Stability and Control Prediction Workshop: STAR-CCM+

2025 AIAA SciTech Forum

Seung (Paul) Yoo

January 7th, 2025

OUTLINE

- Motivation & Introduction
- Solver and Simulation Method
- Results
- Conclusion

MOTIVATION & INTRODUCTION

General Motivation:

- Evaluate current practice of predicting dynamic derivatives and compare the results to the wind tunnel data through "blind" test

Focus of this study

- Use STAR-CCM+ to simulate Common Research Model in periodic oscillation (pitch, roll, and yaw) to produce CFD-based hysteresis response
- Evaluate turbulence models: SA vs. SA-RC-QCR
- Effect of number of steps per cycle

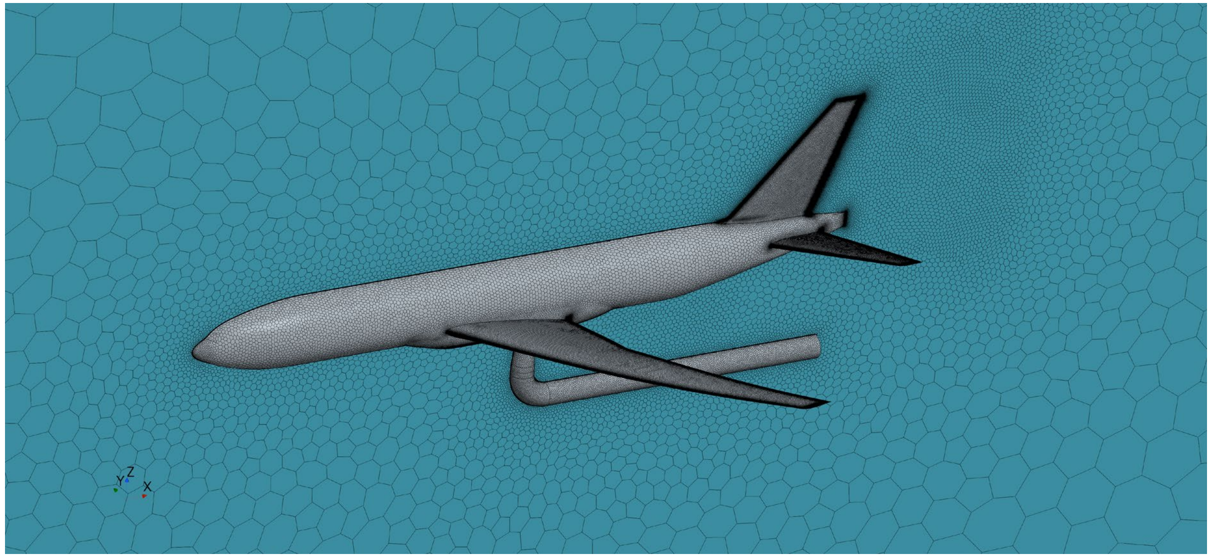
CFD Description

- STAR-CCM+ version 17.06
- Polyhedral mesh
    - unsteady simulation used full-span model due to sting geometries
    - Steady simulation used half-span model for aoa sweep, full-span for beta sweep

SOLVER & SIMULATION METHOD

Solver Description: STAR-CCM+

- Coupled compressible solver in finite-volume formulation
- 2nd order Roe flux-differencing scheme with low Mach preconditioner
- Unsteady-simulation using 2nd order time scheme
- Fully turbulent flow with variations of Spalart-Allmaras (SA) turbulence model
    - SA
    - SA-RC-QCR

