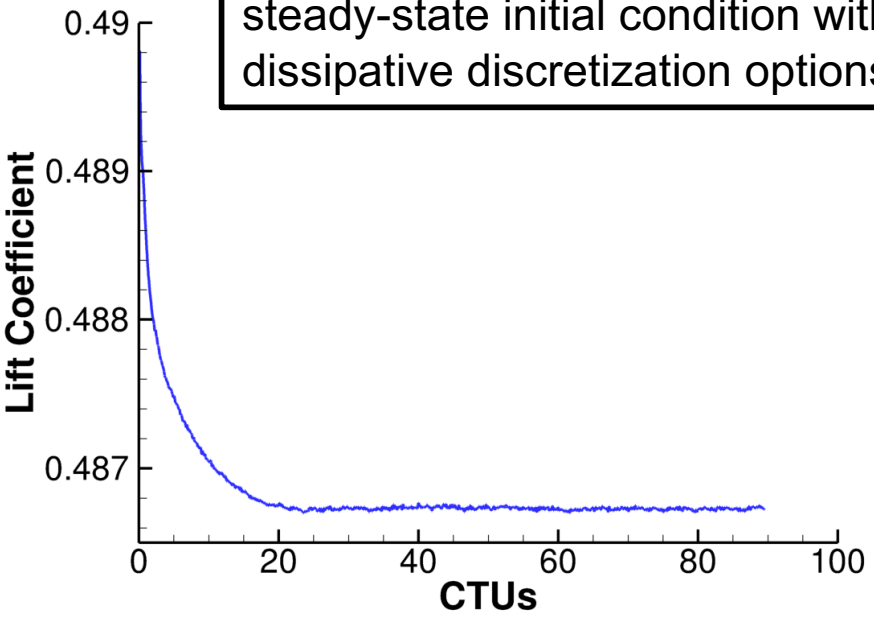


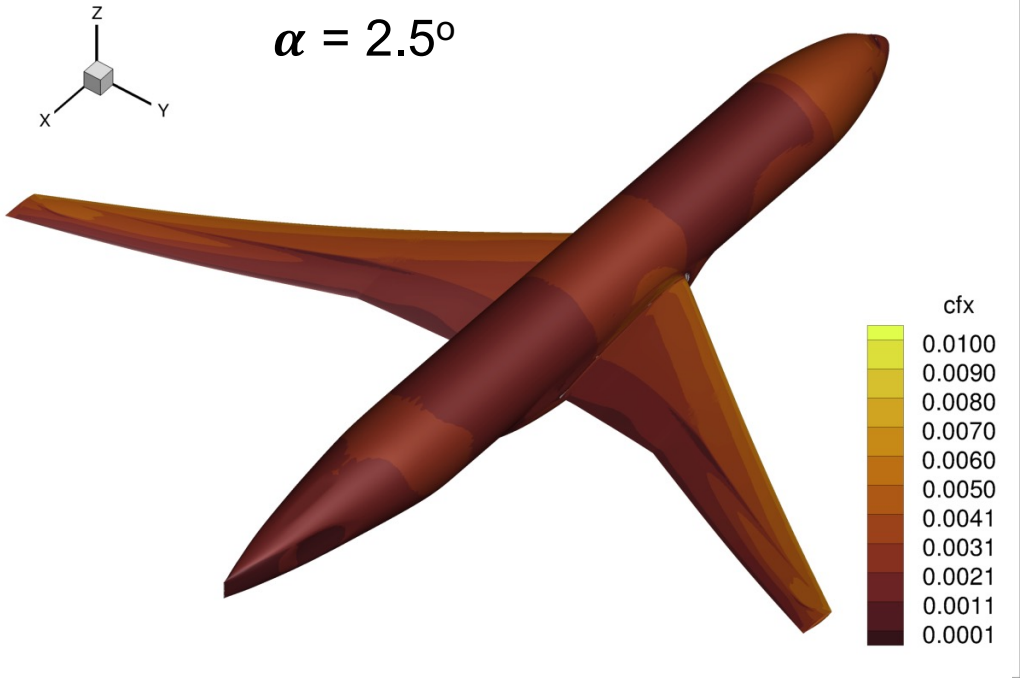


Step 2

Steady-state RANS | Start-Up URANS

Perform URANS analysis using steady-state initial condition with less dissipative discretization options.

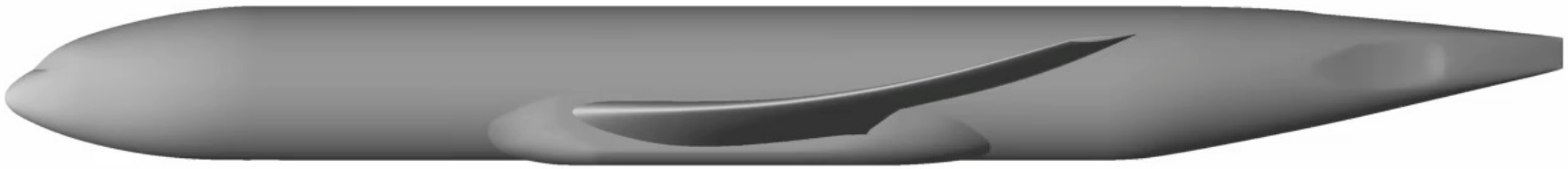




Step 3

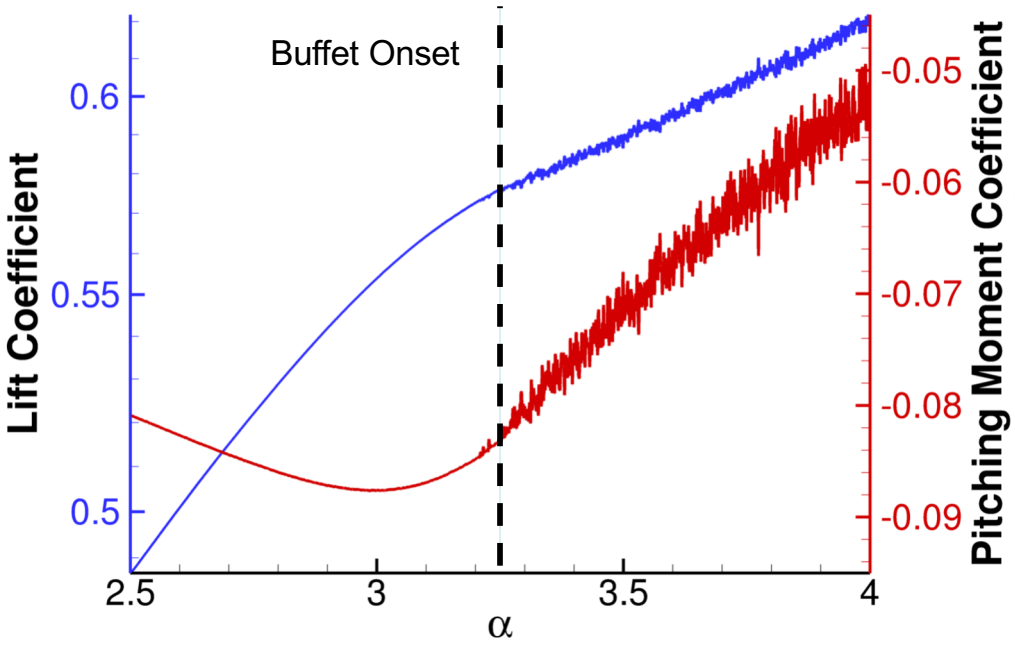
Steady-state RANS | Start-Up URANS | Continuous Pitch

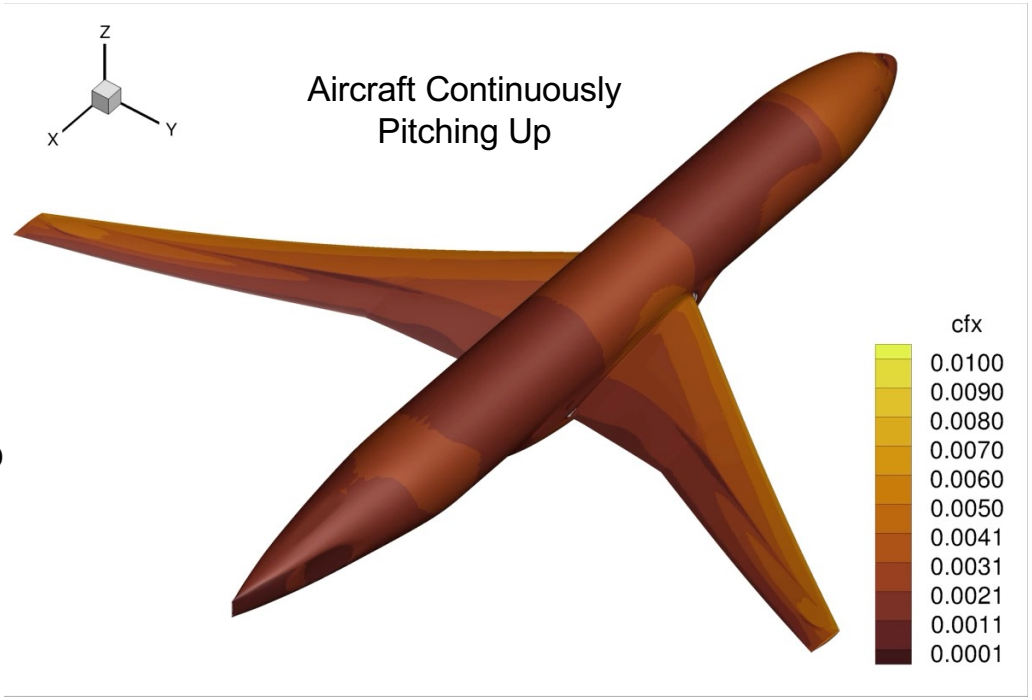
$\alpha = 2.50$



Step 3

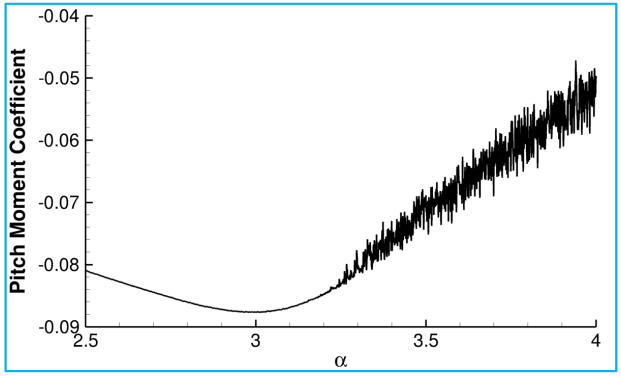
Steady-state RANS | Start-Up URANS | Continuous Pitch



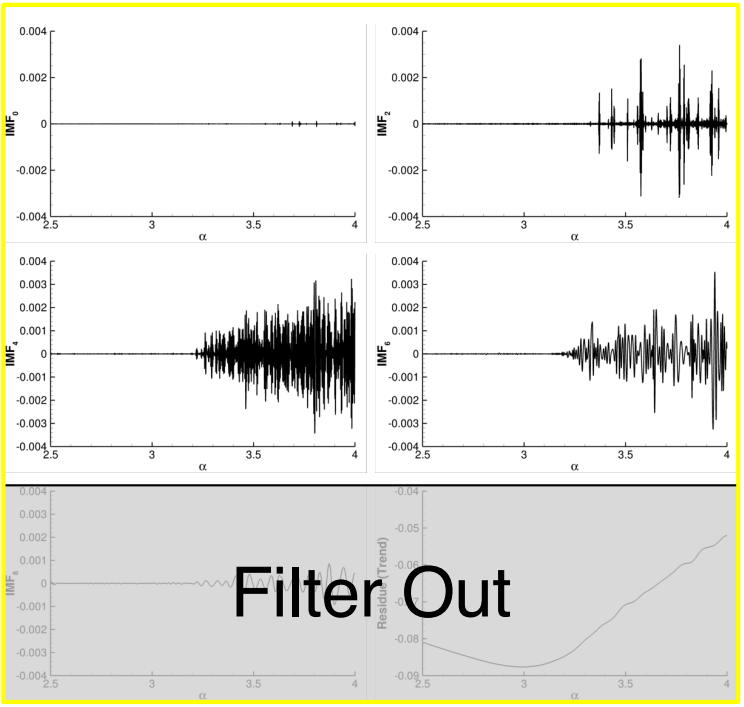


Current Buffet Onset Classification Method

Time History

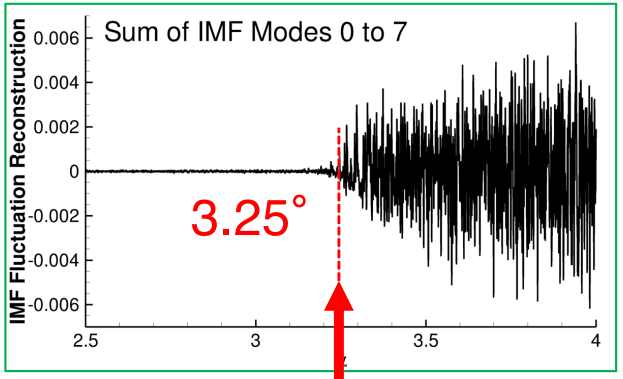


Empirical Mode Decomposition (EMD)



