
Gulfstream™

# DPW-8 URANS BUFFET PREDICTION

Joel St. Onge | 06.02.2026

# OVERVIEW

- Working Group 3 (Buffet) Test Case 1 RANS and URANS results
    - ONERA-OAT15A airfoil
- HeldenMesh, FUN3D, SA variants
- Contents
    - Experimental Backing
    - Gridding Strategy
    - Timestep Determination
    - Test Case 1A: RANS Results/Discussion
    - Test Case 1B: URANS Results/Discussion
    - Conclusions



Gulfstream®


# TEST CASE 1



Gulfstream®

# EXPERIMENTAL BUFFET

- Buffet frequency = ~70 Hz
- Kulite sampling at 10240 Hz, low-pass filtered at 4096 Hz
- Buffet onset occurs at 3.10°, paper focuses on 3.50°
- Shock oscillation observed across "nearly 20% of the chord"

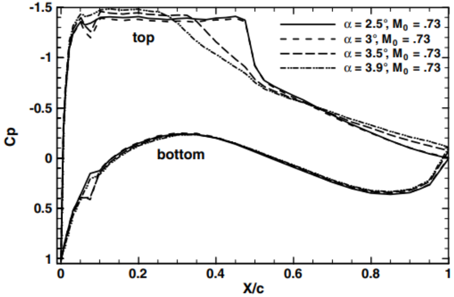


Fig. 7 Mean surface pressure coefficient.

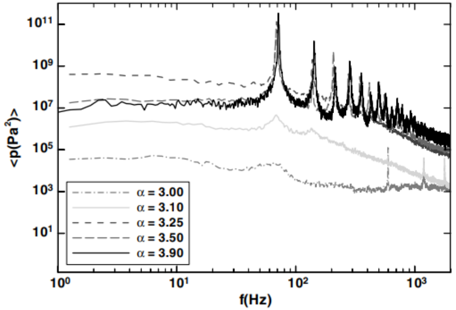


Fig. 10 Influence of incidence on the pressure power spectrum at $X/c = 0.45$ (Kulite no. 7). Upstream Mach number $M_0 = 0.73$.

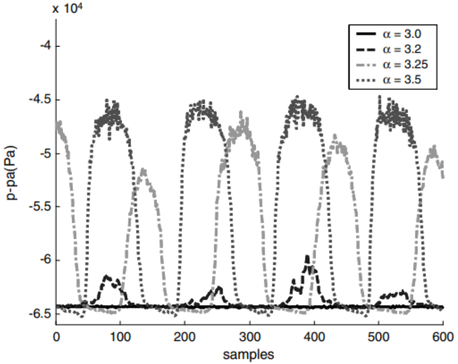


Fig. 8 Time variation of surface pressure signals at $X/c = 0.45$ (Kulite no 7, see Fig. 2b). Upstream Mach number $M_0 = 0.73$.

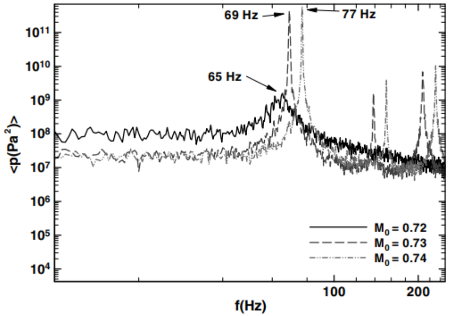


Fig. 11 Influence of Mach number on the pressure power spectrum at $X/c = 0.45$ (Kulite no. 7). Incidence $\alpha = 3.5$ deg.

Jacquin, L., et al. "Experimental Study of Shock Oscillation over a transonic supercritical profile." *AIAA Journal*, vol. 47, no. 9, Sept. 2009, pp. 1985–1994, https://doi.org/10.2514/1.30190.



Gulfstream

# TEST CASE 1 GRIDS

# GRIDDING STRATEGY

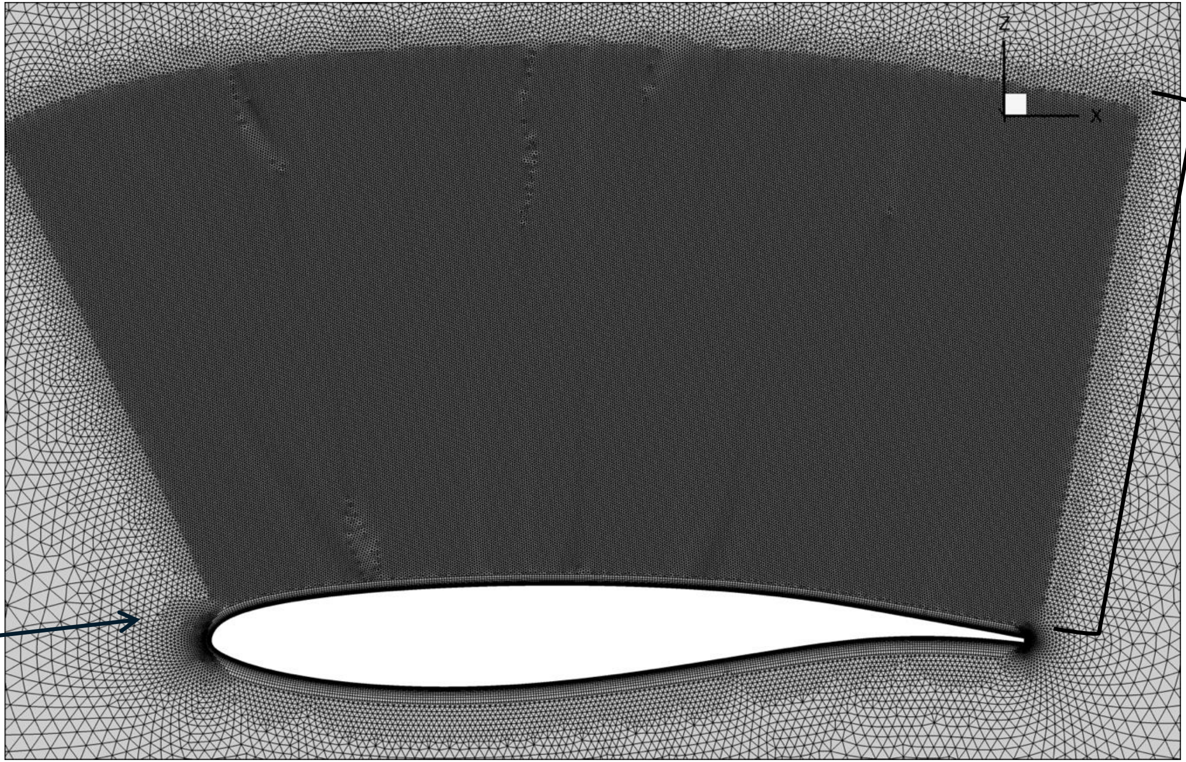
- Custom grids created using HeldenMesh 4.16
- ONERA-OAT15A airfoil at tunnel scale (230 mm) extruded 1 mm
    - FUN3D struggled to run unsteady cases in 2D mode with Helden Quasi-2D mesh (one-cell extruded mesh). This also factored into choosing to create custom meshes instead of using committee grids
- 6 grid levels created using REFINE_FAC (Global source refinement)
- LAYER_H1 = 0.001862, ARATE (Geometric Growth Rate) = 0.150, BRATE (Exponential Growth Rate) = 0.010
- Targeting mesh Y+ of 1.0 at 50% MAC

# MESH PARAMETERS

| Test Case | Refinement Level | Number of Cells (Mixed Element) | Number of Nodes | First Layer Height (mm) | Geometric Growth Rate | Exponential Growth Rate |
|---|---|---|---|---|---|---|
| 1 | L1 | 125,030 | 54,958 | 0.001862 | 15% | 1% |
| 1 | L2 | 225,194 | 93,420 | 0.001862 | 15% | 1% |
| 1 | L3 | 1,295,983 | 382,871 | 0.001862 | 15% | 1% |
| 1 | L4 | 4,455,116 | 1,110,256 | 0.001862 | 15% | 1% |
| 1 | L5 | 17,656,651 | 3,859,611 | 0.001862 | 15% | 1% |
| 1 | L6 | 65,559,441 | 13,133,205 | 0.001862 | 15% | 1% |

# GAC LEVEL 3

2D spanwise cut




Broken-out LE patches to avoid extra radial sourcing

Max mesh length scale on the upper airfoil surface was held constant out to a radius of 150 grid units (mm)



Gulfstream®

# TEST CASE 1A: STEADY (RANS)

# SOLVER PARAMETERS IN USE

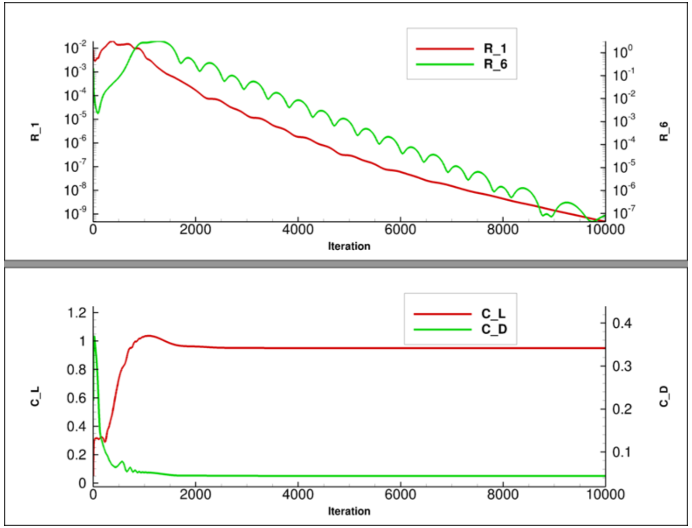
- FUN3D v14.2
  - Finite Volume, unstructured, information stored at nodes
  - Full Navier-Stokes, all cross terms
  - Fully Turbulent, no tripping applied
  - Perfect gas model
  - Time Integration
    - Steady-states RANS
    - $2^{nd}$ Order URANS (Test Case 1B)
  - Roe's Flux Difference Splitting
  - No Flux Limiters used
  - Spalart-Allmaras Turbulence model
    - Negative (SA-NEG), Quadratic Constitutive Relation 2000 (QCR2000), and Modified SSZ (mixing layer compressibility correction) for Test Case 1A
    - Rotation and Modified SSZ corrections for Test Case 1B
    - SSZ refers to the correction researched by Shur, Strelets, and Zaikov (see reference) and referenced by Spalart

Shur, M., et al. "Comparative Numerical Testing of One- and Two-Equation Turbulence Models for Flows with Separation and Reattachment," AIAA 95-0863, January 1995, https://doi.org/10.2514/6.1995-863.