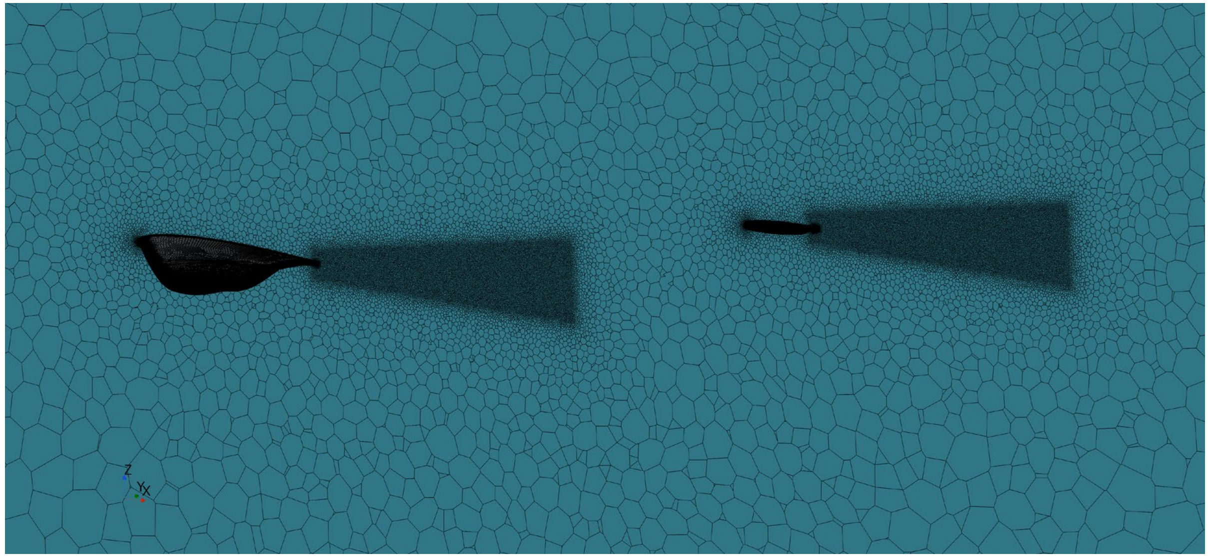


Steady-state Simulation Strategy

- Converged lower AoA solution used as restart for higher AoA

Unsteady Simulation Strategies

- Converged steady-state used as the starting point for the unsteady simulation
- Entire mesh rotates instead of using relative motion
- Adjust number of subiterations to achieve 2 orders of magnitude drop in subit-residual