https://github.com/laszukdawid/PyEMD

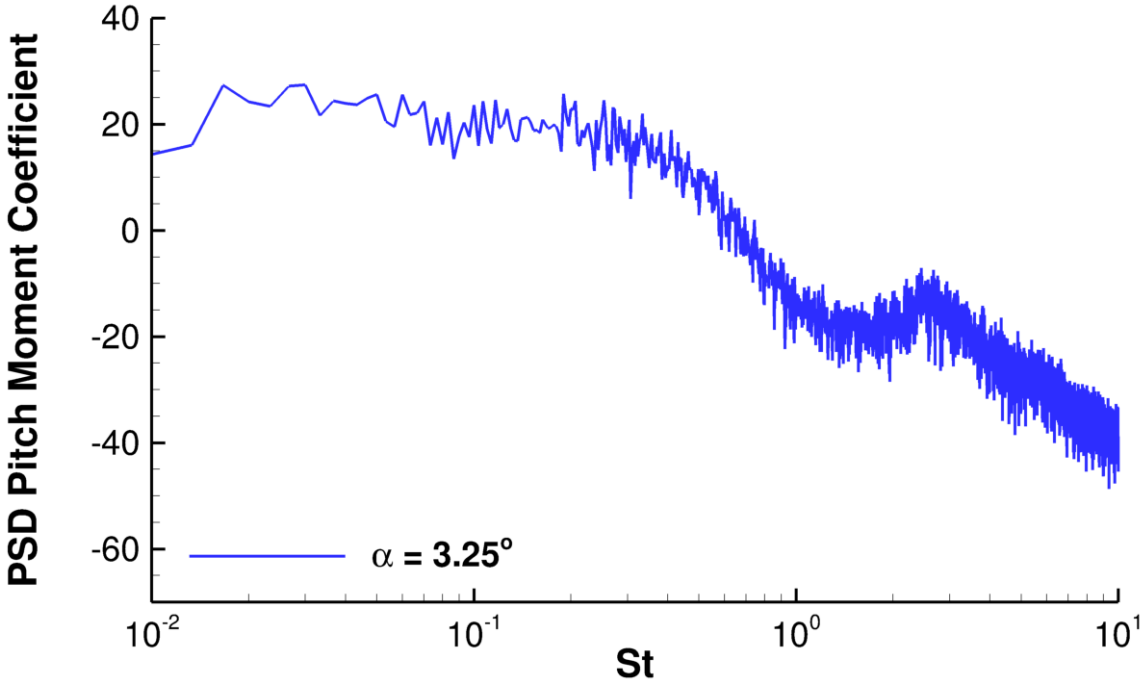
IMF Reconstruction



Visual Inspection for Exponential Growth

Step 4

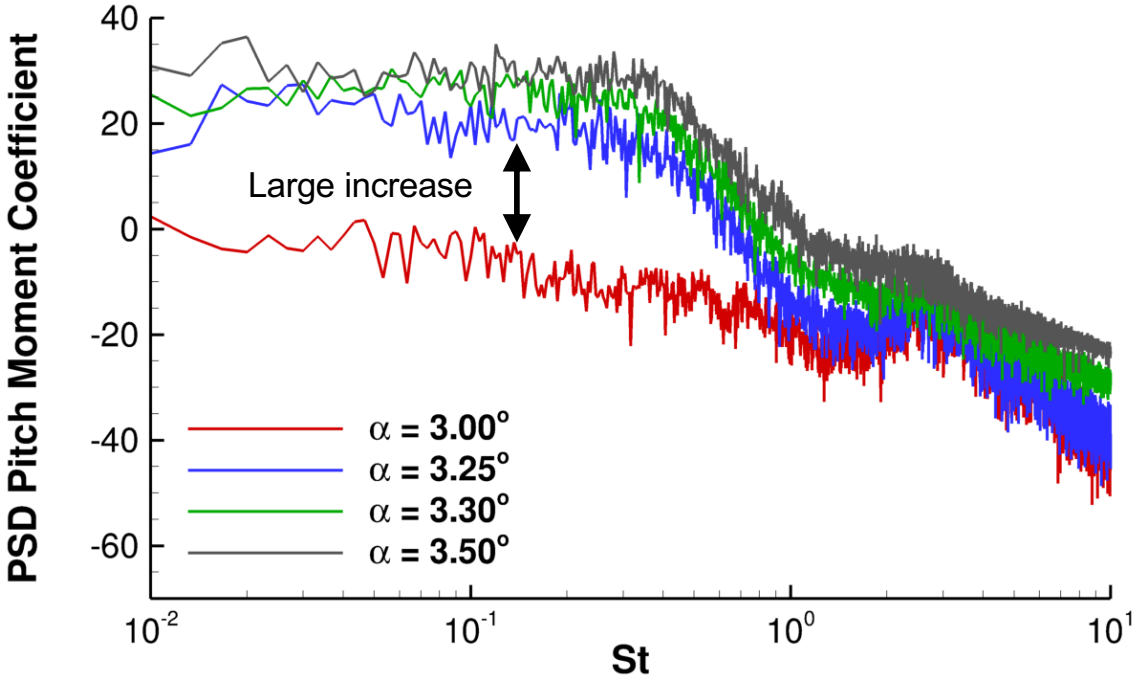
Steady-state RANS | Start-Up URANS | Continuous Pitch | Verification of Buffet



- Based on the predicted buffet onset angle from the moving body simulation a static URANS analysis is performed at this angle of attack starting from free-stream (or precursor steady-state if available)
- A time-history of integrated loads and pressure probes at selected locations are recorded for post-processing

Step 4

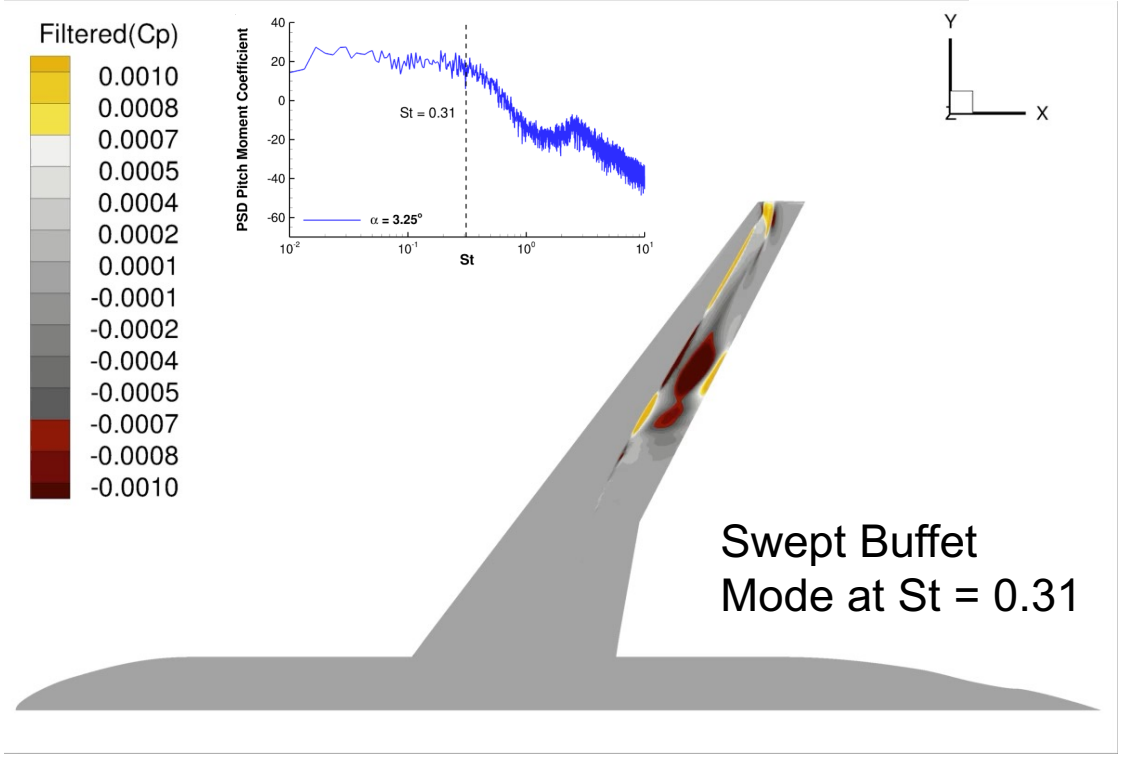
Steady-state RANS | Start-Up URANS | Continuous Pitch | Verification of Buffet



- Perform static URANS analysis at angles of attack above and below predicted onset angle
- Verify the predicted buffet onset through PSD analysis of integrated loads and/or unsteady pressure probes gathered during the simulations

Bonus: Buffet Onset Mechanism Indentification

Steady-state RANS → Start-Up URANS → Continuous Pitch → Verification of Buffet



- FFT analysis is performed using unsteady surface and/or volume data gathered during static URANS analysis at predicted buffet onset
- Filtering the pressure field at different frequencies provides identification of various buffet instability modes

	Long wavelength	Intermediate wavelength	Short wavelength
Wavelength	$\tilde{\lambda} > 10c$	$\tilde{\lambda} \approx c$	$\tilde{\lambda} \approx 0.1c$
Frequency	$St \approx 0.04$	$St \approx 0.4$	$St \approx 1.6$
Phase speed	$Uc < -0.2$	$Uc \approx 0.4$	$Uc \approx 0.3$
Description	Airfoil buffet mode	Swept buffet mode	Shear-layer mode

TABLE 2. Summary of instability-mode attributes for the swept OAT15A wing, with $\Lambda = 30°$.

"*Global instability in the onset of transonic-wing buffet*"
Crouch, Garbaruk and Strelets, JFM (2019)

Advantages and Disadvantages



Advantages

- No apriori knowledge of, or deep steady-state convergence at the buffet onset angle
- No large-scale eigenvalue problem needs to be constructed and solved
- Fine resolution of $\mathbf{C_L}$-$\boldsymbol{\alpha}$, $\mathbf{C_D}$- $\boldsymbol{\alpha}$, and $\mathbf{C_m}$- $\boldsymbol{\alpha}$ over the pre-buffet angle-of-attack range

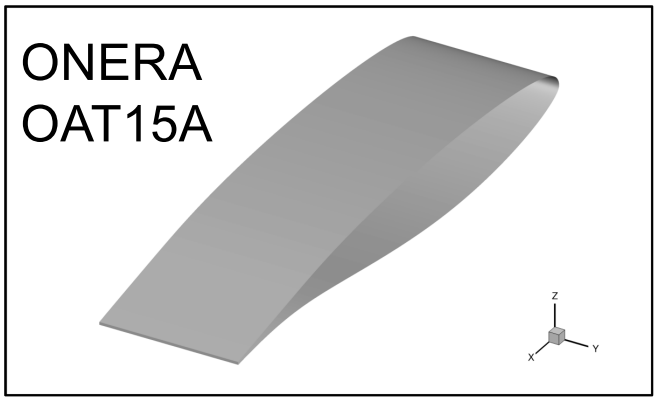
Disadvantages

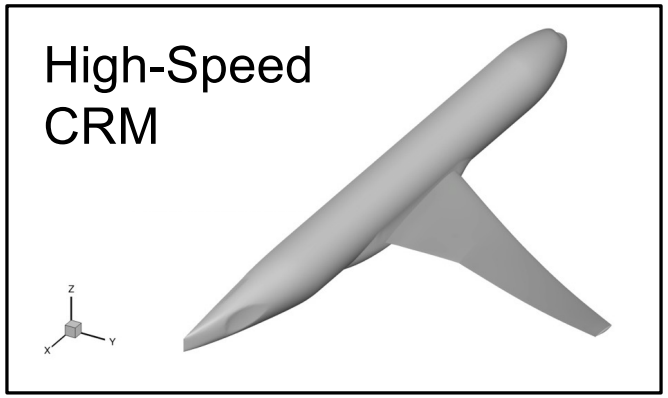
- Potential sensitivities to pitch rate, time-step, mesh resolution, turbulence model, numerical discretization
- Computation cost of performing unsteady moving-body simulation
- Excludes aero-structural coupling (this is future work, B. Lowe)