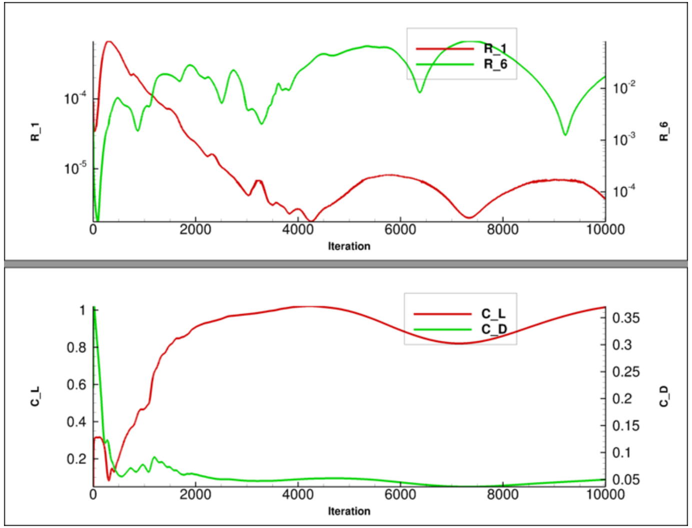


Gulfstream

# RESIDUALS AT BUFFET (AOA 3.50°) RANS




Grid Level 1



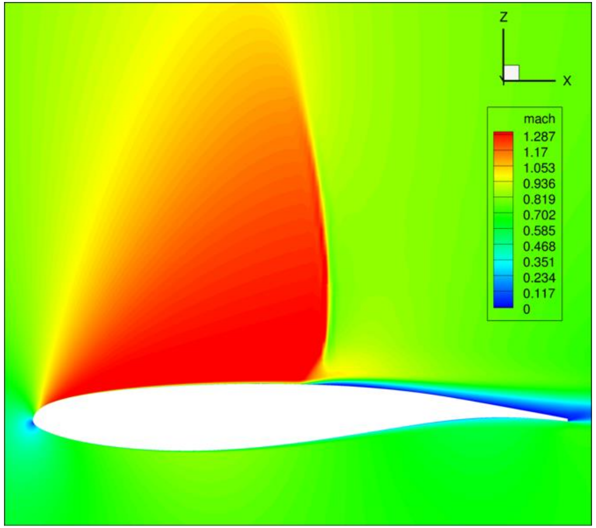

Grid Level 6

RANS converges to a steady-state solution at lower grid levels. L5 was the first grid to fail to converge.

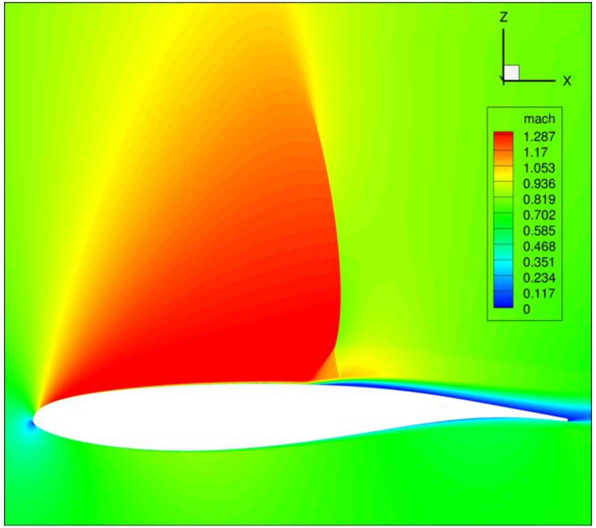


Gulfstream

# GRID REFINEMENT EFFECT ON SHOCK RESOLUTION (AOA 3.50°), RANS




Grid Level 1



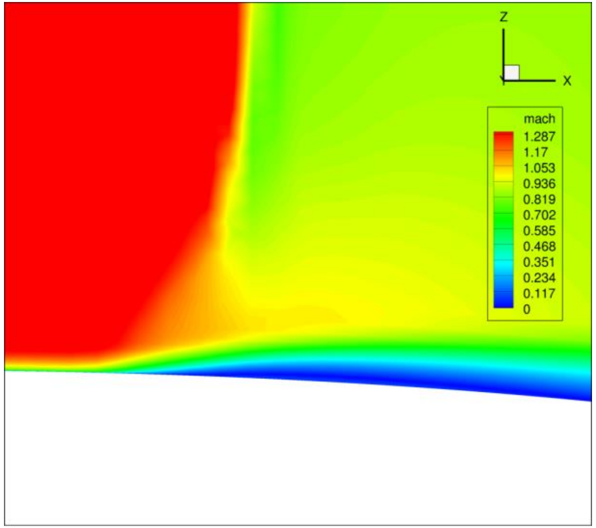

Grid Level 6

RANS Steady-state solution

Mid-span 2D section cut

More resolved lambda shock at Grid Level 6. Post-shock separation is slightly stronger with more refinement.

# GRID REFINEMENT EFFECT ON SHOCK RESOLUTION (AOA 3.50°), RANS

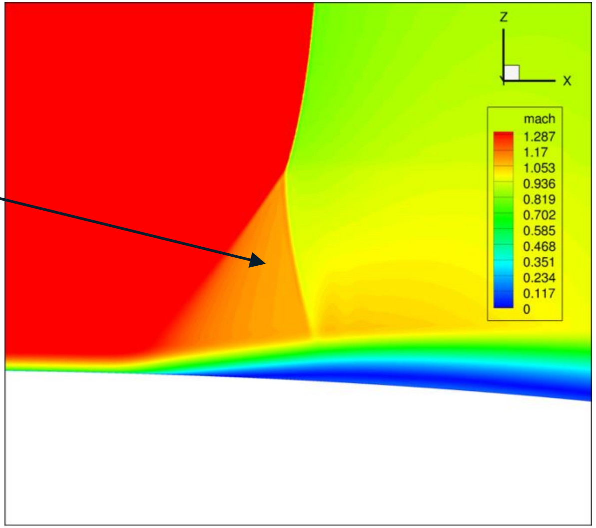



Grid Level 1

Crisper shock definition with more refined grid

RANS Steady-state solution

Mid-span 2D section cut




Grid Level 6

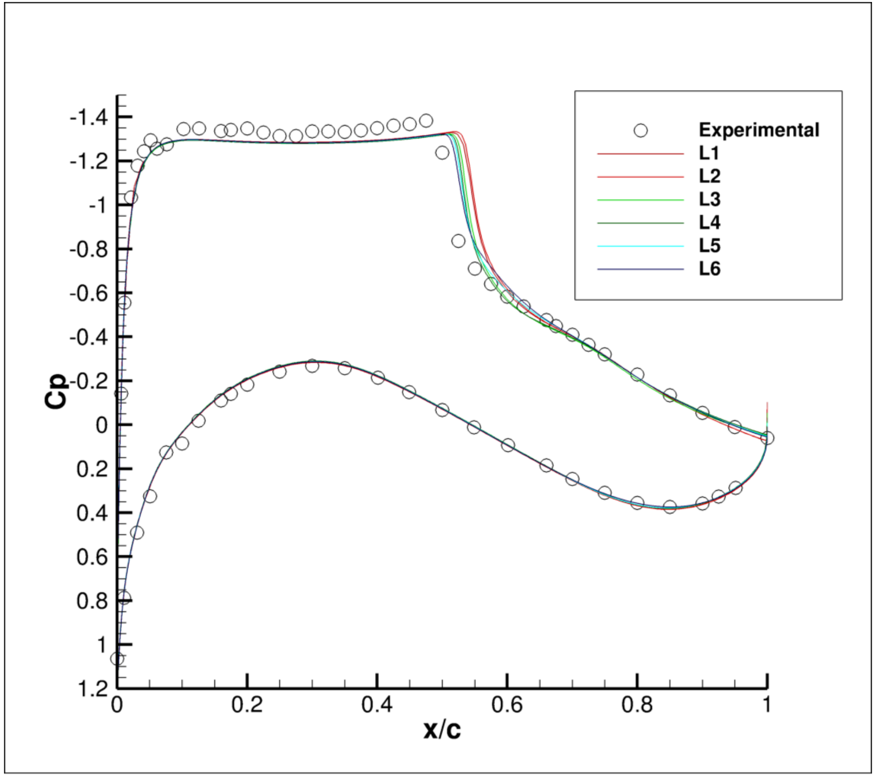
More resolved lambda shock at Grid Level 6. Post-shock separation is slightly stronger with more refinement.