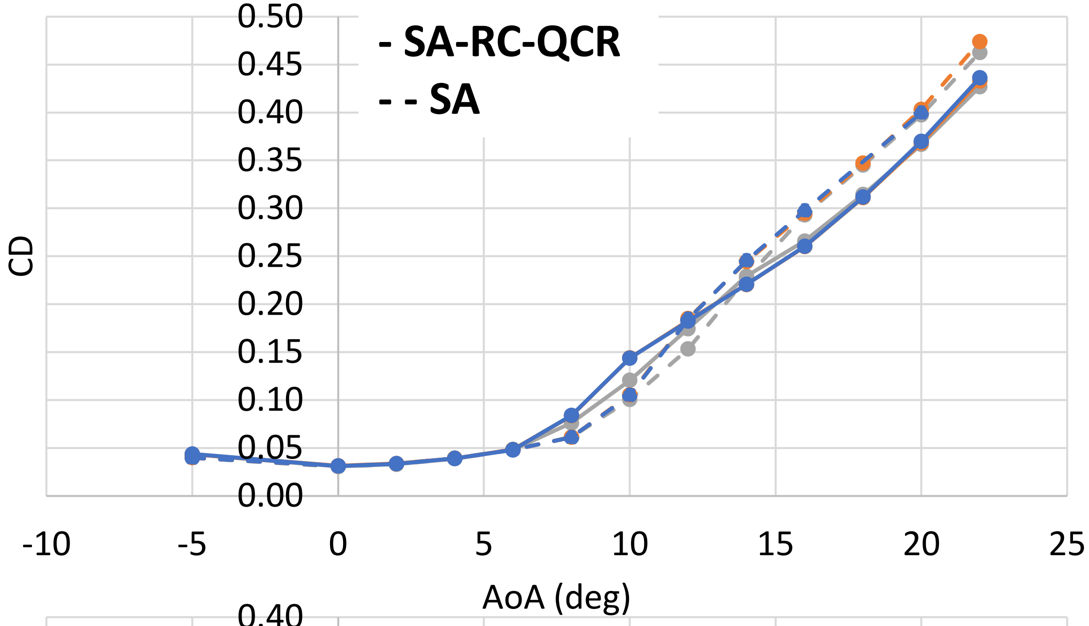


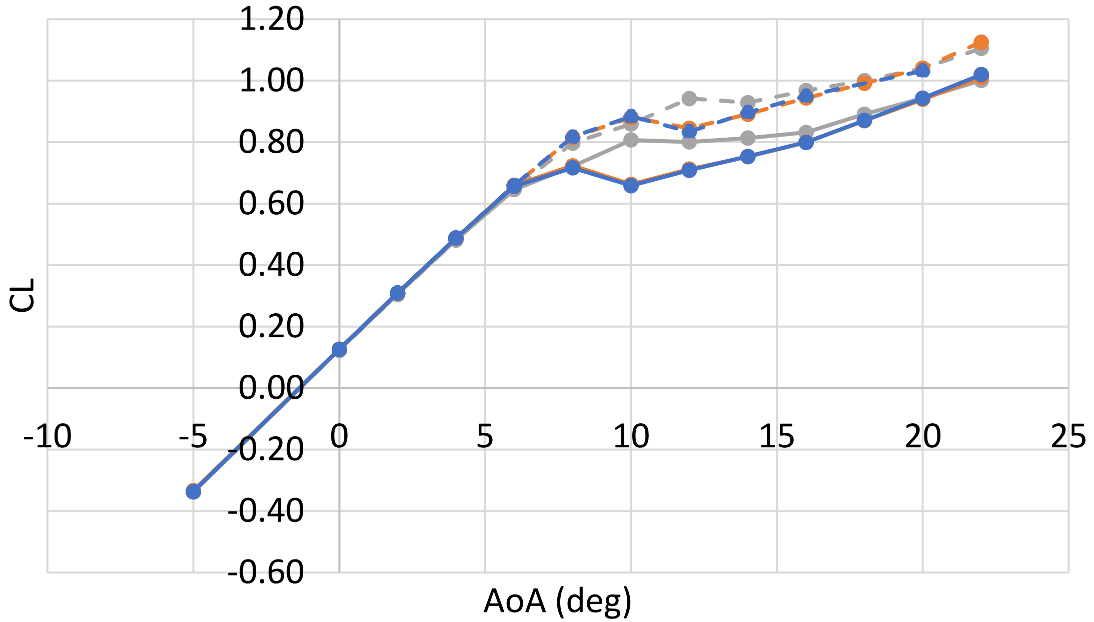
STEADY-STATE RESULTS

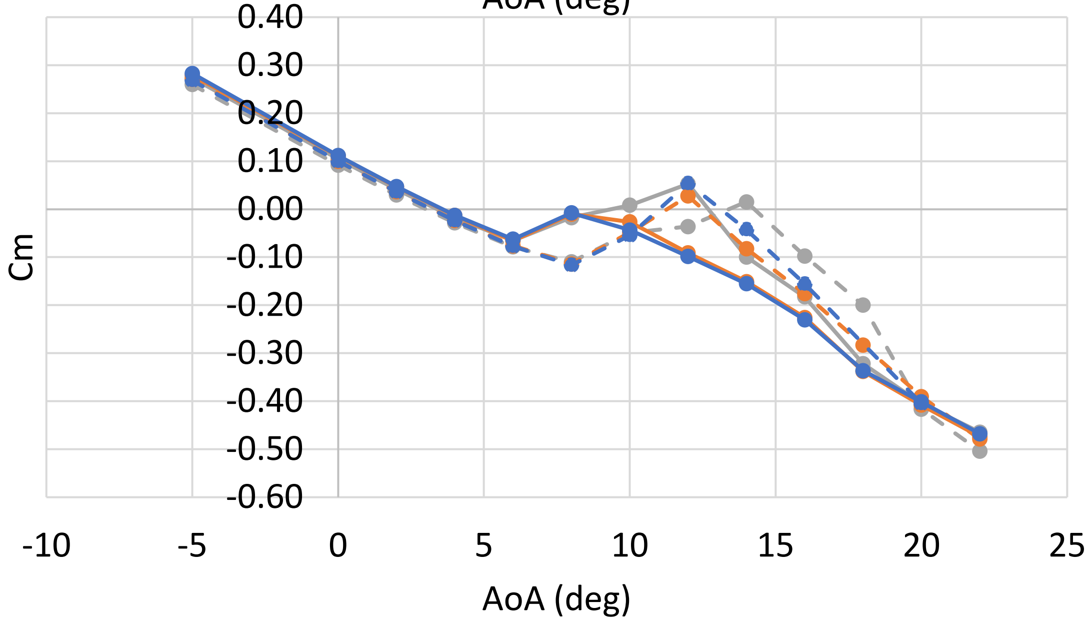
RESULTS: STEADY-STATE AOA SWEEP

- Reynolds number 200,000, Mach 0.052, Static temp 518° R
- AoA: -5°, 0° to 22° at 2° increment, Beta: 0°
- Half-span model
- 3 mesh resolutions: 31mil, **81mil**, 137mil

137 million Cells	SA	SA-RC-QCR	SA-RC-QCR err (%)
$C_{N,aoa}$ (AoA 4°)	0.0878	0.0869	-1.1
$C_{m,aoa}$ (AoA 4°)	-0.0284	-0.0275	-3.1