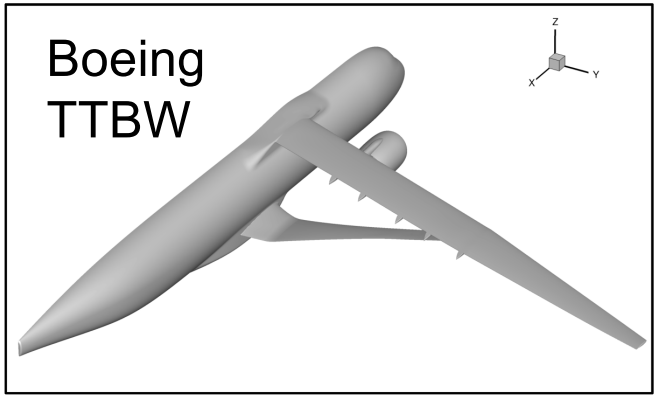


Method Evaluation and Sensitivity Studies

Test Cases and Sensitivity Studies

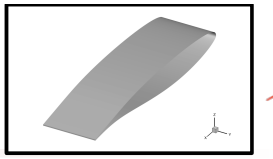


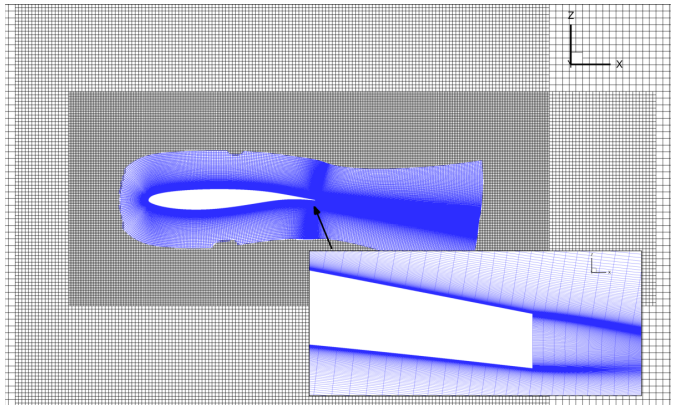


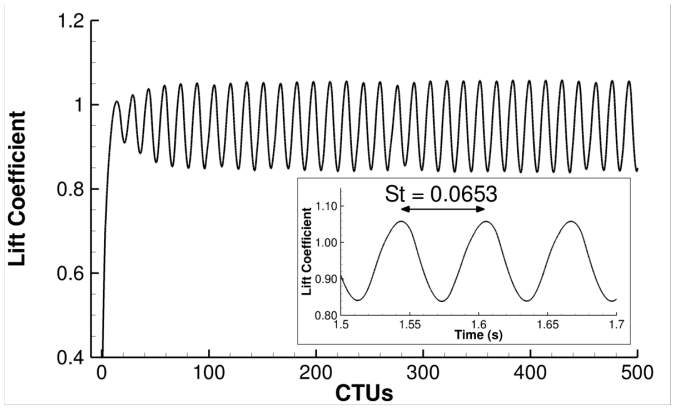


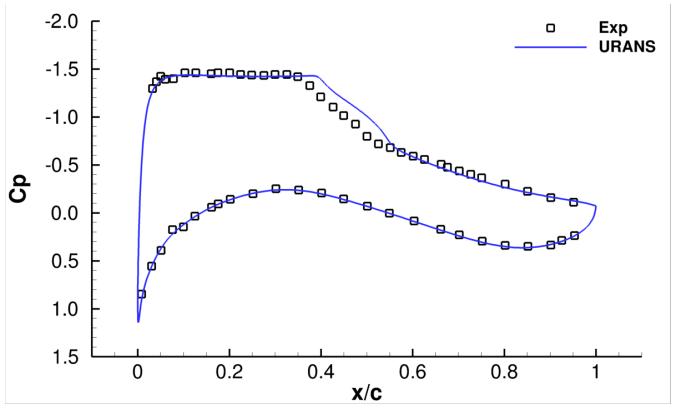
Study	Values	Configuration
Pitch Rate	0.125, 0.25, 0.5 °/sec	OAT15A
Mesh Resolution	Baseline Grid versus Spanwise Refinement	High-Speed CRM
Geometry	Half-Body/Full-Body	High-Speed CRM
Time-Step	[1/20, 1/100, 1/200] CTU	Boeing SUGAR TTBW
Convective Flux Discretization	KEEP, Upwind Blend	Boeing SUGAR TTBW
Initial Angle of Attack	$\alpha = 2.0°$, $\alpha = 2.75°$	Boeing SUGAR TTBW

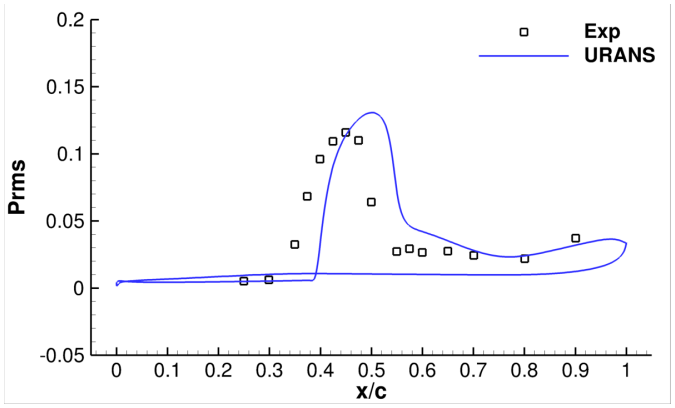
ONERA OAT15A Pitch Rate Study





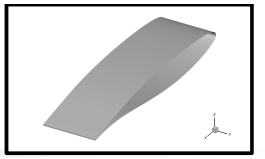


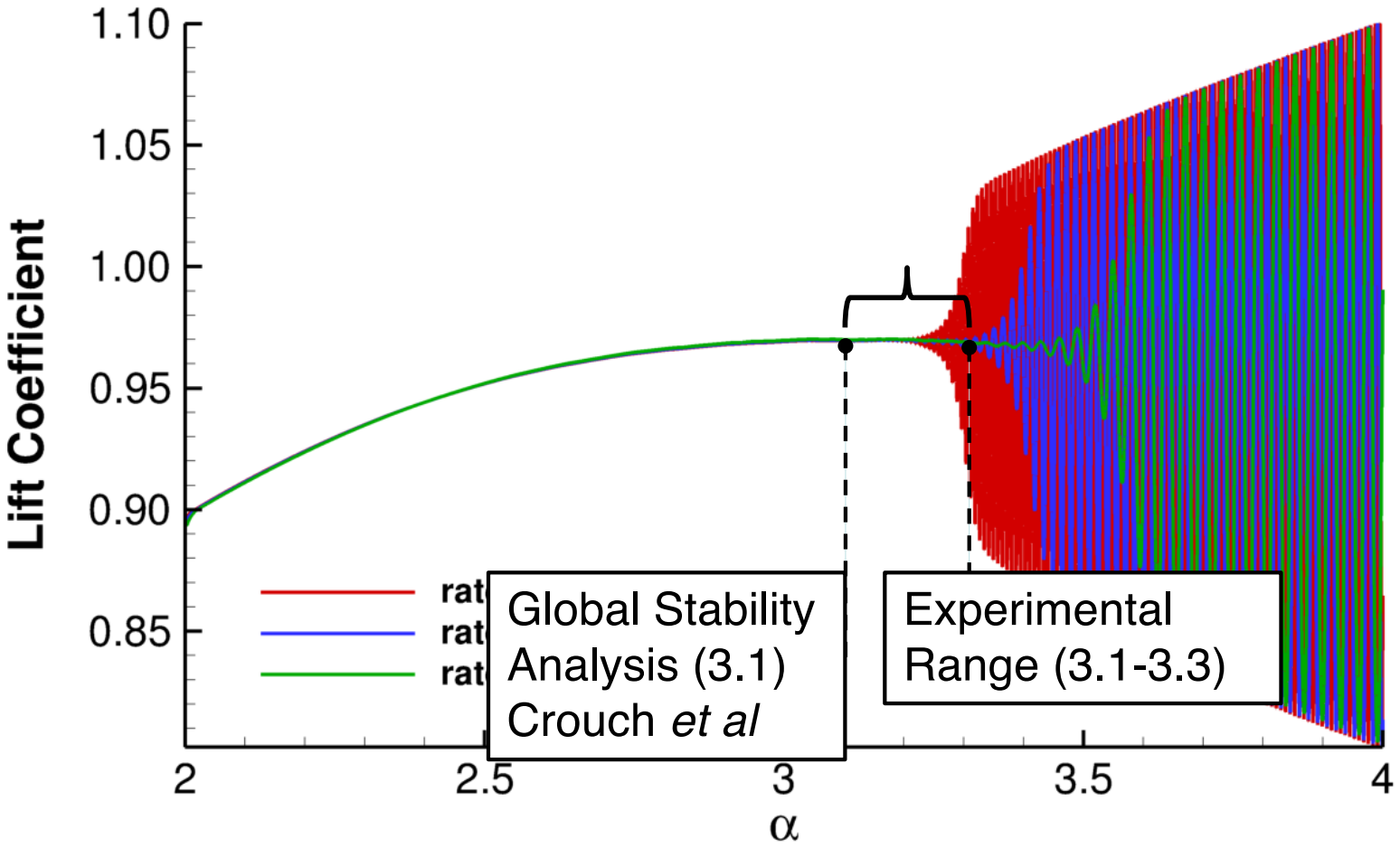




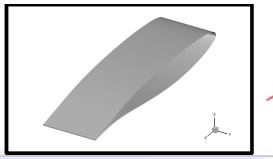
- Structured overset grid with 294K points on the 2D plane
- Results from static URANS (SAneg-RC-CC)
  - Mach 0.73
  - Re_c = 3 million
  - Alpha 3.5-degrees
- Time-averaged Cp compares well with experiment measurements
- Small over-prediction and downstream shift in P_{RMS}
- Experimental buffet Strouhal of 0.0626 slightly over-predicted

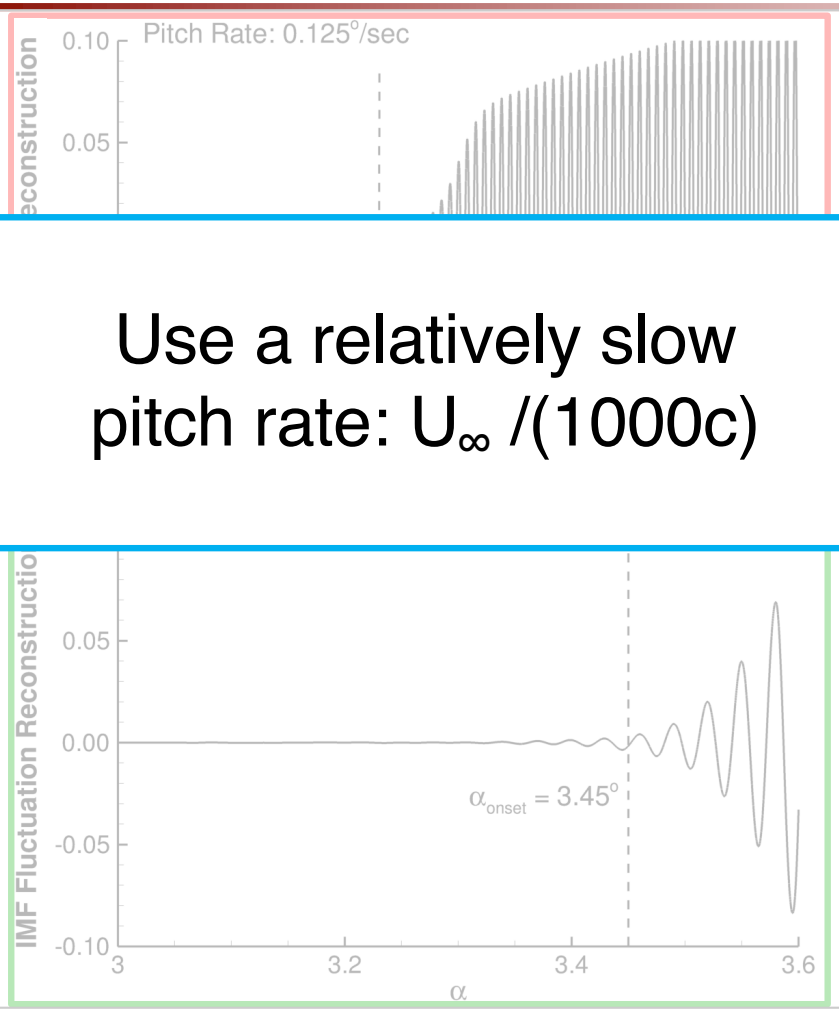
ONERA OAT15A Pitch Rate Study



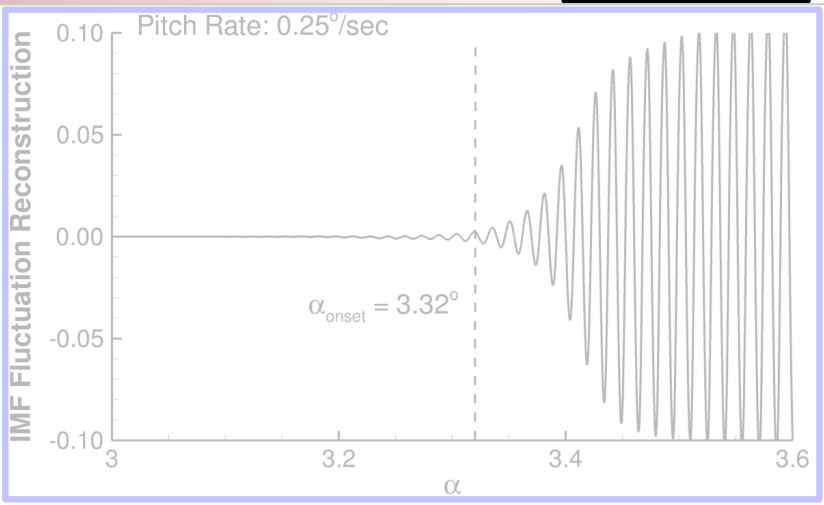


ONERA OAT15A Pitch Rate Study



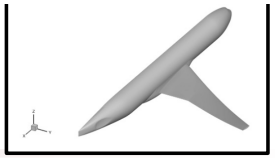


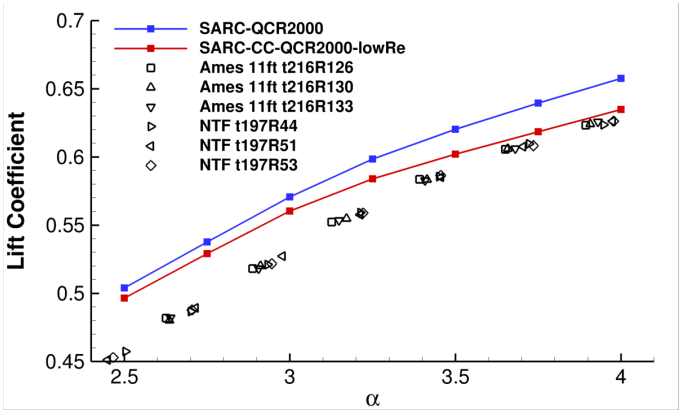
Use a relatively slow pitch rate: U_∞ /(1000c)