Gulfstream

# MACH 0.73, ALPHA 2.50 (RANS)

RANS matches tunnel results well at all grid levels prior to buffet onset




- SA-NEG
- QCR2000

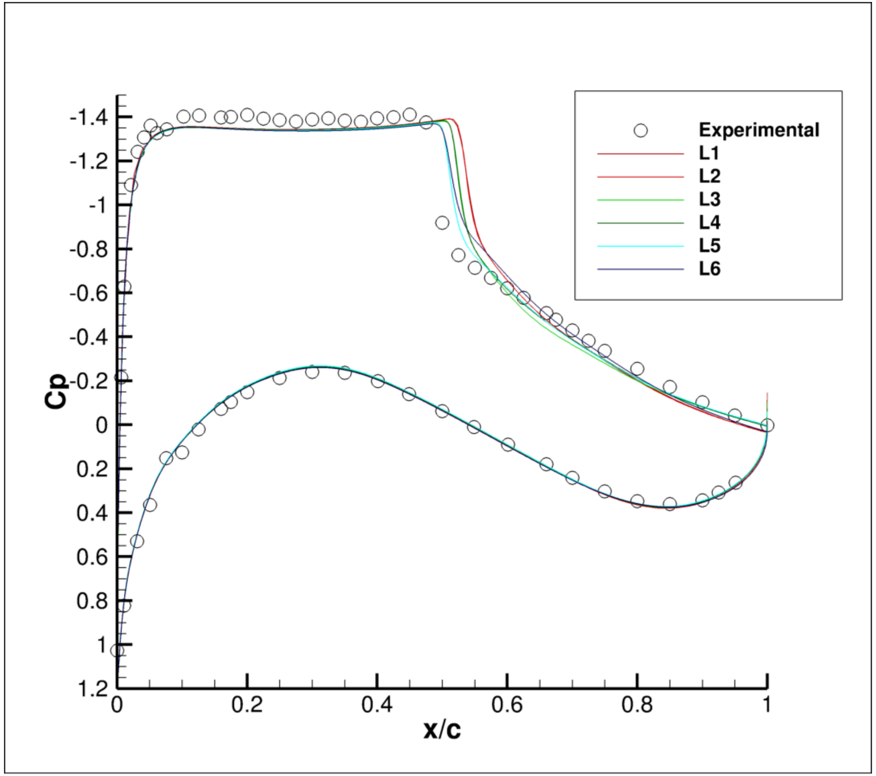
RANS Steady-state solution



Gulfstream

# MACH 0.73, ALPHA 3.00 (RANS)

RANS matches tunnel results well at all grid levels prior to buffet onset




- SA-NEG
- QCR2000

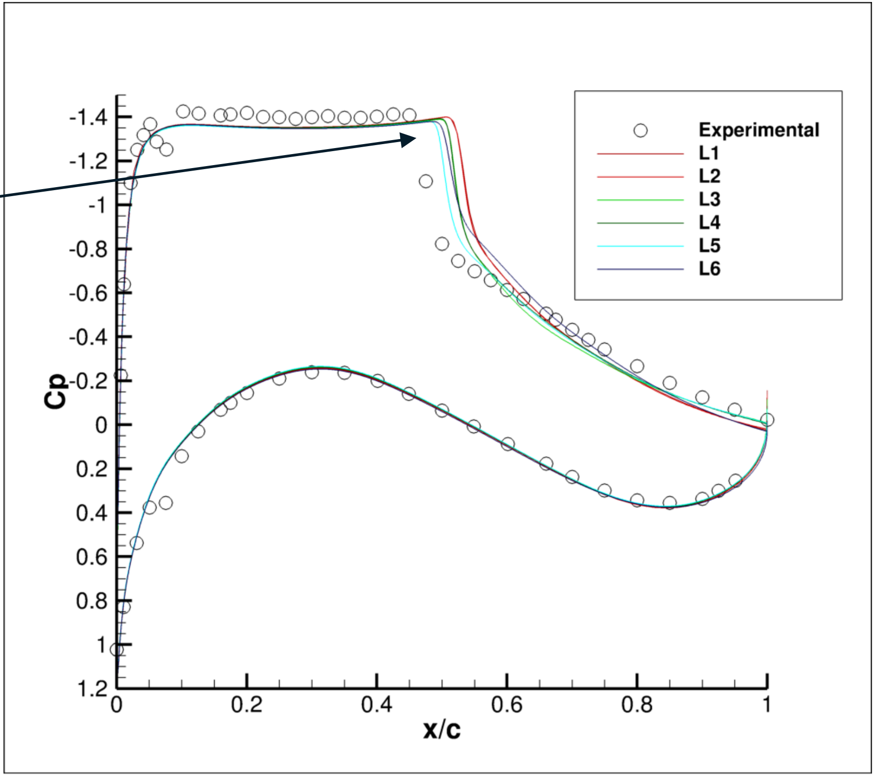
RANS Steady-state solution



Gulfstream

# MACH 0.73, ALPHA 3.10 (RANS)

As buffet begins to set in, RANS holds shock position while tunnel shock position begins to oscillate




- SA-NEG
- QCR2000

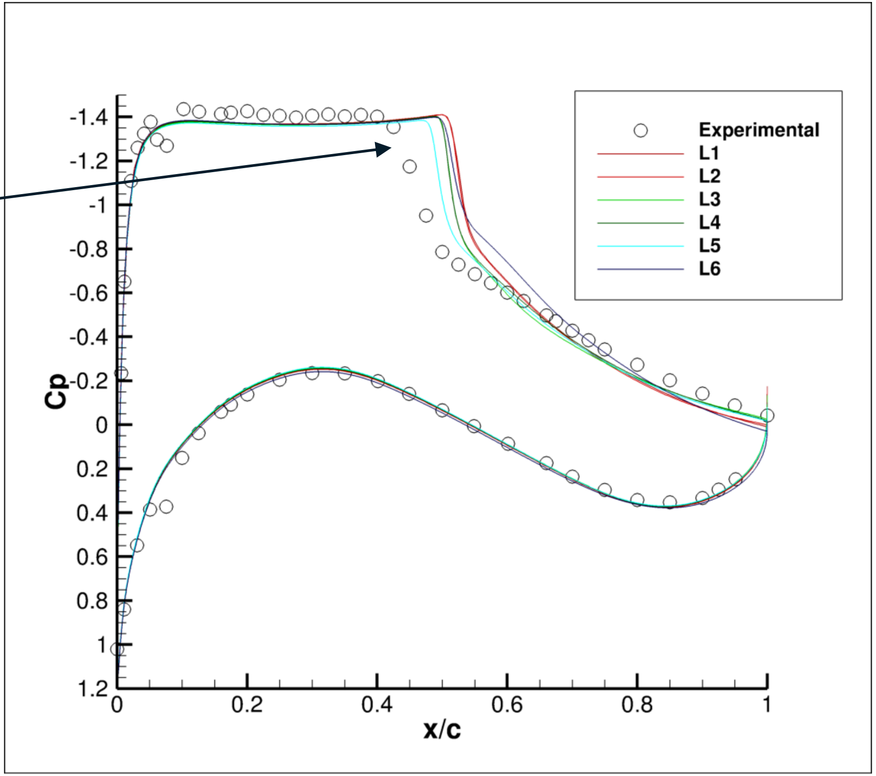
RANS Steady-state solution



Gulfstream

# MACH 0.73, ALPHA 3.25 (RANS)

As buffet begins to set in, RANS holds shock position while tunnel shock position begins to oscillate




- SA-NEG
- QCR2000

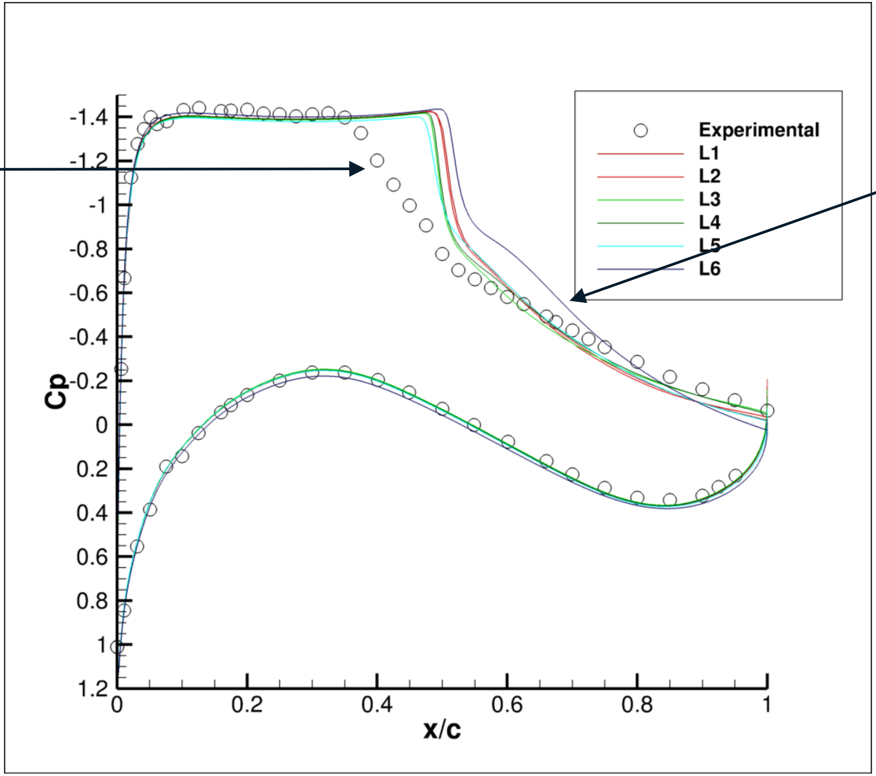
RANS Steady-state solution



Gulfstream

# MACH 0.73, ALPHA 3.50 (RANS)

Tunnel values well into buffet, RANS holding shock position




Post-shock separation strengthening with grid refinement

- SA-NEG
- QCR2000

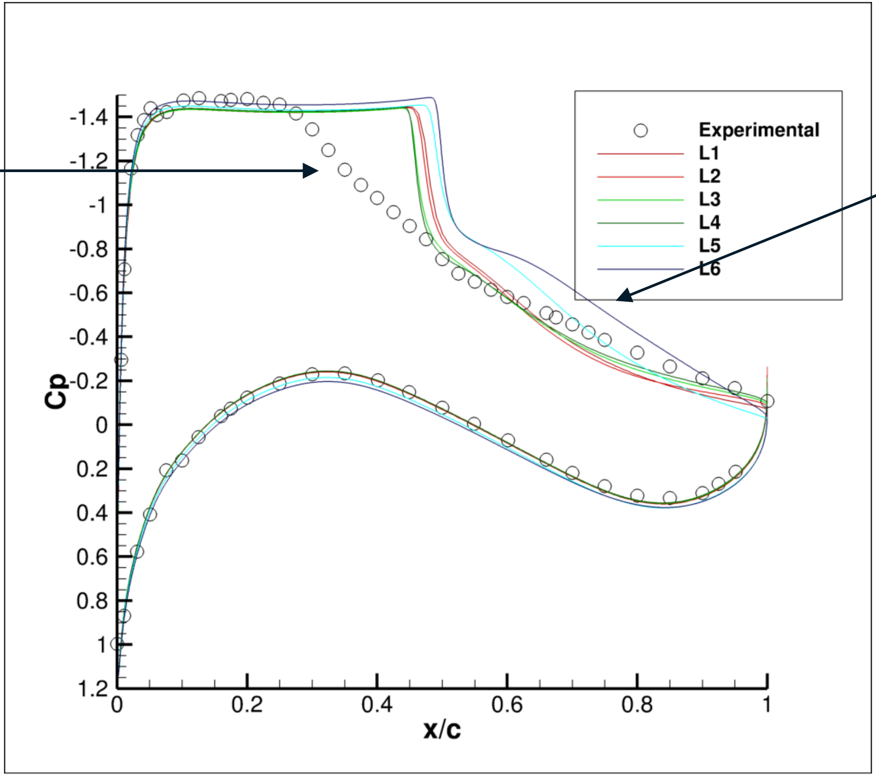
RANS Steady-state solution



Gulfstream

# MACH 0.73, ALPHA 3.90 (RANS)

Tunnel values well into buffet, RANS holding shock position




Post-shock separation strengthening with grid refinement

- SA-NEG
- QCR2000

RANS Steady-state solution



Gulfstream

# TEST CASE 1B: UNSTEADY



Gulfstream®

# UNSTEADY CFD APPROACHES

- Two approaches: URANS and DDES
- URANS
  - SA-RC, 'ssz' correction, QCR2000
  - time_accuracy = '2ndorderOPT'
  - Subiterations set to 30 initially, dropped to 15-20 depending on convergence
  - CFL = 20, CFL Turb = 10
- DDES
  - SA
  - Subiterations set to 50 for convergence
- Both approaches used seeding from Test Case 1A steady solutions. Solutions run for 2000 timesteps initially before time-averaging.
- **Only URANS submitted to workshop, more exploration needed for DDES to determine proper settings/grid**

# NON-DIMENSIONAL TIMESTEP

- Targeting lift oscillation frequency of 70 Hz
- $t^*_{chr} = \frac{1}{f} = \frac{1}{70\ Hz} = 0.014286\ s$
- Length scales are the same between CFD and experiment, $\left(\frac{L_{ref}}{L^*_{ref}}\right) = 1,\ a^*_{ref} = 329{,}924\ \frac{mm}{s}$ for given conditions
- For N = 100 samples/CTU, non-dimensional $\Delta t = 47.132$



Gulfstream®

# ADDITIONAL PARAMETER VS STEADY

- Original URANS and DDES results had difficulty matching tunnel results in buffet
- URANS trended towards a RANS-like solution while DDES predicted strong shock and post-shock separation
- Based on research, a variety of limiters and SA turbulence model parameters were tested for URANS
  - Barth, heuristic MINMOD, limiters
  - SA-RC (Rotational correction)
  - SA compressibility correction proposed by Spalart in “Trends in Turbulence Treatments” (designated “CC”)
- Final URANS results run with SA-RC and ‘ssz’ correction, without limiters

Spalart, Philippe. “Trends in turbulence treatments.” *Fluids 2000 Conference and Exhibit*, 19 June 2000, https://doi.org/10.2514/6.2000-2306.