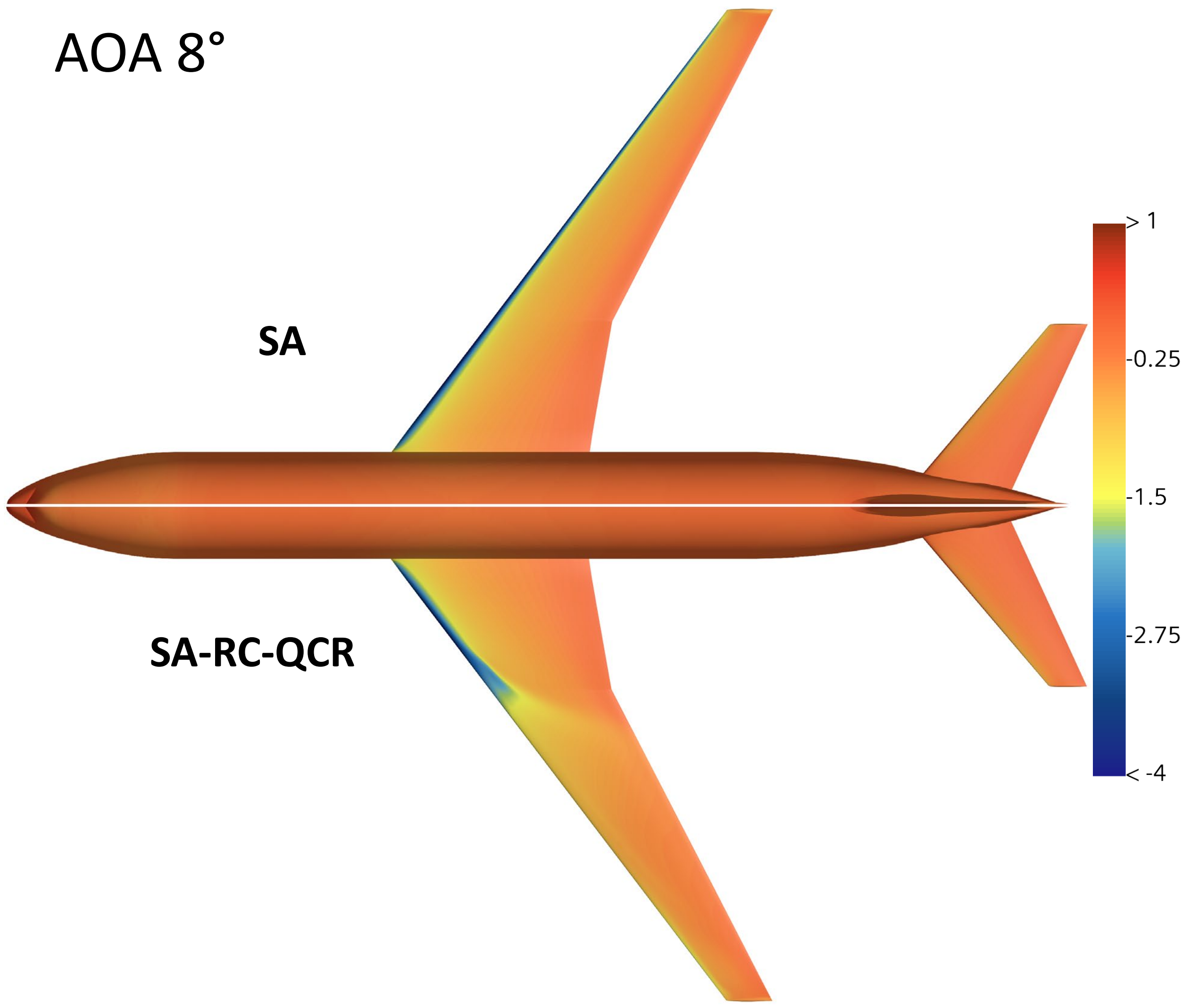




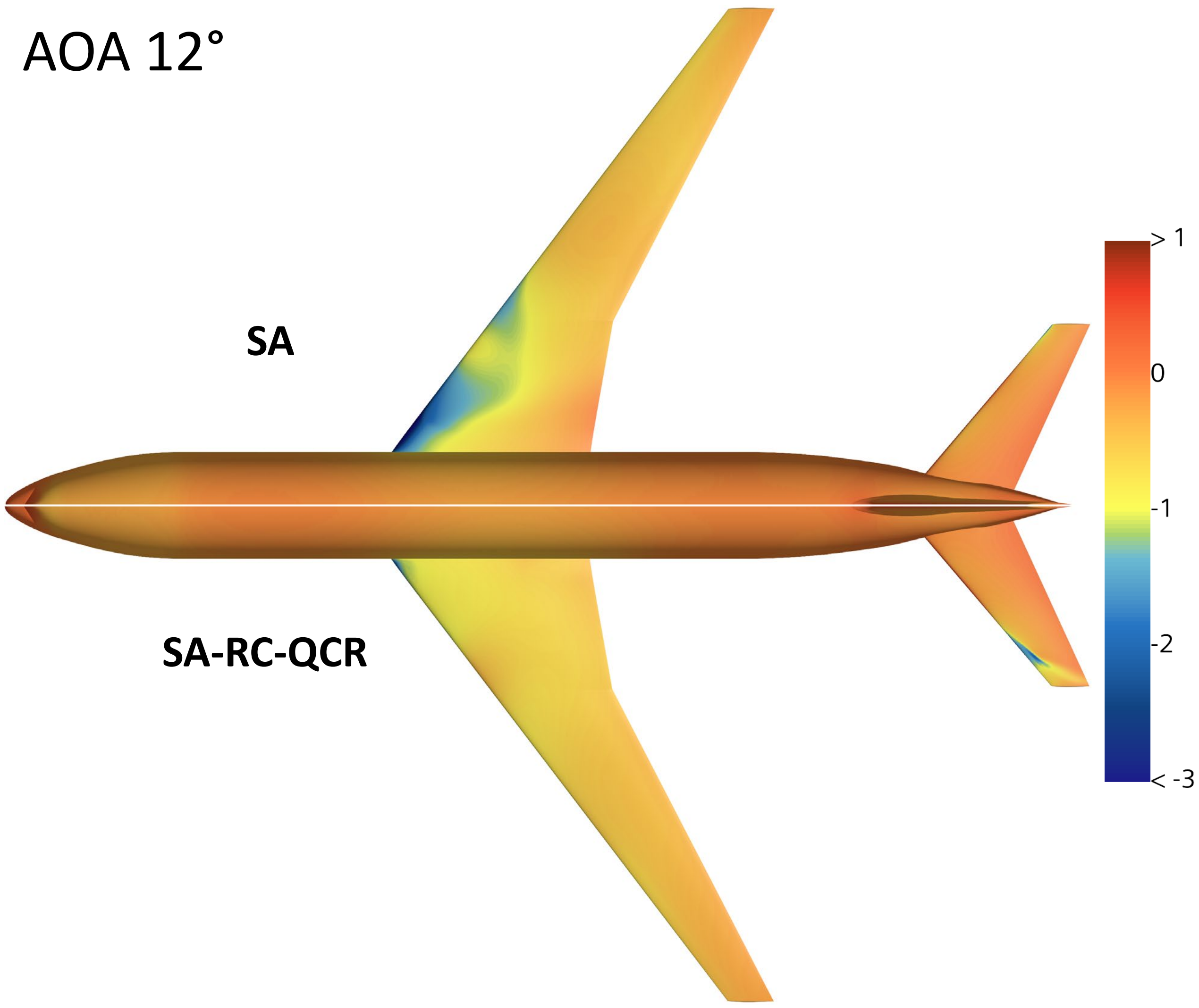


RESULTS: STEADY-STATE, PRESSURE COEFFICIENT

AOA 8°



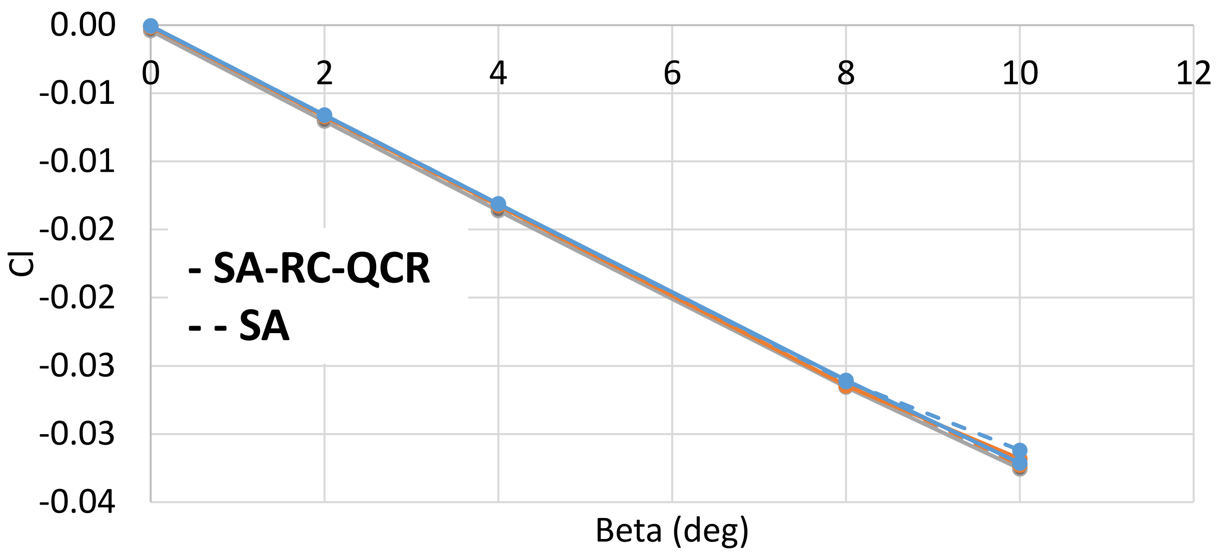
AOA 12°

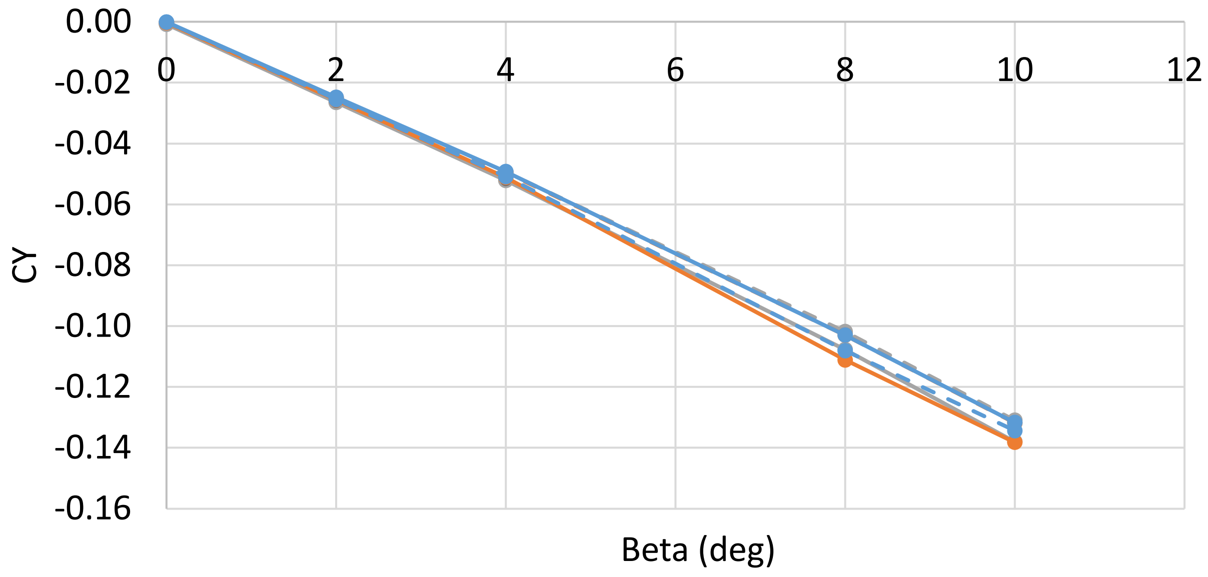