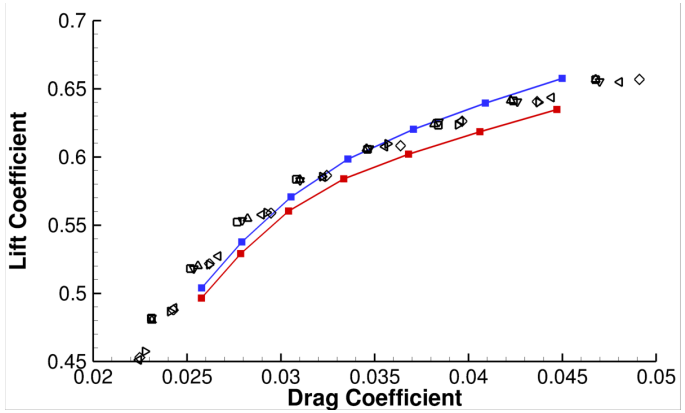


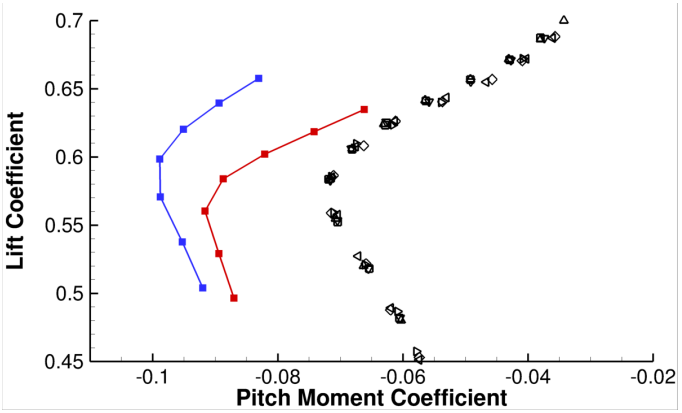
Color	Pitch Rate	α_{onset}	Difference
	0.125°/sec	3.23	2.7%
	0.25°/sec	3.32	-
	0.5°/sec	3.45	3.9%

High-Speed CRM



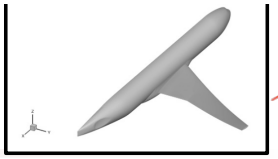


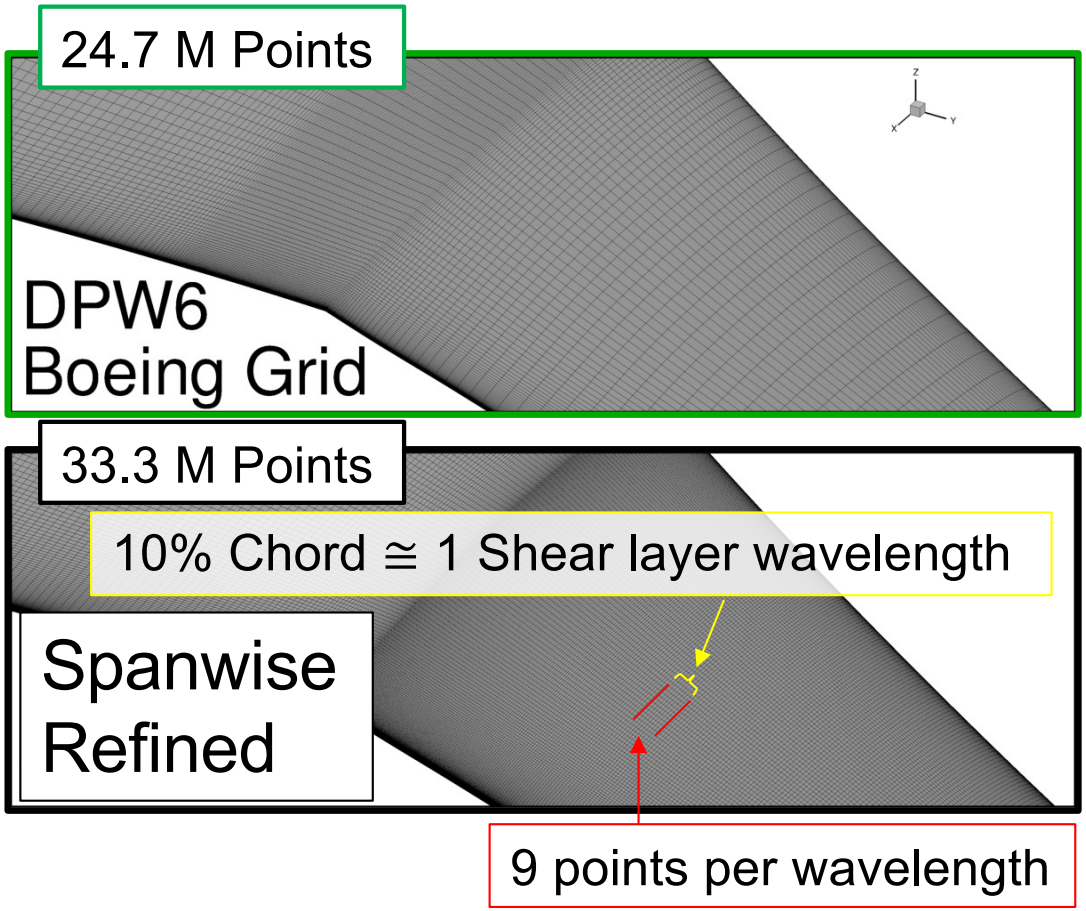


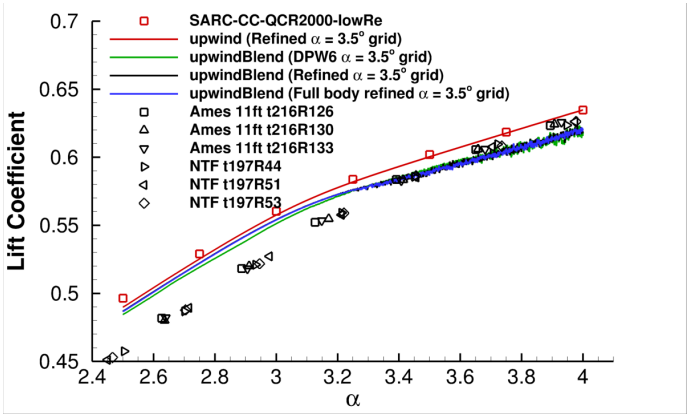


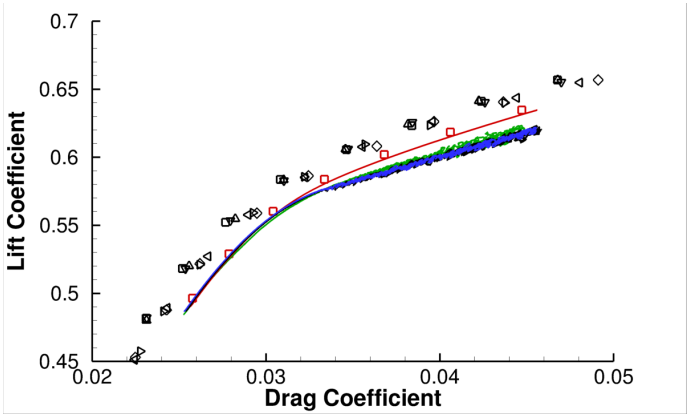
- Steady-state RANS analysis was performed at select angles of attack between 2.5- to 4-degrees angle of attack using structured overset grids developed by Boeing (L. Serrano) for DPW6
- Each angle of attack has a different grid associated with the changes in wing deflection with increasing load
- Both SARC-QCR2000 and SARC-CC-QCR2000-LRe turbulence closures are compared with Ames 11ft and NTF wind-tunnel data
- Based on the superior Cl-alpha slope (alpha >= 3.5-degrees) and qualitative shape of the pitch moment, the SARC-CC-QCR2000-Lre was chosen for exploration of the buffet onset method

High-Speed CRM Mesh/Geometry Sensitivity

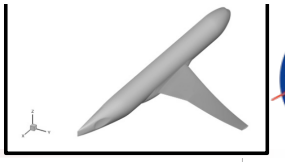


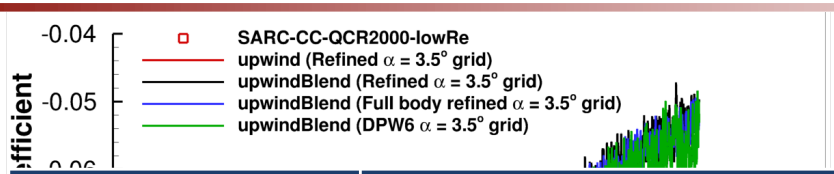


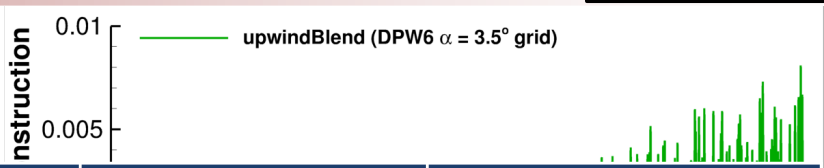




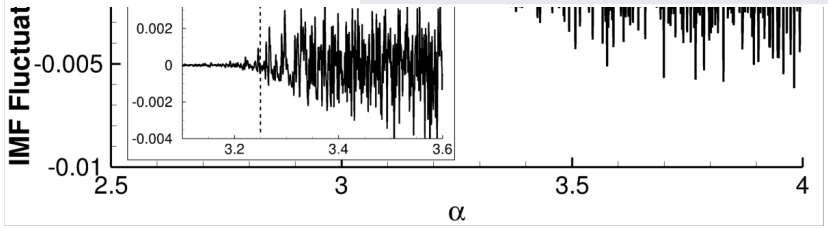
High-Speed CRM Mesh/Geometry Sensitivity

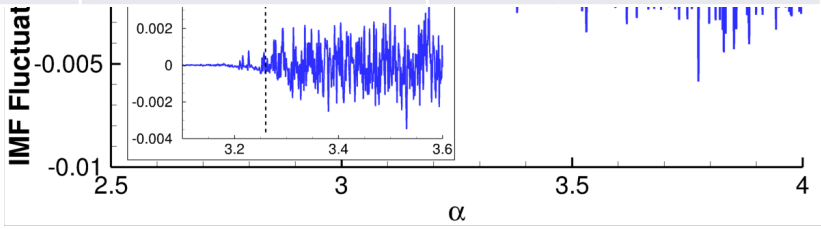




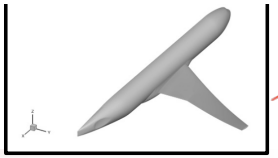


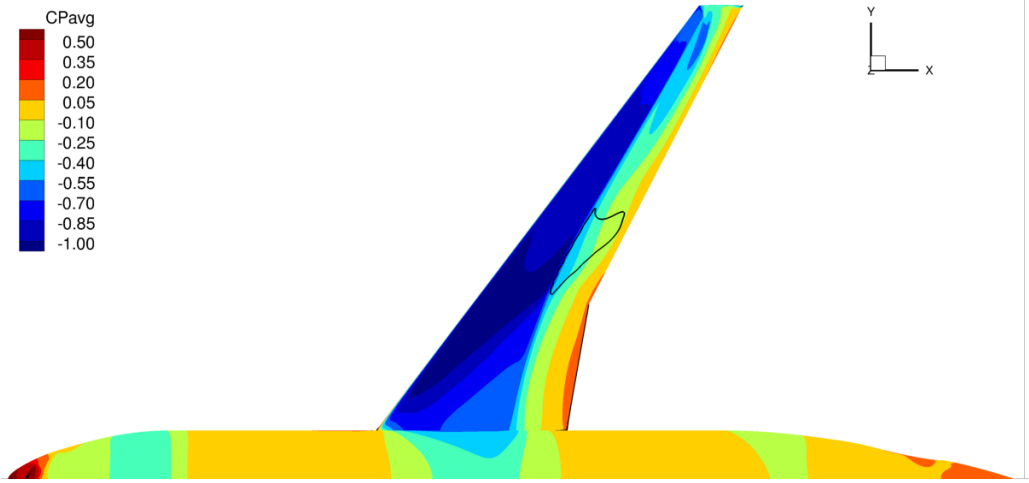
Color	Grid	α_{onset}	$C_{L\ onset}$
	DPW6	3.38	0.584
	Refined	3.25	0.576
	Full-Body	3.26	0.576
	Delta	3.8%	1.4%