Balakumar, Ponnampalam, et al. “Turbulence simulations of transonic flows over an NACA-0012 airfoil (invited).” *AIAA SCITECH 2023 Forum*, 19 Jan. 2023, https://doi.org/10.2514/6.2023-0254.

Shur, M., et al. "Comparative Numerical Testing of One- and Two-Equation Turbulence Models for Flows with Separation and Reattachment," AIAA 95-0863, January 1995, https://doi.org/10.2514/6.1995-863.

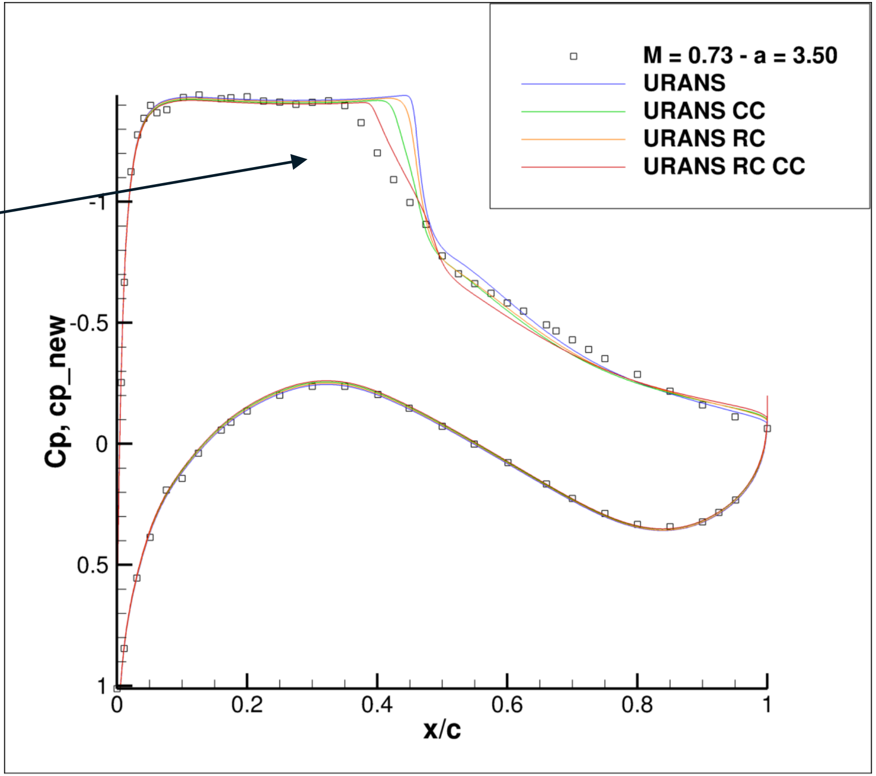
# URANS RESULTS (AVERAGED)

# ISOLATED PARAMETER STUDIES

- Original URANS and DDES results had difficulty matching tunnel results in buffet
- URANS trended towards a RANS-like solution while DDES predicted strong shock and post-shock separation
- Based on research, a variety of limiters and SA turbulence model parameters were tested for URANS and DDES
    - Barth, heuristic MINMOD, limiters
    - SA-RC (Rotational correction)
    - SA compressibility correction proposed by Spalart in “Trends in Turbulence Treatments” (designated “CC”)
- DDES exhibits small sensitivity to kappa_umuscl, but results still being investigated
- DDES showed sensitivity to grid span, but results still being investigated
- All testing performed for Alpha 3.50°
- **Note: Isolated studies were performed on different grids than submitted grids. These grids are of similar construction.**

# SA-RC AND CC, URANS

Using both the RC and compressibility corrections results in URANS best capturing shock position and oscillation




10 grid unit span
L4.5 refinement

Grids different than submitted, but consistent in plot

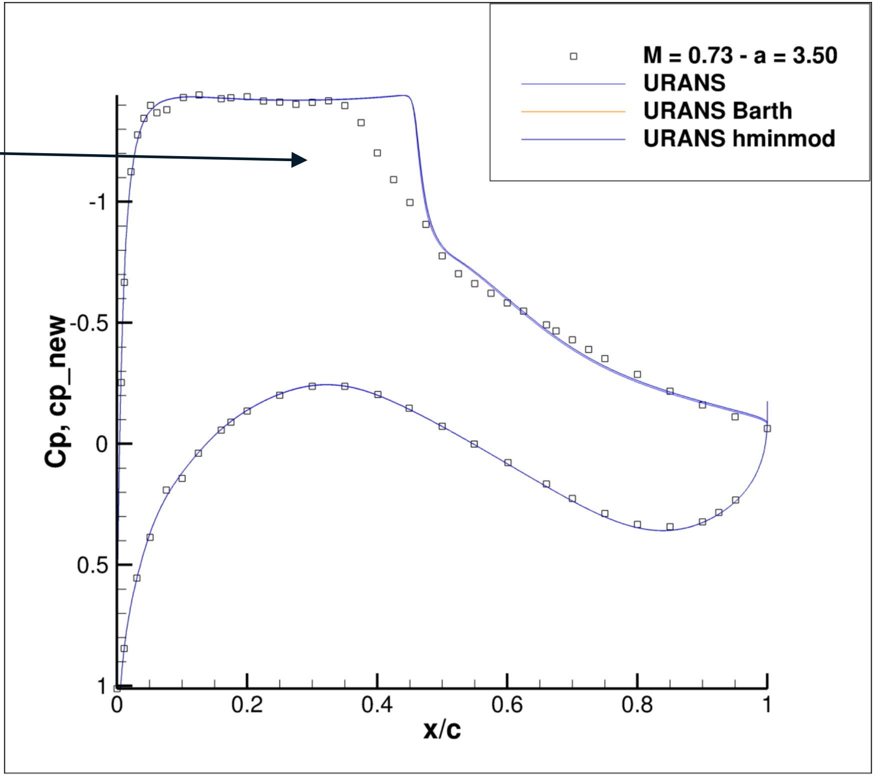
URANS Time-averaged solution



Gulfstream

# LIMITERS, URANS

Negligible change with selected limiters




10 grid unit span
L4.5 refinement

Grids different than submitted, but consistent in plot

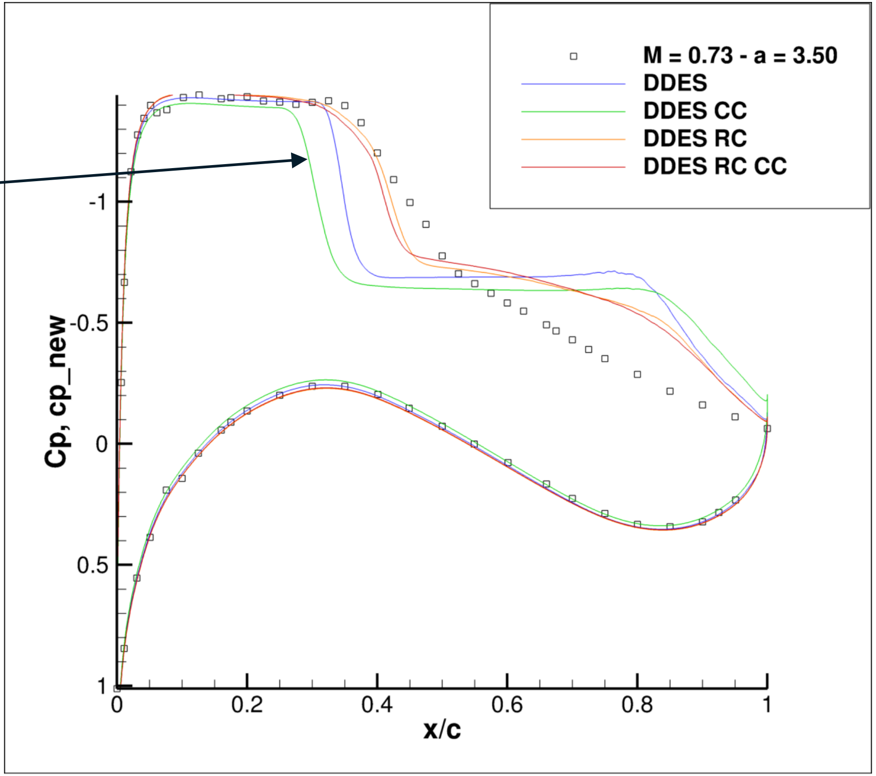
URANS Time-averaged solution



Gulfstream

# SA-RC AND CC, DDES

DDES predictions of shock shape and post-shock separation improve with RC corrections