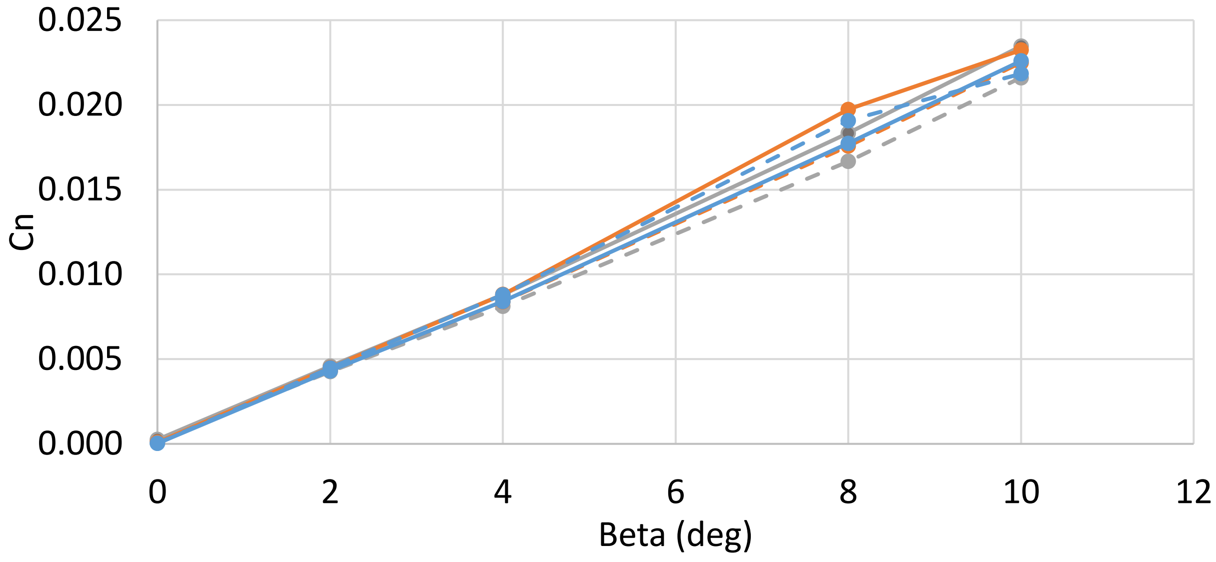
RESULTS: STEADY-STATE BETA SWEEP

- Reynolds number 200,000, Mach 0.052, Static temp 518° R
- AoA: 4°, Beta: -10° to 10° at 2° increment
- Full-span model
- 3 mesh resolutions: 42mil, **90mil**, 163mil

163 million cells	SA	SA-RC-QCR	SA-RC-QCR err (%)
Cn,beta (0° beta)	0.00214	0.00222	3.9
Cl,beta (0° beta)	-0.00328	-0.00327	-0.2
CY,beta (0° beta)	-0.01234	-0.01270	2.9