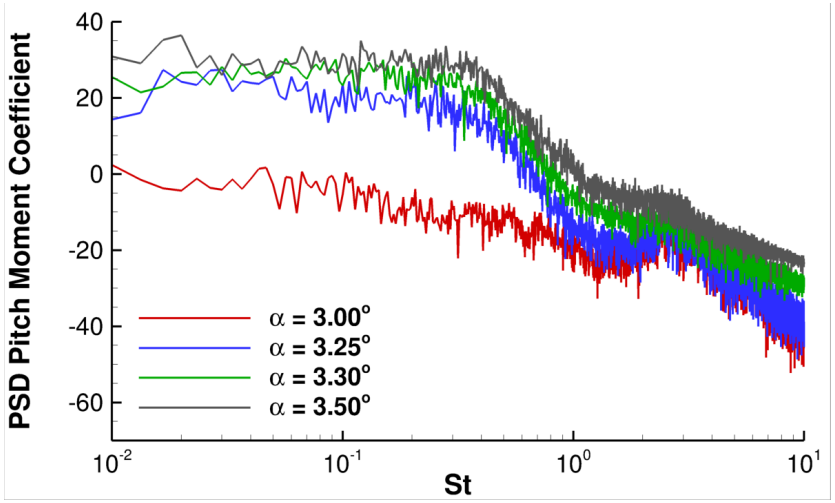


High-Speed CRM Buffet Onset Verification



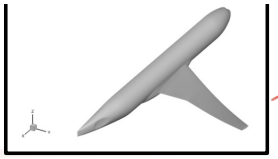


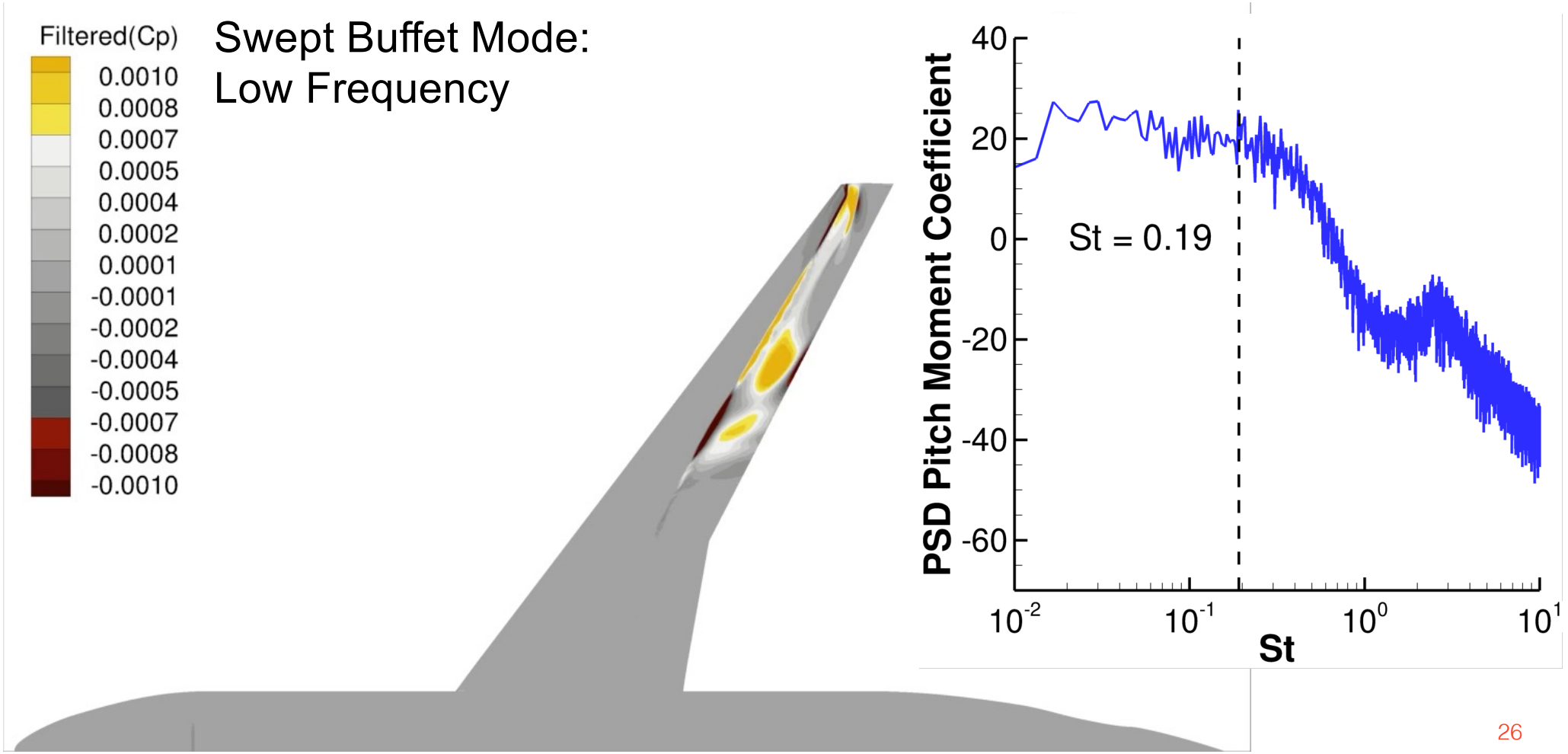




- Four static URANS simulations were performed
  - 3.25-degrees (predicted buffet onset)
  - 3.00-degrees (pre-onset)
  - 3.30-degrees (post-onset)
  - 3.50-degrees (post-onset)
- PSD of pitch moment shows large increase in levels for St < 1 starting at alpha 3.25-degrees
- Increased levels are broadband in nature
- All angles of attack show increased PSD levels at 2 < St < 3 (shear layer instability)

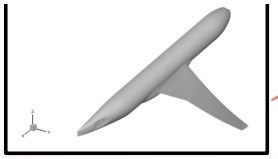
High-Speed CRM Buffet Mechanism(s)

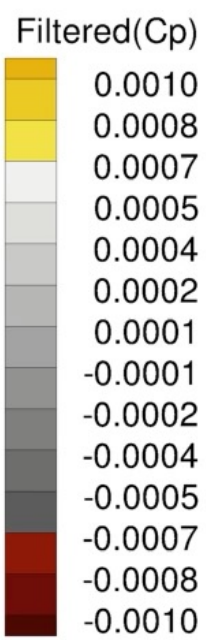




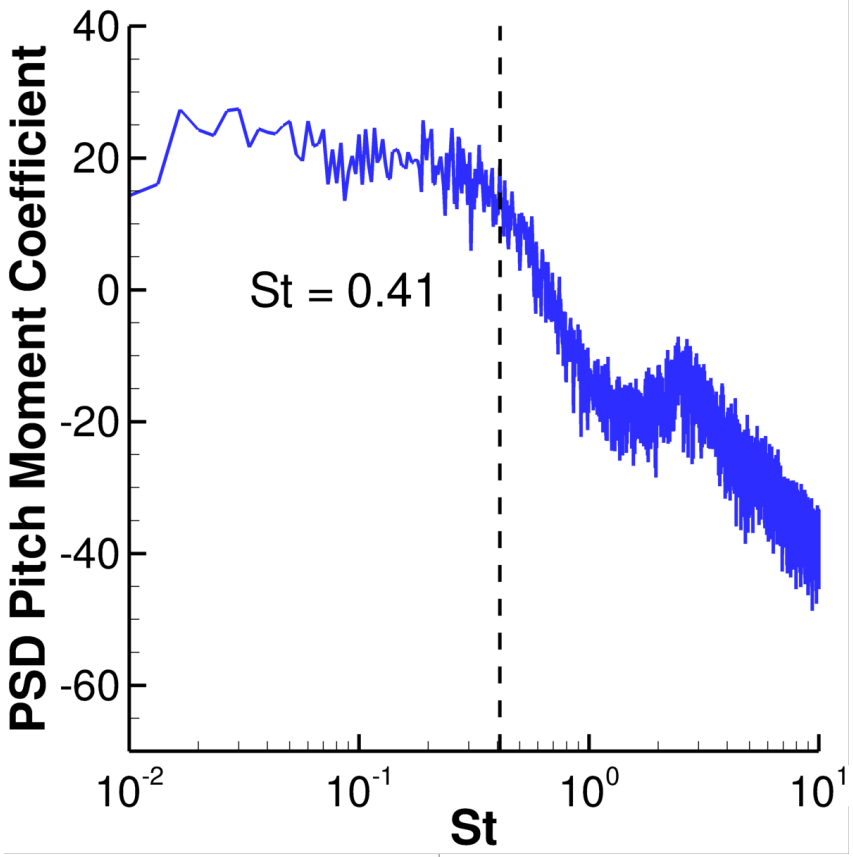
Swept Buffet Mode:
Low Frequency

High-Speed CRM Buffet Mechanism(s)