10 grid unit span
L4.5 refinement

Grids different than submitted, but consistent in plot

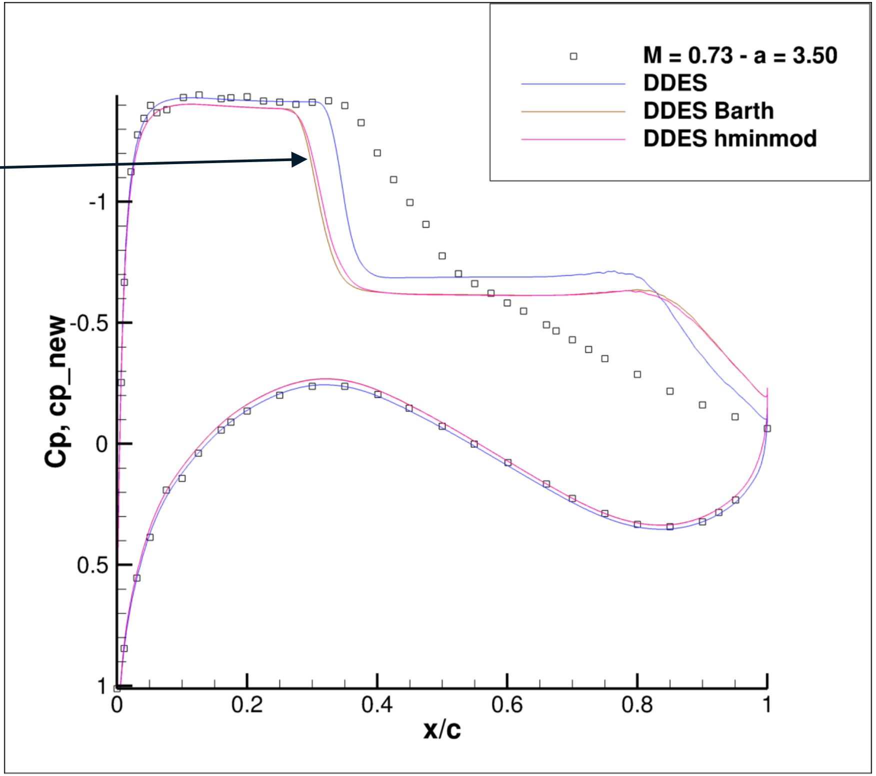
DDES Time-averaged solution



Gulfstream

# LIMITERS, DDES

Application of limiters worsens shock location prediction for DDES




10 grid unit span
L4.5 refinement

Grids different than submitted, but consistent in plot

DDES Time-averaged solution



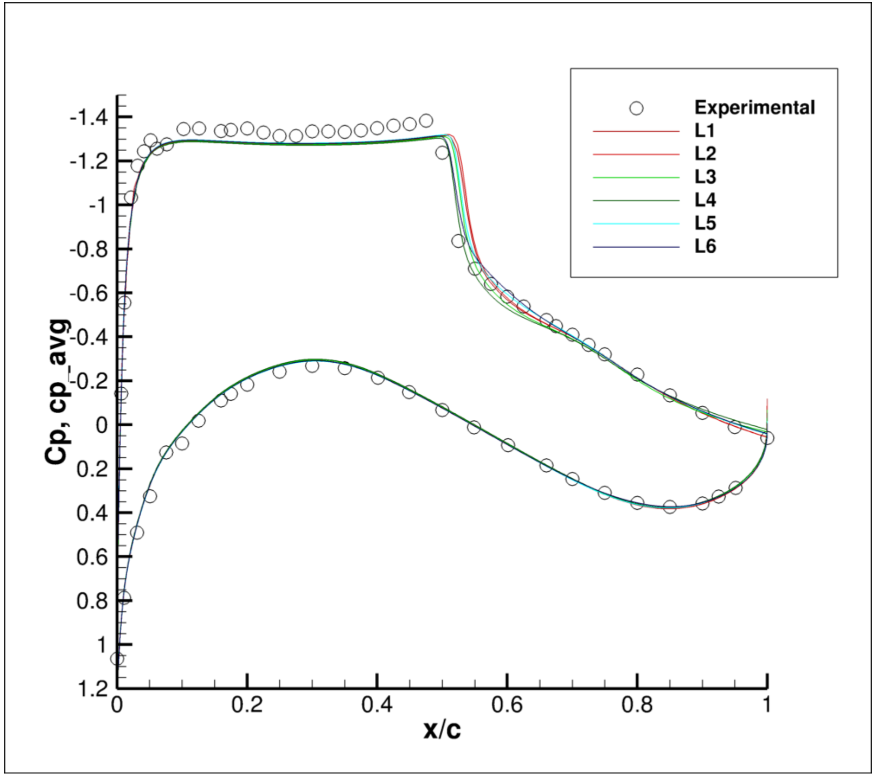
Gulfstream

# MACH 0.73, ALPHA 2.50 (URANS)

URANS results very similar to RANS at low alphas

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution

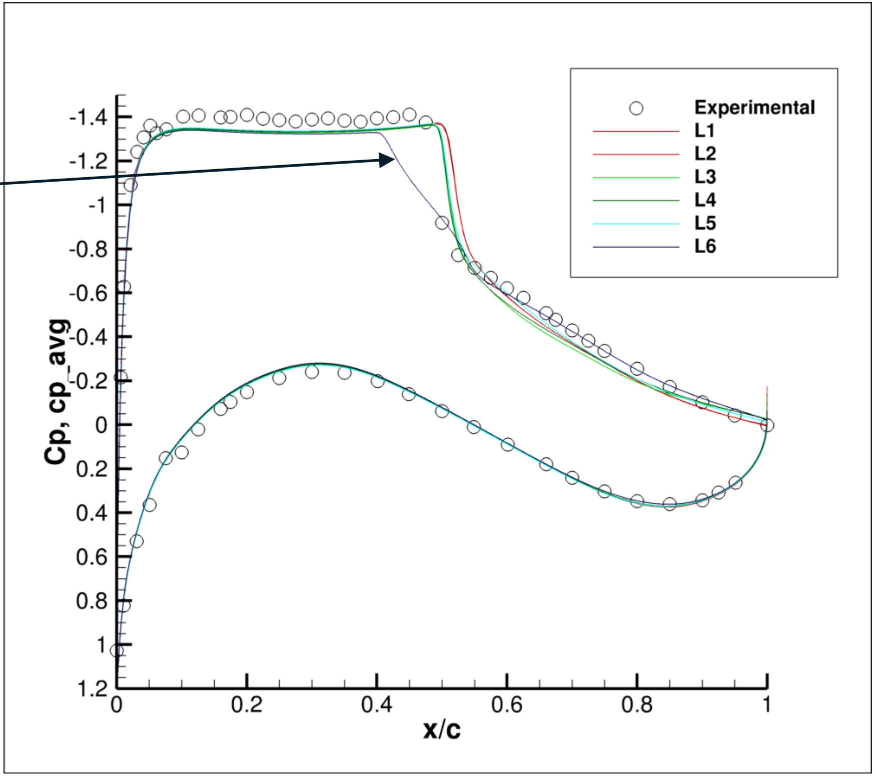





Gulfstream

# MACH 0.73, ALPHA 3.00 (URANS)

Highest grid level shows movement of shock just prior to experimental buffet onset