UNSTEADY RESULTS

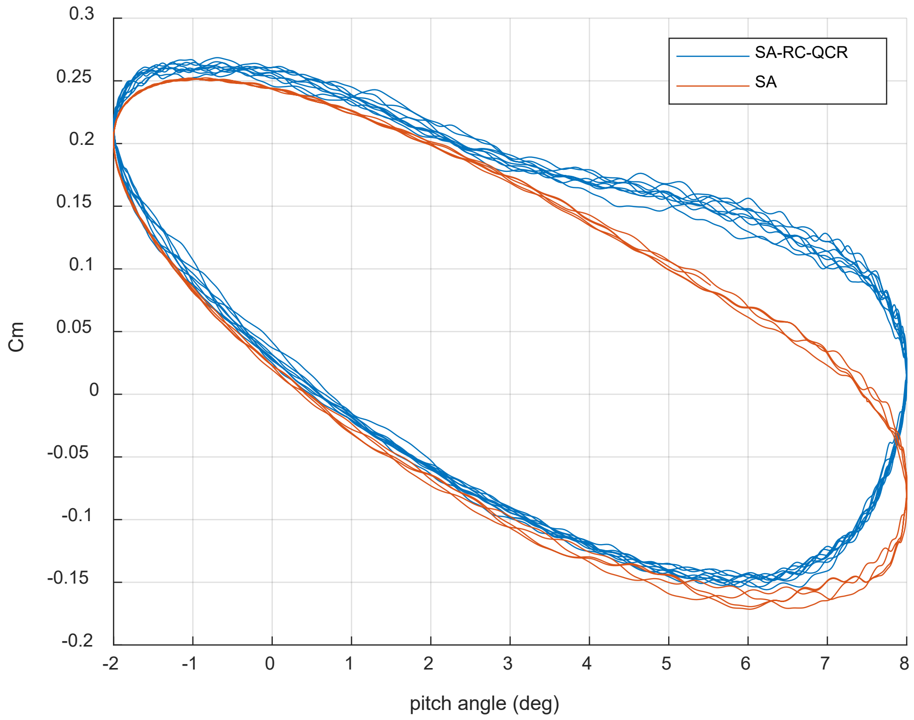
RESULTS: UNSTEADY OSCILLATIONS

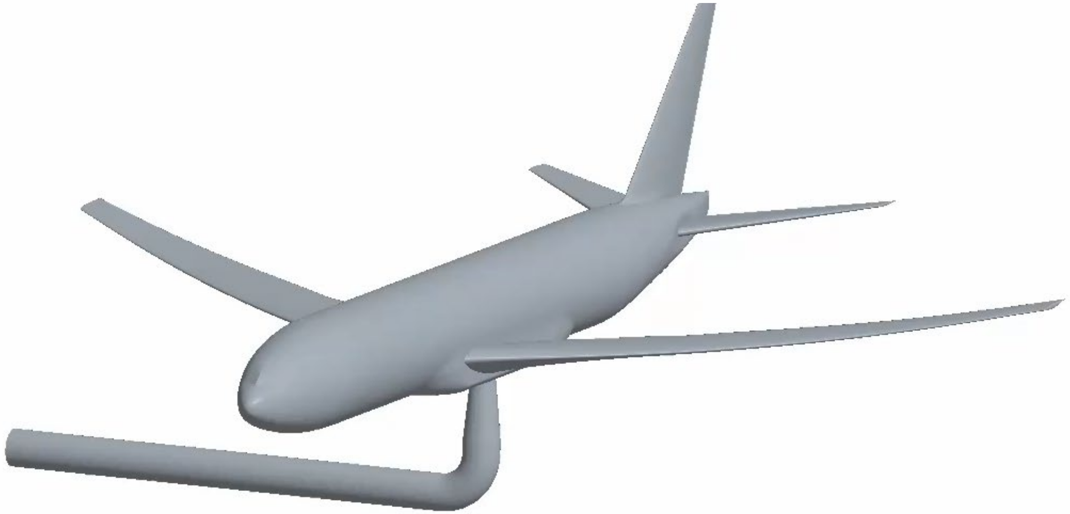
- Restart from converged steady-state simulation
  - Steady-state at inital AoA. AoA specified via angled AoA vector while AC is “horizontal”
  - Unsteady: AC oscillates delta AoA while freestream vector remains constant
- Achieve 2 orders of magnitude drop in sub-iteration residual
  - Between 9 – 15 subiteration
- Entire mesh rotates about the Moment Reference Center, no relative motion
- 2 turbulence models: SA, SA-RC-QCR

case	Reynolds number	Mach	Initial AoA (deg)	Initial beta (deg)	Amplitude (deg)	reduced freq	oscillation freq (hz)
pitch	140000	0.0358	3	0	5	0.04	0.0222
roll	140000	0.0358	3	0	5	0.4	0.0264
yaw	140000	0.0358	3	0	5	0.4	0.0264