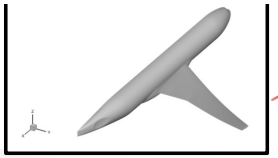


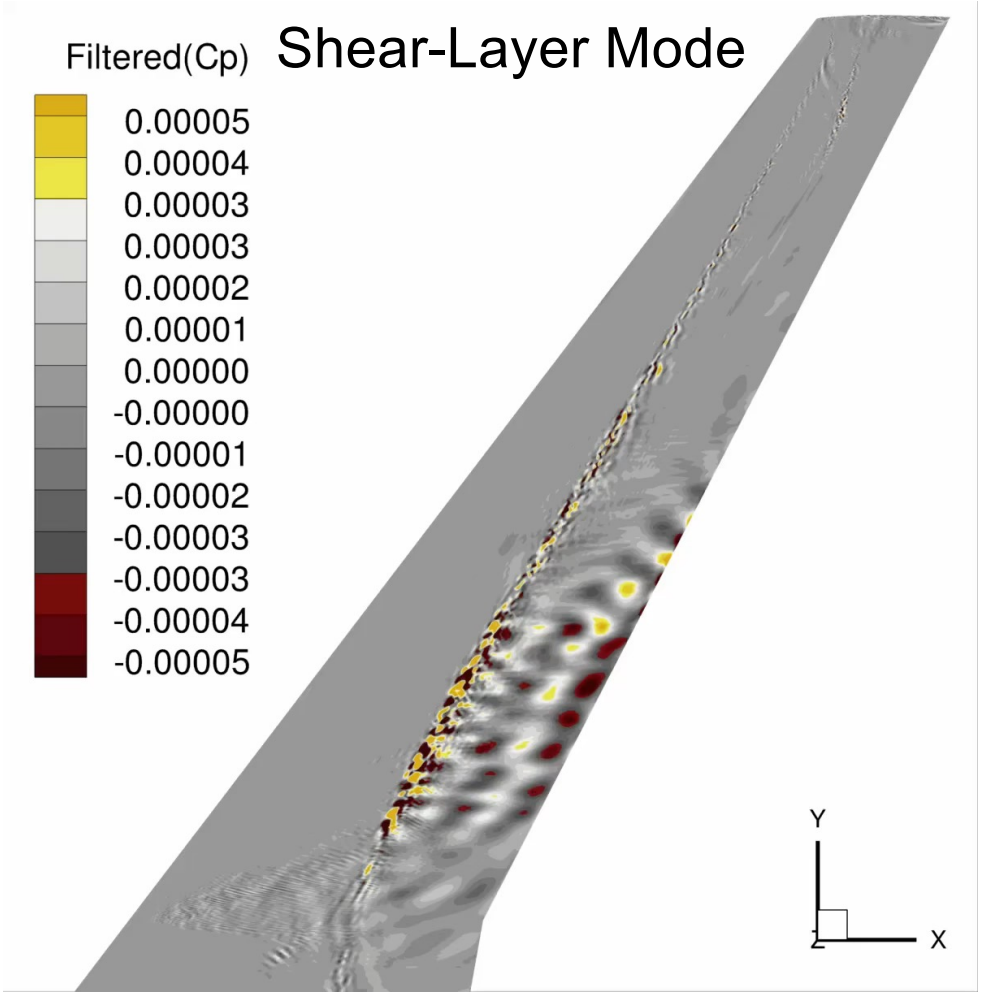


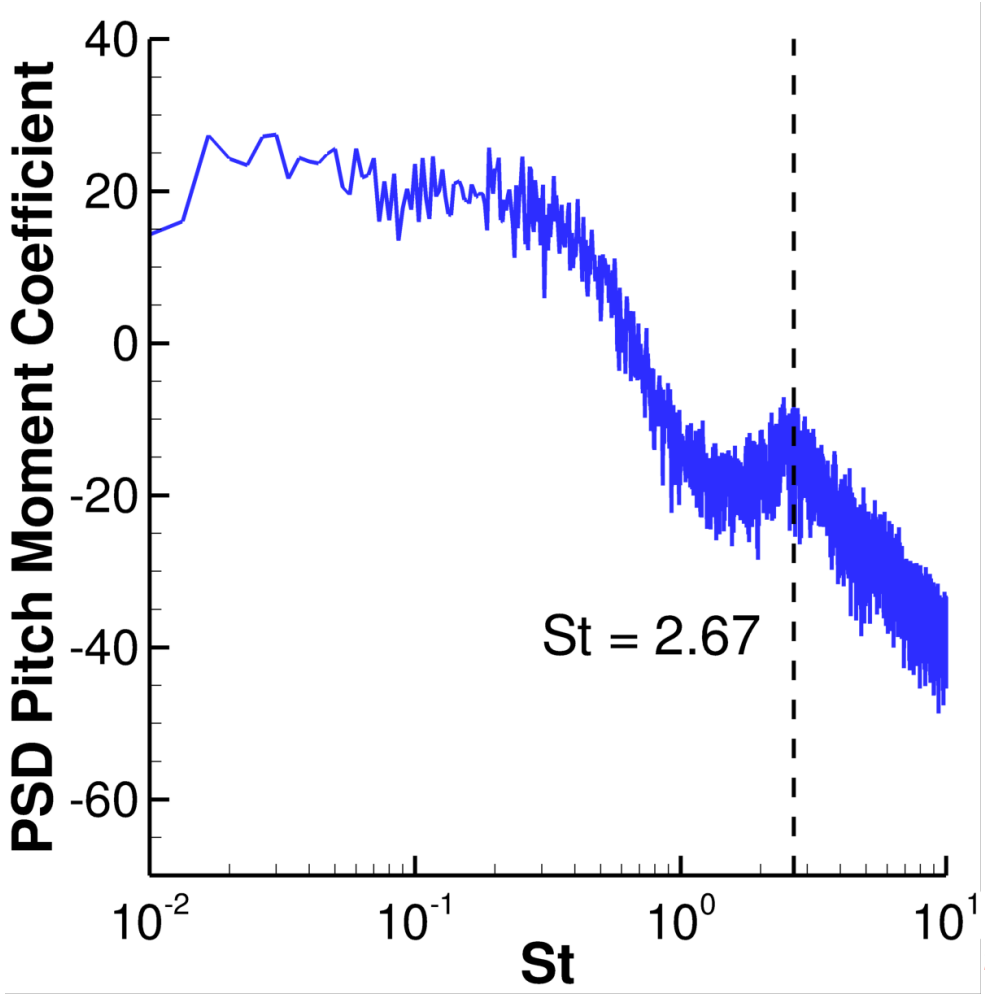
Swept Buffet Mode:
High Frequency



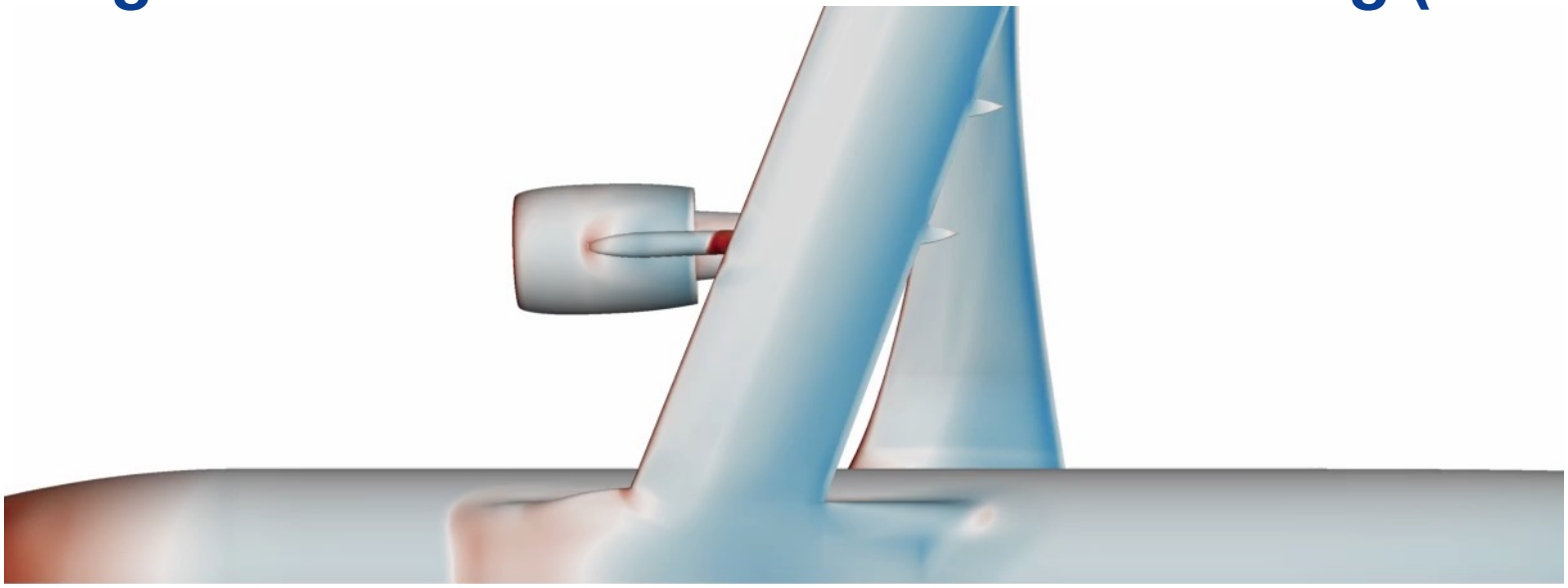
High-Speed CRM Buffet Mechanism(s)







Physics-Based Unsteady RANS Method for Buffet Onset Prediction Applied to the Boeing SUGAR Transonic Truss Braced Wing (TTBW)



Introduction to the Boeing Phase V TTBW Geometry



Features:
- High aspect ratio
- Large span
- High L/D
- Strut braced wing

Conditions
- Mach = 0.8
- Re_{MAC} = 5.18 million

LAVA Related Publications

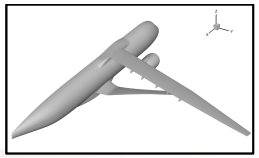
Maldonado *et al* AIAA-2020-1649

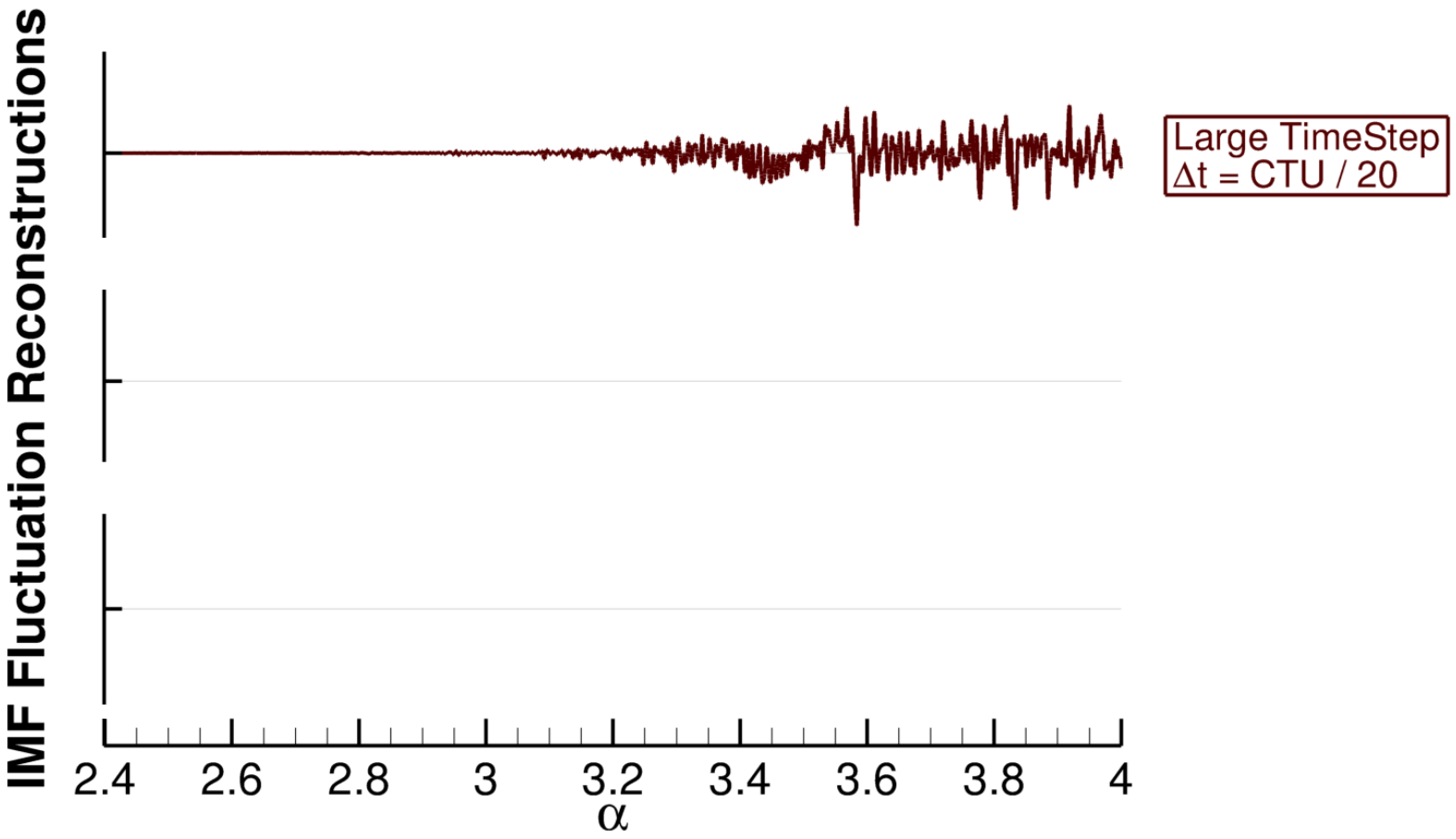
Maldonado *et al* AIAA-2021-1531

Browne *et al* JAIR (accepted)

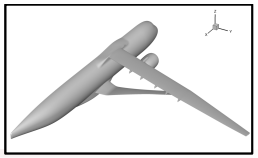
Maldonado *et al* AIAA-2024-3639

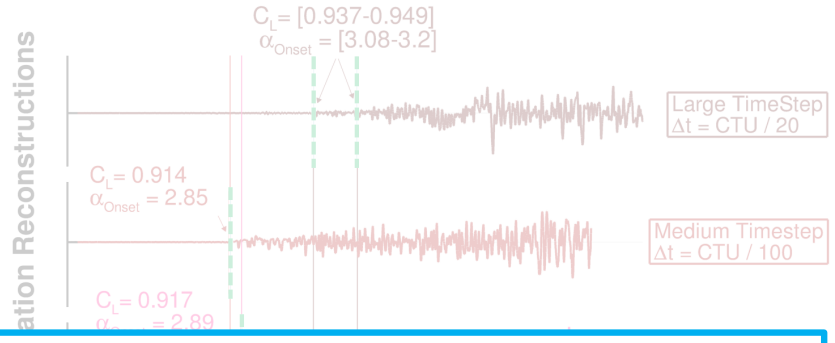
Time Step




IMF Fluctuation Reconstructions
Large TimeStep
Δt = CTU / 20
2.4
2.6
2.8
3
3.2
3.4
3.6
3.8
4
α