URANS requires significant levels of grid refinement to capture unsteadiness

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution



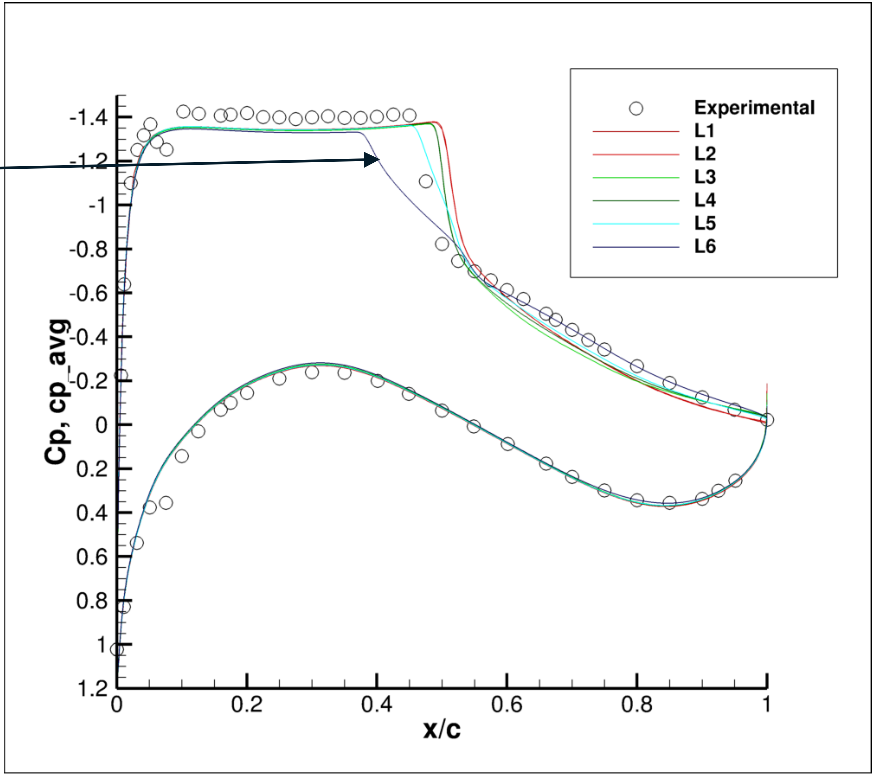
Gulfstream

# MACH 0.73, ALPHA 3.10 (URANS)

Finest grid level shows larger movement of shock at buffet onset

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution

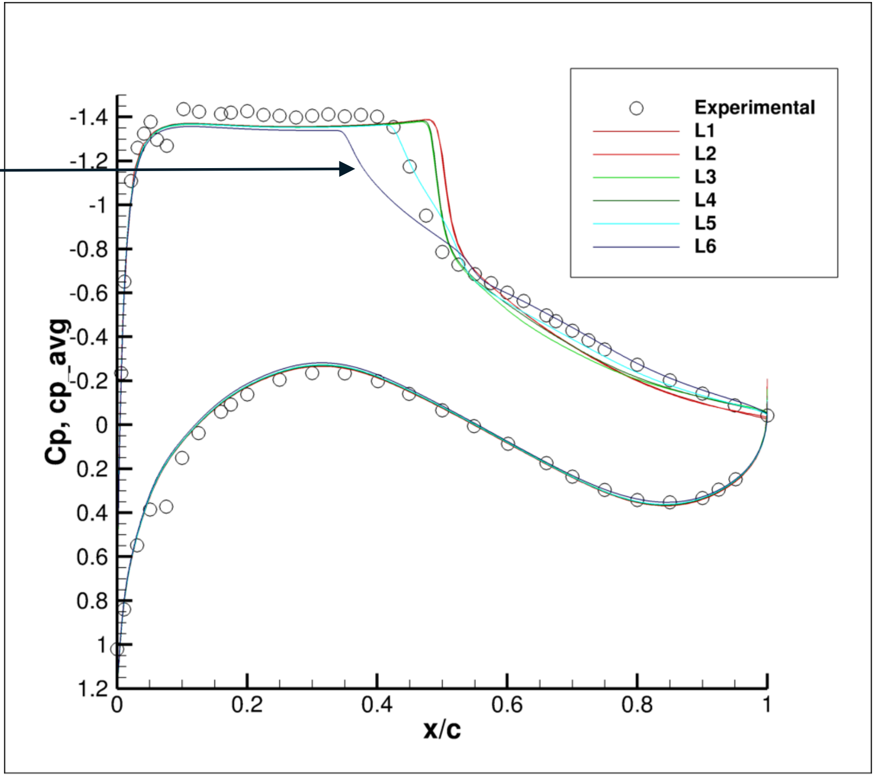



URANS requires significant levels of grid refinement to capture unsteadiness


Gulfstream

# MACH 0.73, ALPHA 3.25 (URANS)

Highest grid level shows larger movement of shock early in buffet




URANS requires significant levels of grid refinement to capture unsteadiness

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution



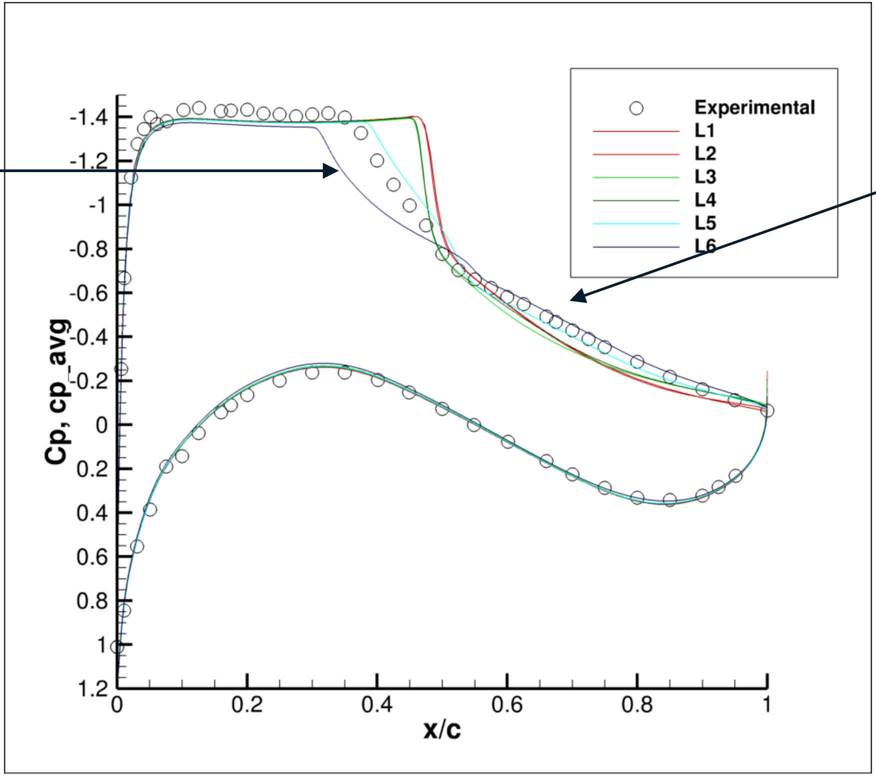
Gulfstream

# MACH 0.73, ALPHA 3.50 (URANS)

Highest grid level shows larger movement of shock in buffet

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution



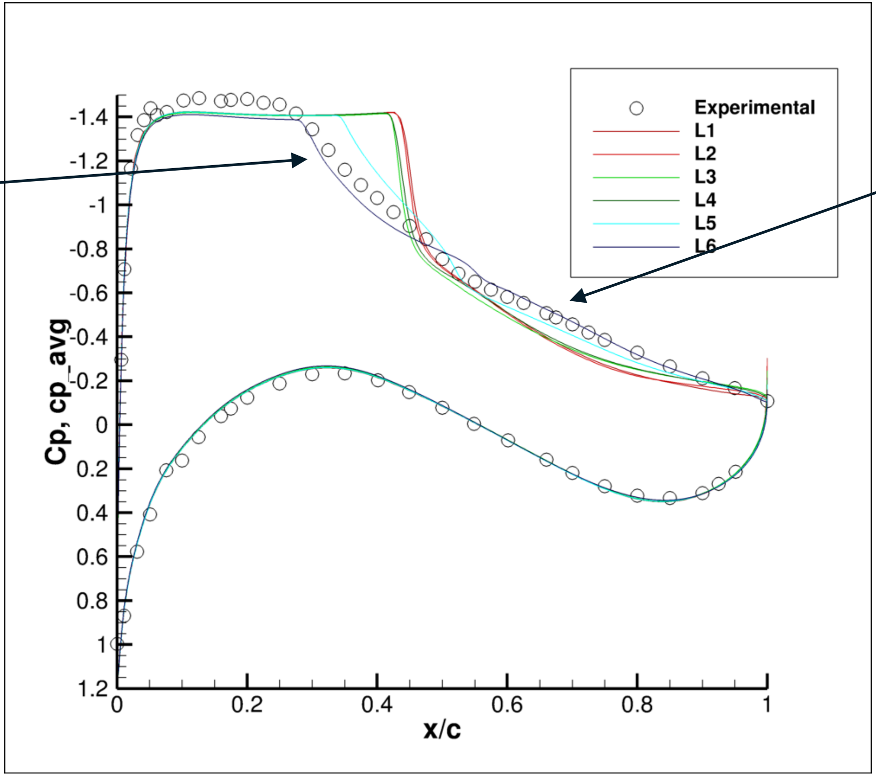

Higher grid levels predict post-shock separation with greater accuracy



Gulfstream

# MACH 0.73, ALPHA 3.90 (URANS)

Highest grid level predicts post-buffet shock position with greater accuracy




Higher grid levels predict post-shock separation with greater accuracy

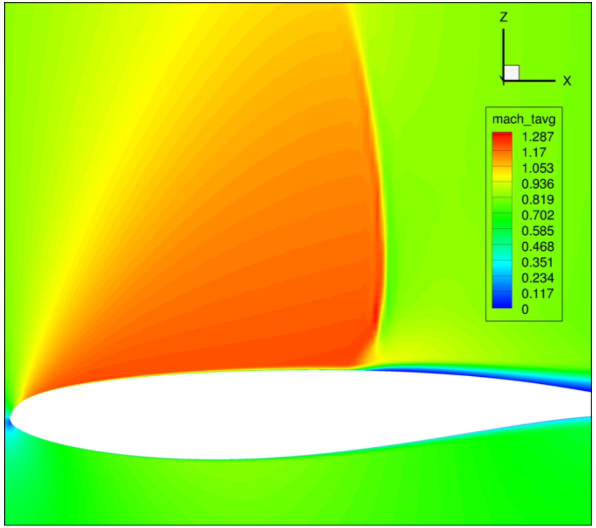
- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution



Gulfstream

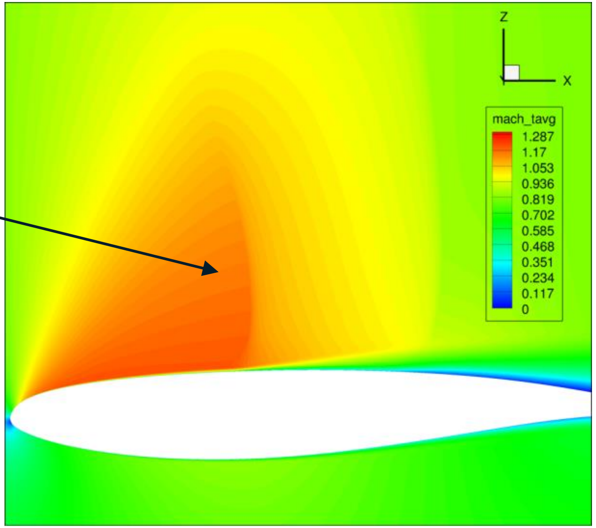
# GRID REFINEMENT EFFECT ON SHOCK RESOLUTION (AOA 3.50°), URANS




Grid Level 1

Average Mach shows movement of shock at more refined grid levels

URANS Time-averaged solution




Grid Level 6

Mid-chord cut

Unsteadiness in result shows up with more grid refinement



Gulfstream

# CP_RMS, URANS



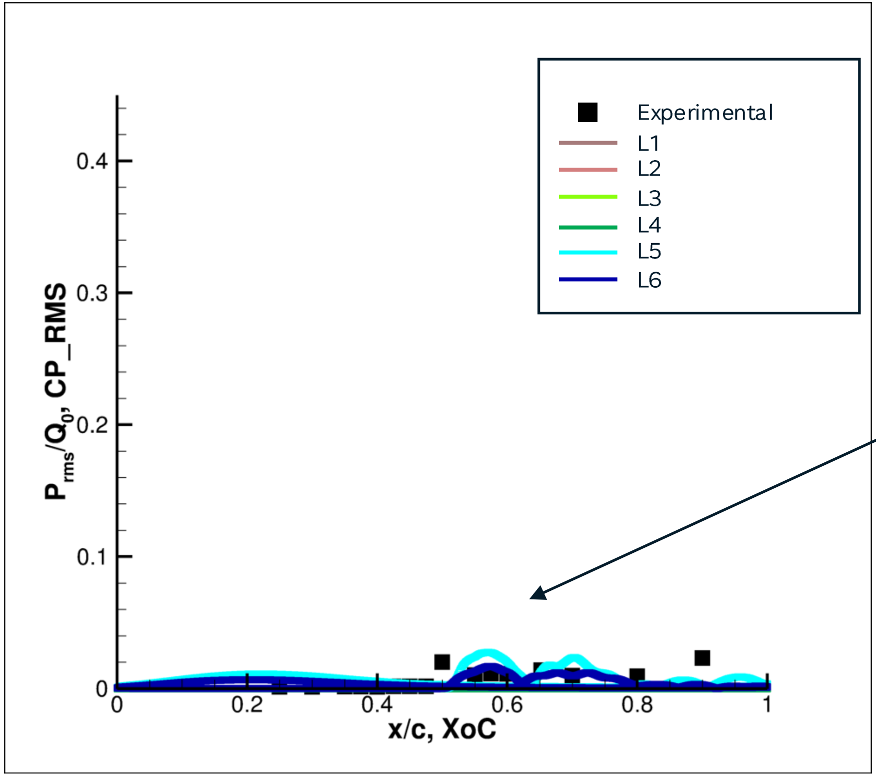
Gulfstream

# MACH 0.73, ALPHA 2.50, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




Little unsteadiness at α = 2.50°



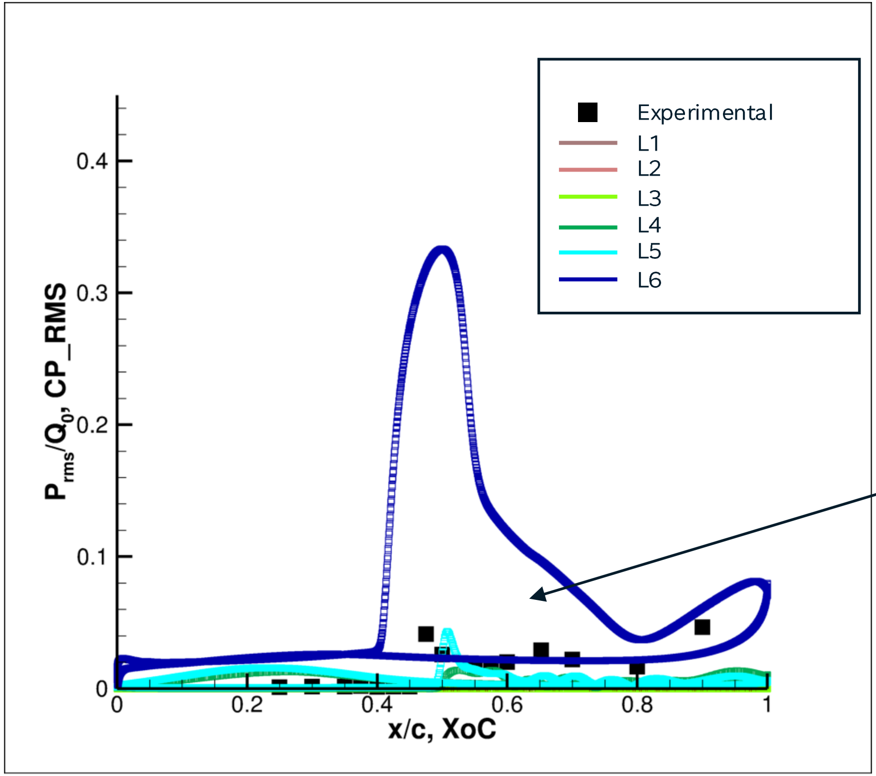
Gulfstream

# MACH 0.73, ALPHA 3.00, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




L6 grid predicts shock movement at α = 3.00°, earlier than experimental data



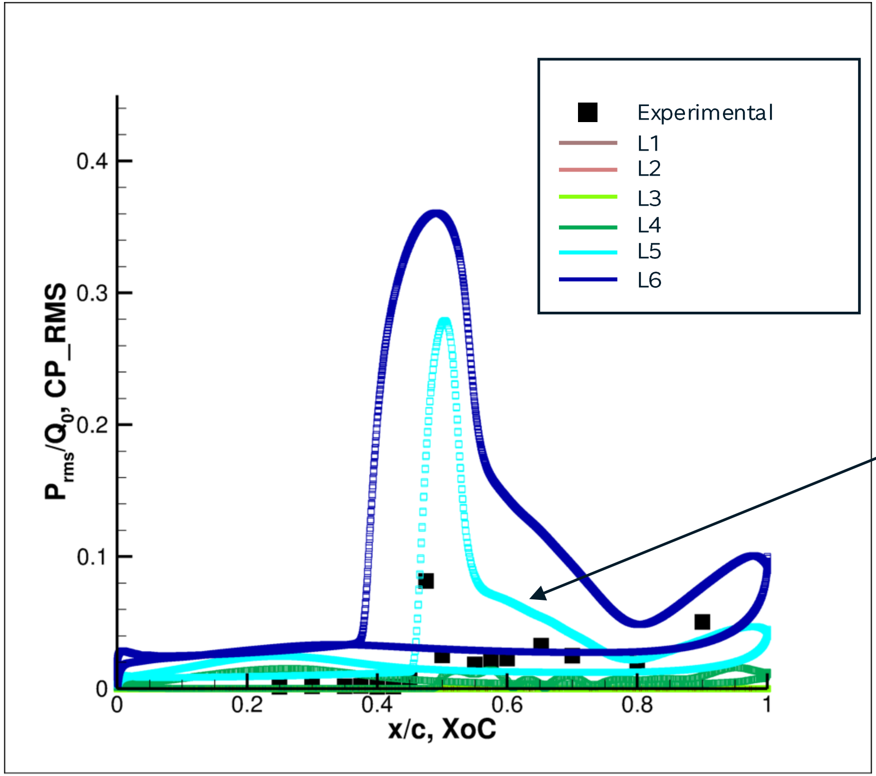
Gulfstream

# MACH 0.73, ALPHA 3.10, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




Grid dependence in CP_RMS magnitude at peak



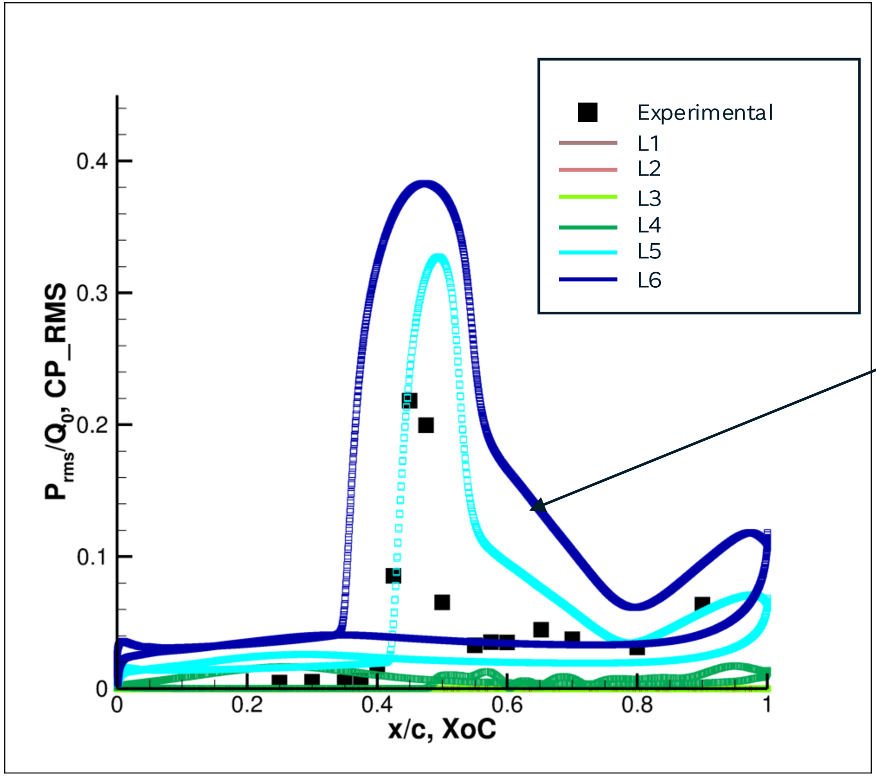
Gulfstream

# MACH 0.73, ALPHA 3.25, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




Grid dependence in CP_RMS magnitude at peak

URANS predicts shock location well, but not amplitudes



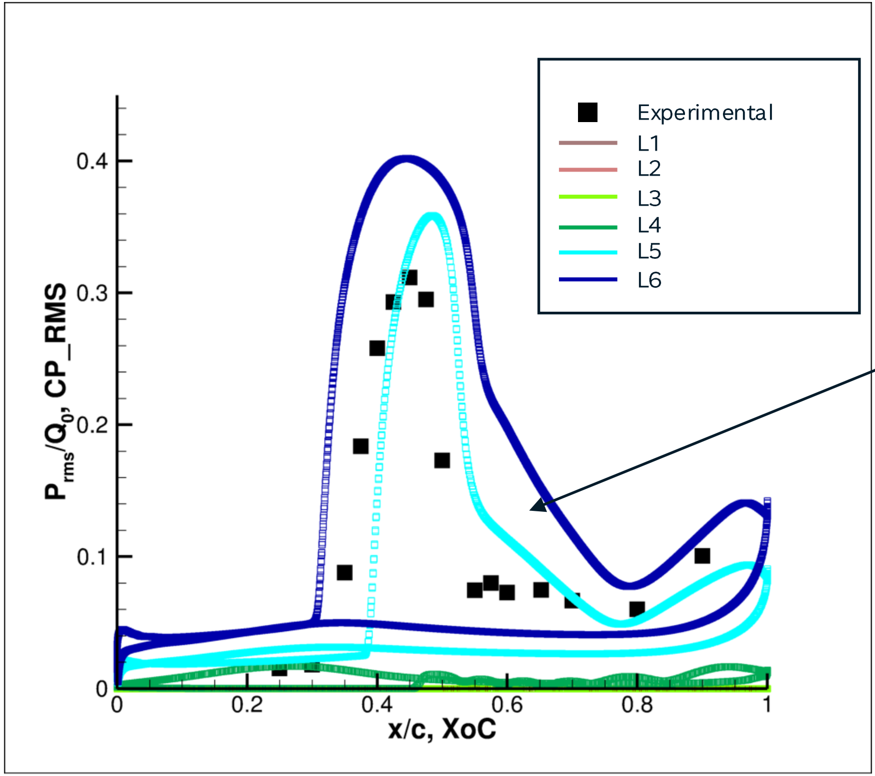
Gulfstream

# MACH 0.73, ALPHA 3.50, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




Grid dependence in CP_RMS magnitude at peak

URANS predicts shock location well, but not amplitudes



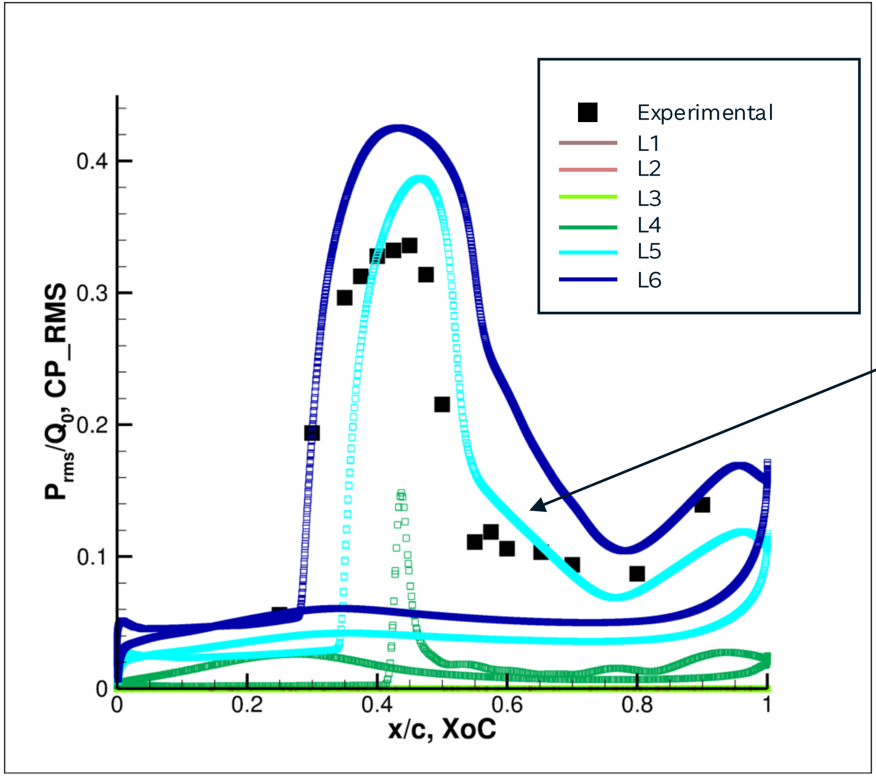
Gulfstream

# MACH 0.73, ALPHA 3.90, CP_RMS (URANS)

General magnitude of unsteadiness is higher with URANS

- SA-RC
- Compressibility Correction
- QCR2000

URANS Time-averaged solution




Grid dependence in CP_RMS magnitude at peak

URANS predicts shock location well, but not amplitudes



Gulfstream®

# CONCLUSIONS

- RANS predicts pressures well outside of the shock
- URANS required a significant amount of refinement to capture unsteadiness for the ONERA-OAT15A
- Use of Rotational Correction and Compressibility Correction allowed URANS to better capture the unsteadiness of the shock at higher levels of refinement
- URANS captures x/c location of peak CP_RMS, but magnitude is overpredicted and appears to be grid-dependent
- More exploration needed on DDES, DDES appears to be sensitive to span in grid for 2D extruded case


Gulfstream™
A GENERAL DYNAMICS COMPANY

# THANK YOU

PROPRIETARY NOTICE: THIS DATA AND INFORMATION CONTAINED HEREIN IS PROPRIETARY DATA OF GULFSTREAM AEROSPACE CORPORATION. NEITHER THIS DATA NOR THE DATA CONTAINED HEREIN SHALL BE REPRODUCED, USED OR DISCLOSED TO OTHERS WITHOUT THE EXPRESS WRITTEN AUTHORIZATION OF GULFSTREAM AEROSPACE CORPORATION.