Time Step

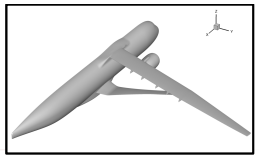


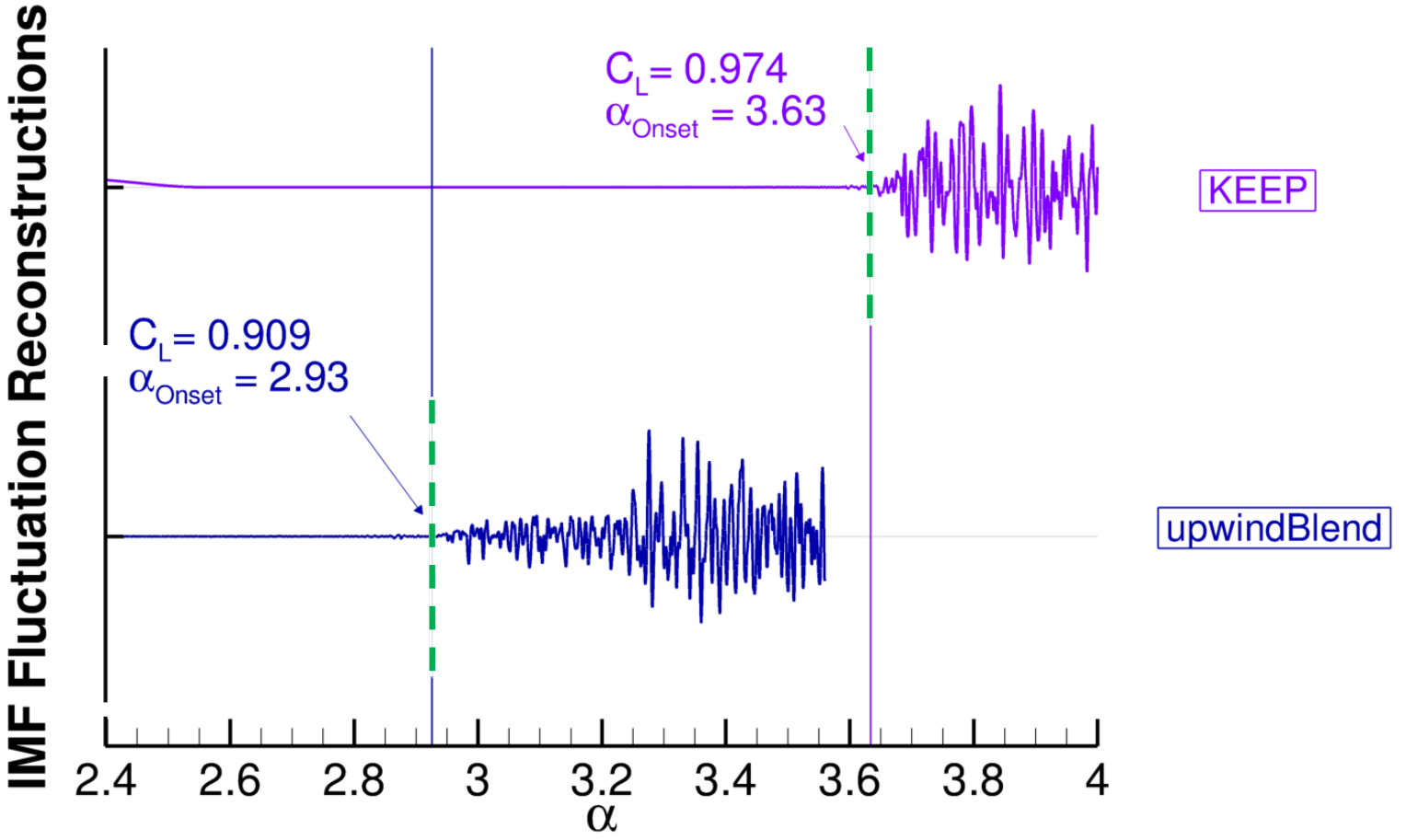


Use a timestep of CTU/100

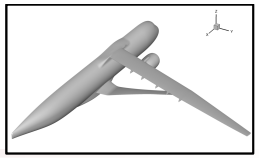
Color	Ti		$C_{L\ onset}$
	CT		0.937-0.949
	CTU / 100	2.85	0.914
	CTU / 200	2.89	0.916
	Difference Between CTU/100 vs CTU/200	1.4%	0.2%

Convective Flux Discretization





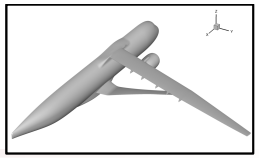
Convective Flux Discretization

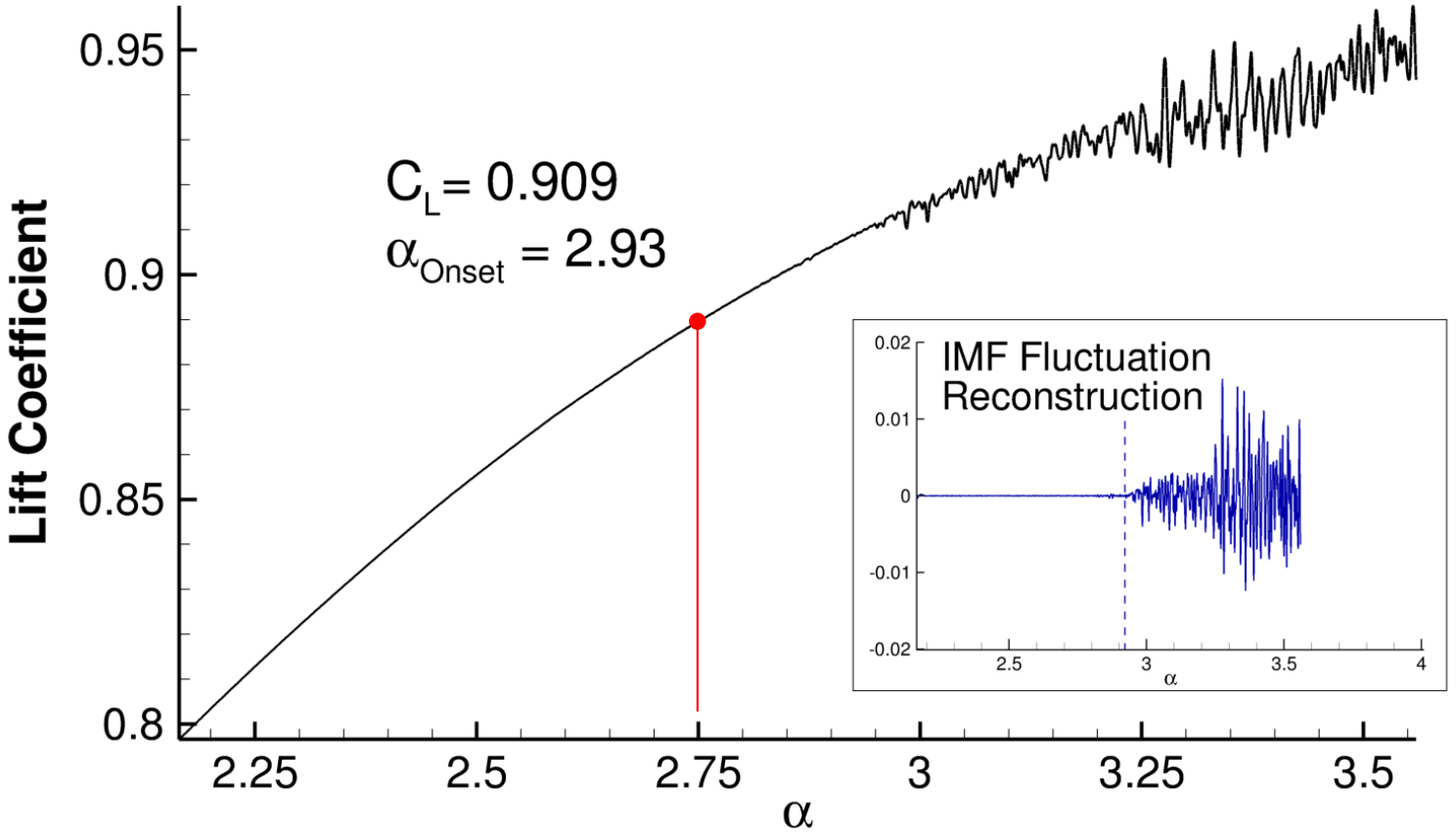


Use a low dissipation scheme that is numerically stable and able to capture physical instabilities

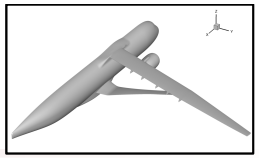
Color	Convective Flux Discretization	α_{onset}	$C_{L\ onset}$
	KEEP	3.63	0.974
	upwindBlend	2.93	0.909
	Difference	19.3%	6.6%

Continuous Pitch Initialization Angle





Continuous Pitch Initialization Angle



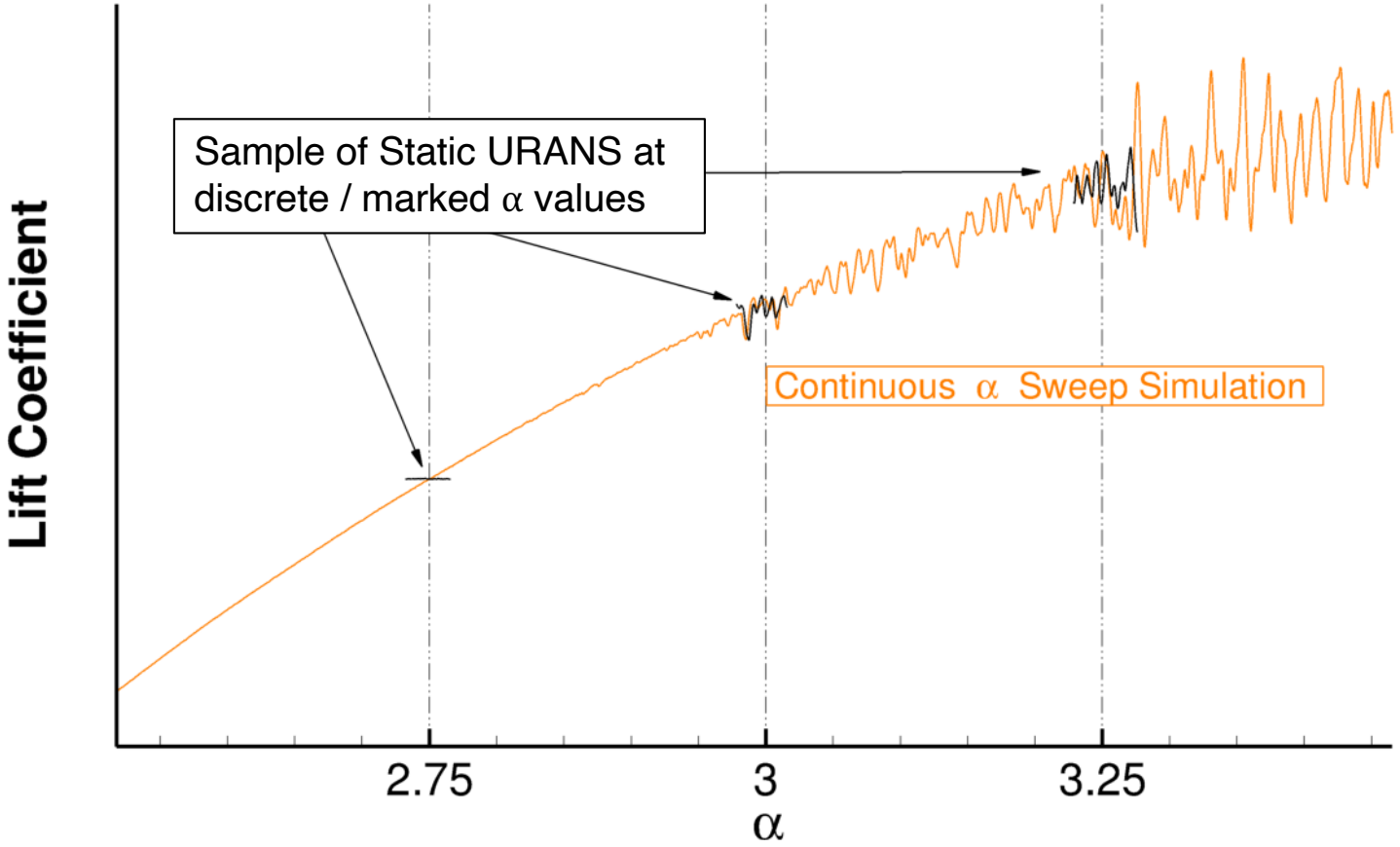
Use an initial alpha as close to buffet onset as possible

Color	Initialization α	α_{onset}	$C_{L\ onset}$
	2.0°	2.93	0.909
	2.75°	2.97	0.913
	Difference	1.4%	0.4%

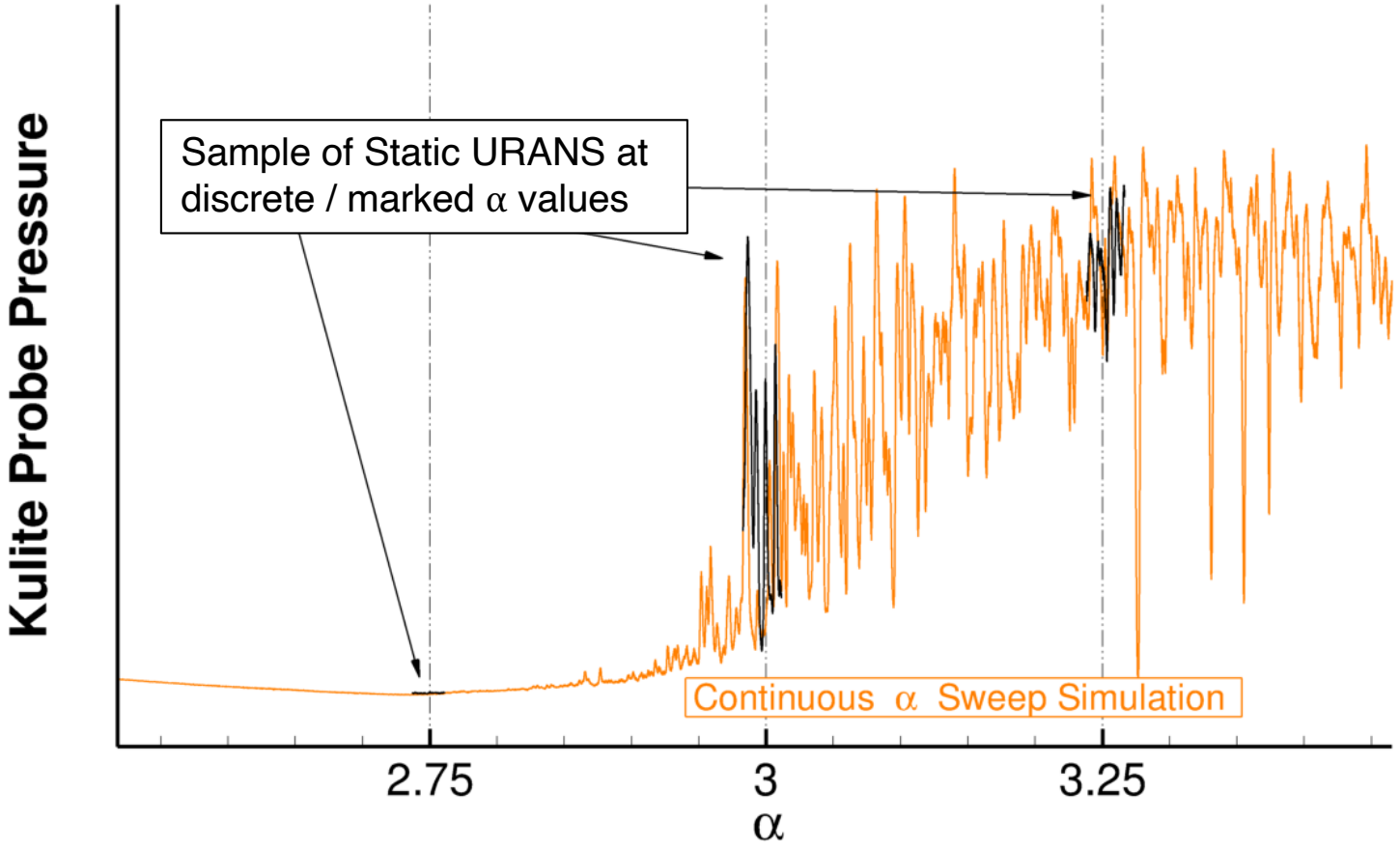


Verification and Validation

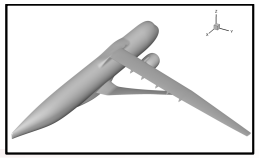
Continuous Pitch is Representative of Static URANS at discrete angles of attack.



Continuous Pitch is Representative of Static URANS at discrete angles of attack.



Validation



Simulations

Simulation Method	Buffet Extraction Method	$C_{L\ onset}$
Continuous Pitch URANS	Empirical Mode Decomposition	0.913
HRLES (Browne *et al.*)	Kulites	0.925

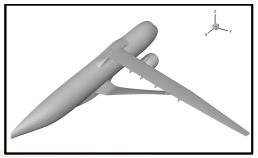
Experiment

Buffet Extraction Method	$C_{L\ onset}$
Pitch Break	0.76
Trailing Edge Divergence	0.89
Accelerometer	0.936-0.999
Strain Gauge RMS	0.96-0.98
Kulites	0.99
Axial Force Offset	1.02



Cost Analysis

Cost Breakdown



Actual cost for each step of the method

Step	Run	Node Type	Cost (CPU-hours)
1	Steady-State RANS	AMD Rome	575
2	Start-Up URANS	AMD Rome	156.7k
3	Continuous Pitch (1 Degree)	AMD Rome	853.4k
4	URANS for Verification / Run	AMD Rome	622.1k

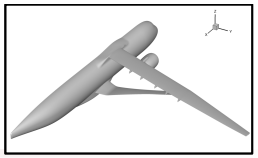
Continuous Pitch URANS becomes cost efficient vs start-up URANS:

When desired precision of buffet onset of 0.2-degrees or less is desired.

Continuous Pitch URANS is of same order cost as full static URANS:

Since continuous pitch data is representative of URANS at any discrete angle it is potentially more beneficial.

Cost Breakdown (Continued)



Application of RANS-Based Method:

Each experimental angle of attack was run using static RANS before applying empirical methods and doing flow and convergence analysis to determine buffet onset.

Application of Static URANS-Based Method:

Starting at an angle near cruise run URANS simulations increasing angle of attack (stepping by 0.5 degrees) until buffet like behavior is observed. Then iteratively converge at the angle at which onset occurs.

Cost of Previous Buffet Onset Prediction Methods

Buffet Prediction Method	Number of Runs	Cost (CPU-hours)
RANS-Based Method	33	19.0 k
Static URANS-Based Method	9	2336.4k
Continuous Pitch URANS	1	1437.3K



Conclusion, Current Best Practices, Ongoing Work, and Future Work

Concluding Remarks



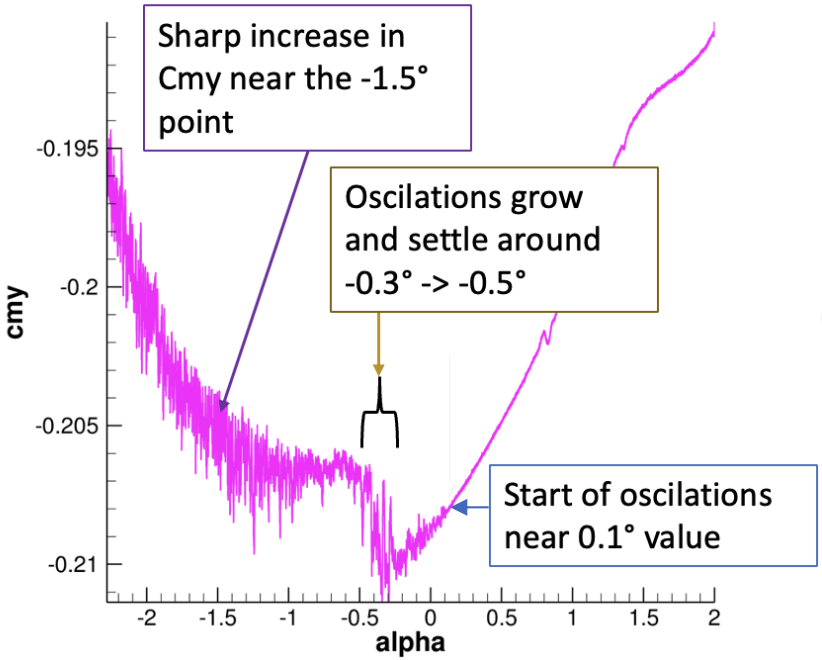
The method was verified and validated for several configurations against experiments and other methods. Sensitivities were observed.

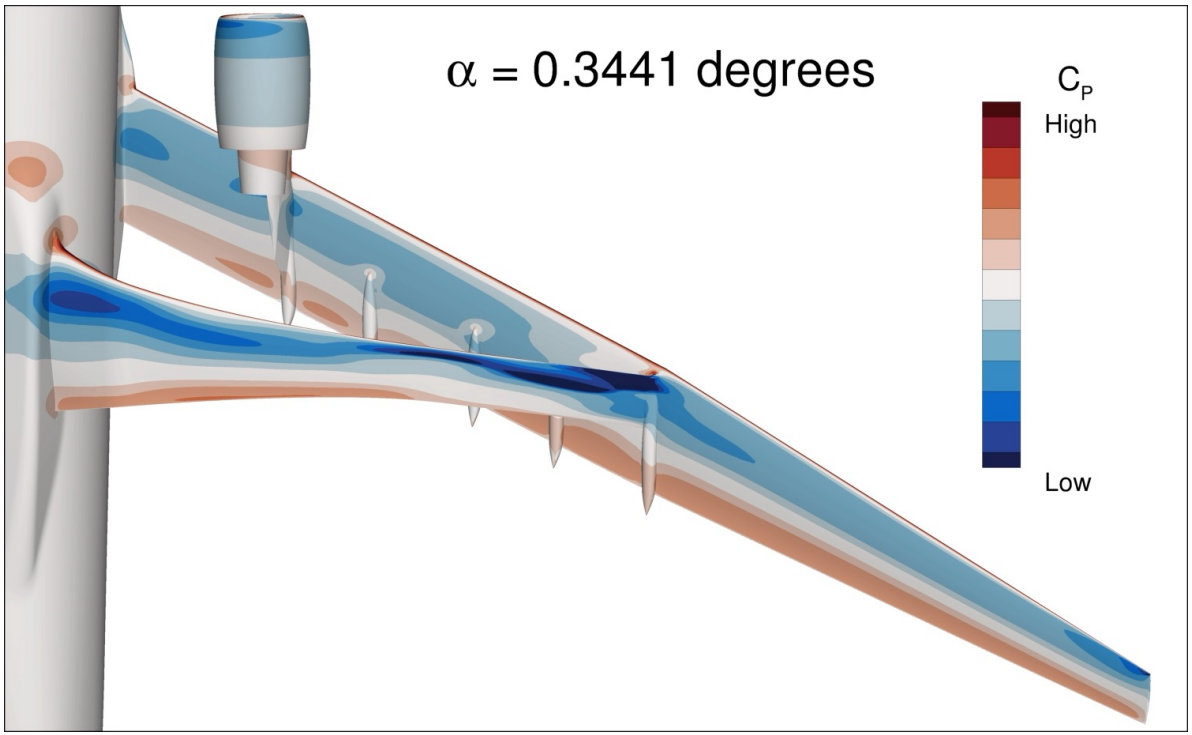
- Suggestions Based on Sensitivities
  - Suggested pitch rate: U_∞ /(1000c)
  - Refine wing mesh to resolve shear layer mode waves
  - Suggested time-step: CTU/100
  - Use a stable low dissipation convective flux scheme that does not suppress physical instabilities
  - Initialize continuous pitch at an angle close & prior to buffet onset.

- The method is cost efficient compared to URANS based methods.

Ongoing Work with Reverse Continuous Pitch

For the reverse continuous pitch run, we start with 2 degrees and decrease angle of attack at the same rate and timestep found as best practice.





Other Ongoing and Future Work



- The method is currently being explored for the AIAA Drag Prediction Workshop 8
  - Validation data has been made available by JAXA for the CRM Wing-Body-Tail configuration at a lower Reynolds number

- Further characterization of the method's sensitivities and maturation of the best practices
- Utilization of spectrogram analysis to remove step 4
- Application of EMD to unsteady surface and volume data
- Extension of the method to hybrid RANS/LES and WMLES simulations

Acknowledgements

- Funding: Advanced Air Transport Technology (AATT) and Transformational Tools & Technologies Projects (T^3) under NASA Aeronautics Research Mission Directorate.

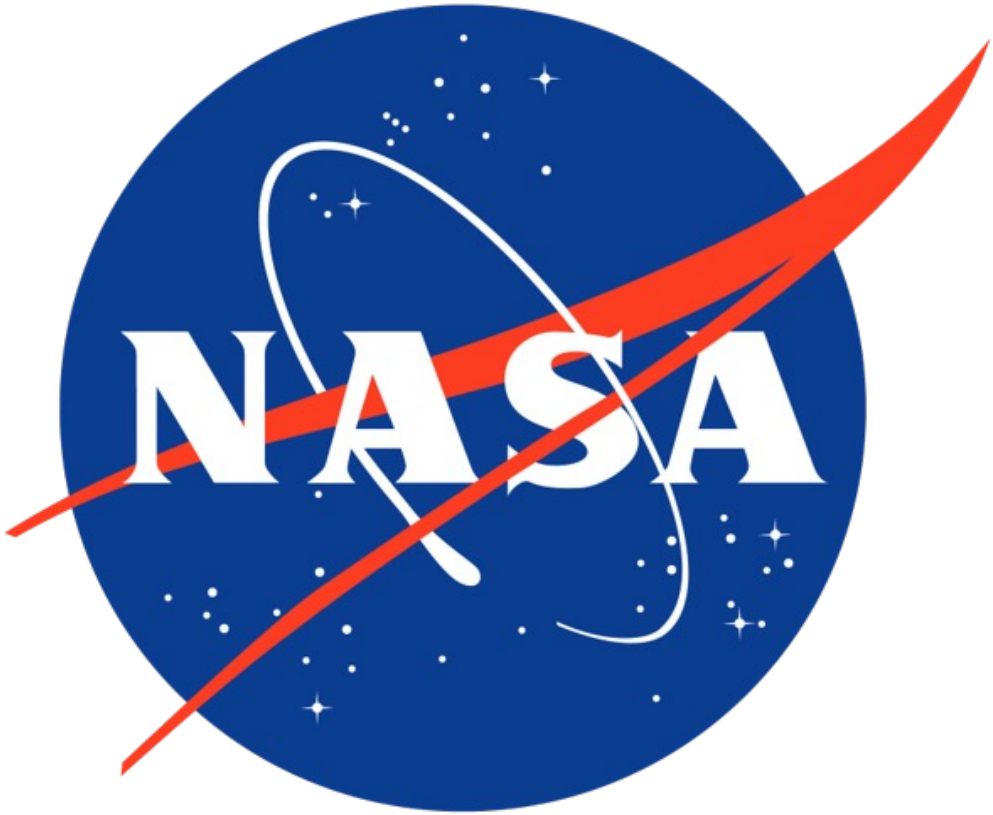
- Computer resources were provided by the NASA Advanced Supercomputing facility, under the HECC Project.

- Contributions from: Oliver Browne for his insights and making experimental data more accessible.

- Internal Reviewers: Luis D. Fernandes, David C. Penner, William M. Chan, Chase P. Ashby, Leonardo M. Machado, and Brandon Lowe.

- Boeing Team for guidance and research provided.

- Technical Point of Contact: Greg Gatlin for TTBW experimental unsteady data



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