# BACKUP

# UNSTEADY CFD APPROACHES

- Two approaches: URANS and DDES
- URANS
  - Maintaining SA-NEG and QCR2000
  - time_accuracy = ‘2ndorderOPT’
  - Subiterations set to 30 initially, dropped to 15-20 depending on convergence
  - CFL = 20, CFL Turb = 10
- DDES
  - Delayed Detached Eddy Simulation
  - SA flavor
  - Subiterations set to 50 for convergence
- Both approaches used seeding from Test Case 1A steady solutions. Solutions run for 2000 timesteps initially before time-averaging.
- Only URANS submitted to workshop, more exploration needed for DDES to determine proper settings/grid


Gulfstream®

# TIMESTEP DETERMINATION

- Non-dimensional timestep can be chosen by one of two methods:
  - Targeted frequency (such as lift oscillation freq.)
  - Approximate particle time of travel (time it takes a particle to traverse a reference length at freestream velocity)
- Dimensional timesteps (dimensional quantities denoted with *)
  - Targeted Frequency (Lift Oscillation)
    - $t^*_{chr} = \frac{1}{f} = \frac{1}{70\ Hz} = 0.014286\ s$
  - Particle Travel
    - $t^*_{chr} = \frac{cref}{Uinf} = \frac{230\ mm}{0.73 * 329{,}924\ \frac{mm}{s}} = 0.000955\ s$
- Non-dimensional timestep for FUN3D is determined by scaling based on speed of sound in grid units
  - $t_{chr} = t^*_{chr}\ a^*_{ref}\left(\frac{L_{ref}}{L^*_{ref}}\right), \Delta\mathrm{t} = \frac{t_{chr}}{N}$
- Length scales are the same between CFD and experiment, $\left(\frac{L_{ref}}{L^*_{ref}}\right) = 1,\ a^*_{ref} = 329{,}924\ \frac{mm}{s}$ for given conditions



Gulfstream

# TIMESTEP DETERMINATION (CONT.)

- Target frequency
  - $t_{chr} = 4713.2$
  - For N = 100 samples/CTU, $\Delta t = 47.132$
- Particle travel
  - $t_{chr} = 315.068$
  - For N = 100 samples/CTU, $\Delta t = 3.151$
- CTU: Convective Time Unit. Generally, the amount of time it takes one "cycle" of a measured phenomenon to occur
  - In this case, lift oscillation
- Initially, smaller timesteps were chosen to better capture buffet, but lack of oscillation in solution in reasonable number of iterations forced use of larger timesteps.
- Using $\Delta t = 47.132$ yielded well sampled results for buffet at expected frequencies
- Same timesteps used for URANS and DDES runs



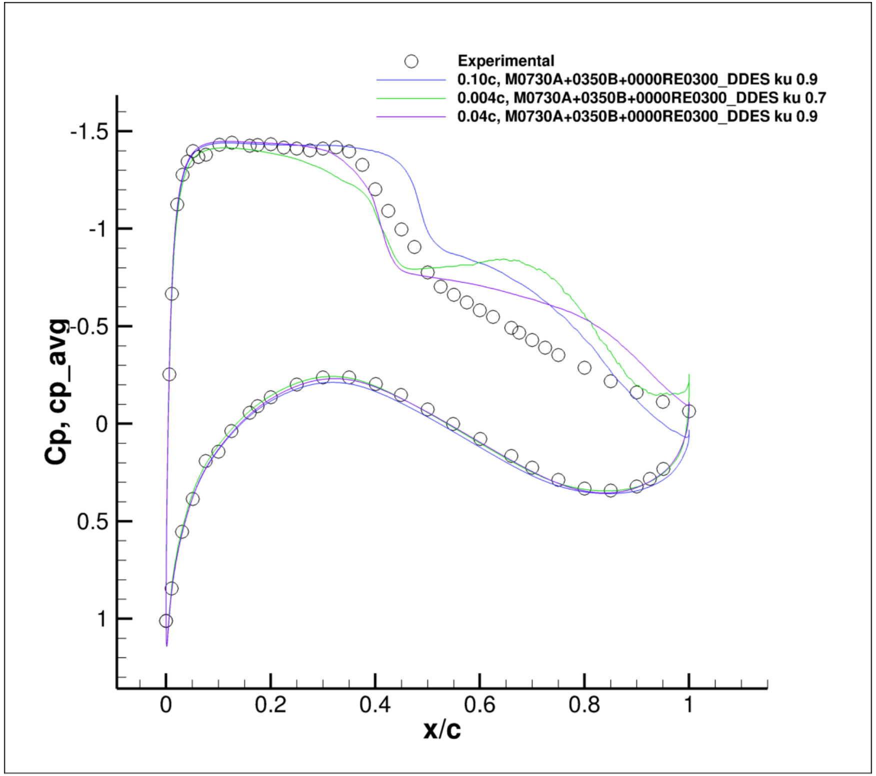
Gulfstream®

# TESTING

- Original URANS and DDES results had difficulty matching tunnel results in buffet
- URANS trended towards a RANS-like solution while DDES predicted strong shock and post-shock separation
- Based on research, a variety of limiters and SA turbulence model parameters were tested for URANS and DDES
  - Barth, heuristic MINMOD, limiters
  - SA-RC (Rotational correction)
  - SA compressibility correction proposed by Spalart in “Trends in Turbulence Treatments” (designated “CC”)
- DDES was tested for sensitivity to extruded span
  - Spans of 10 mm (0.04c) and 23 mm (0.10c)
- DDES tested for effect of kappa_umuscl parameter
  - Amount of upwinding in MUSCL reconstruction scheme, 1.0 is the unstable central-difference discretization and 0.0 is the upwing biased discretization. Range [0,1] is a blend of the two.
  - Tested 0.1, 0.3, 0.5 (default), 0.7, and 0.9
- All testing performed for Alpha 3.50°, leading edge patches NOT broken out unless otherwise specified

# SPAN, DDES (RC AND CC APPLIED)

DDES is very sensitive to change in span, as well as change in LE volume refinement



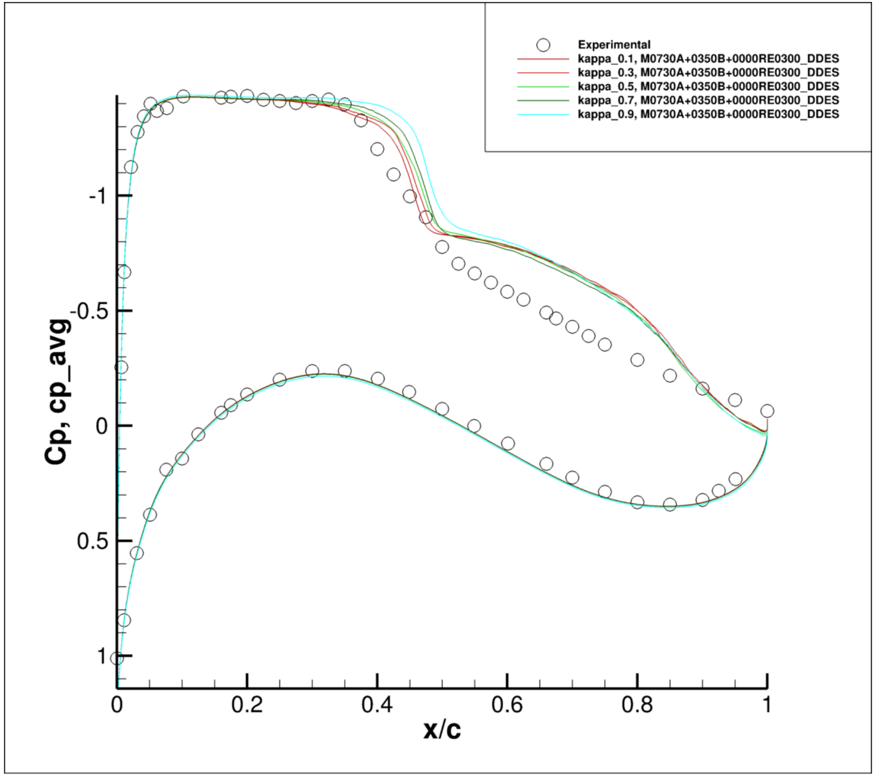

L5 surface refinement, LE broken out



Gulfstream®

# KAPPA, DDES (RC AND CC APPLIED)

Some change in shock position based on kappa




L5 surface refinement, LE broken out

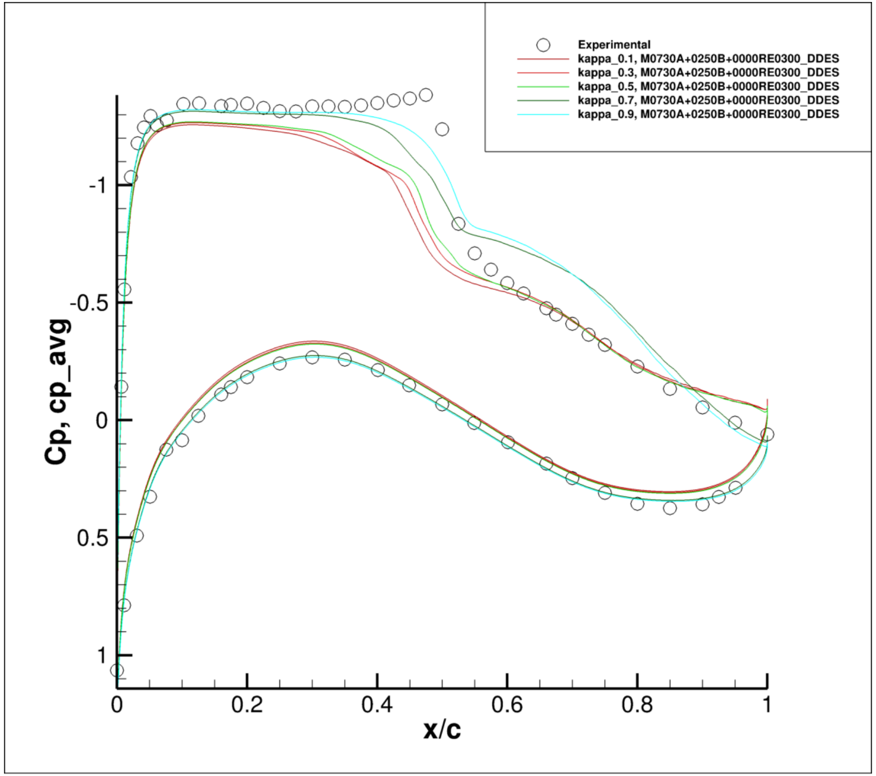
1 GU span



Gulfstream

# KAPPA, DDES (RC AND CC APPLIED) ALPHA 2.50°

Larger sensitivity to kappa at lower alphas




L5 surface refinement, LE broken out



Gulfstream®