RESULTS: UNSTEADY PITCH OSCILLATION

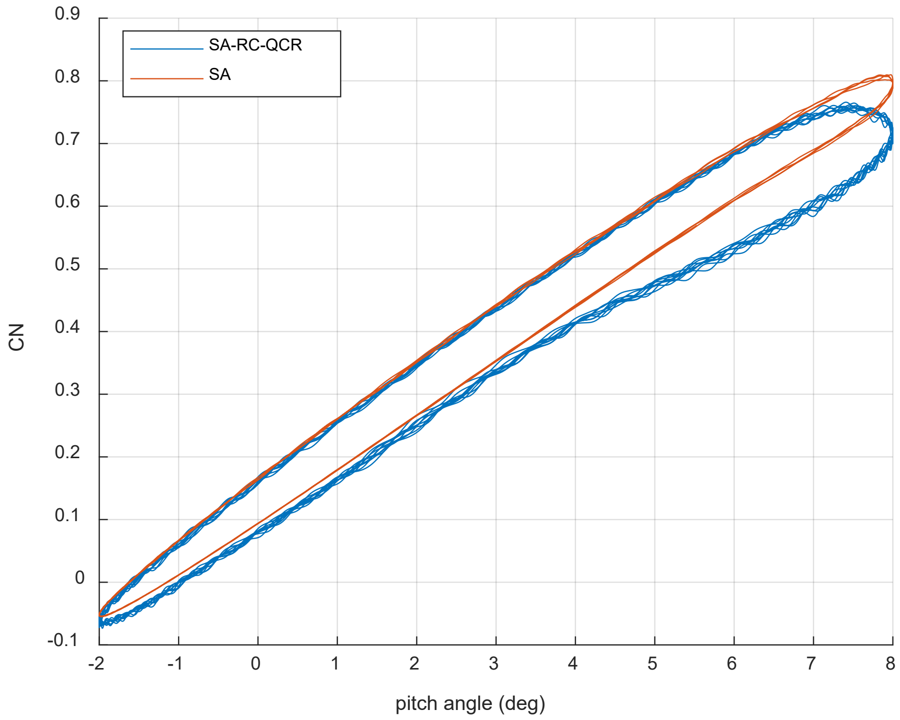
- AoA = 3° ± 5°, Beta = 0°
- Reynolds number 140000
- Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.04, Oscillation Freq 0.0222 Hz
  - 1000 steps per cycle -> 0.045 sec
- 128 million cells mesh
  - Based on mesh setting of 81 million steady-state mesh





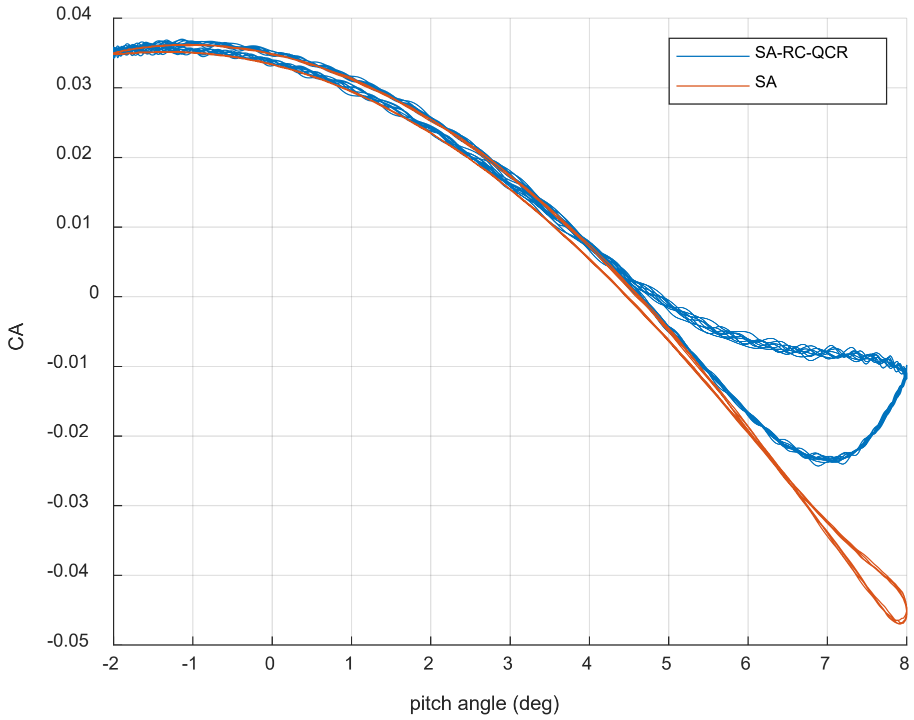
RESULTS: UNSTEADY PITCH OSCILLATION

- AoA = 3° ± 5°, Beta = 0°
- Reynolds number 140000
- Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.04, Oscillation Freq 0.0222 Hz
  - 1000 steps per cycle -> 0.045 sec
- 128 million cells mesh
  - Based on mesh setting of 81 million steady-state mesh



RESULTS: UNSTEADY PITCH OSCILLATION

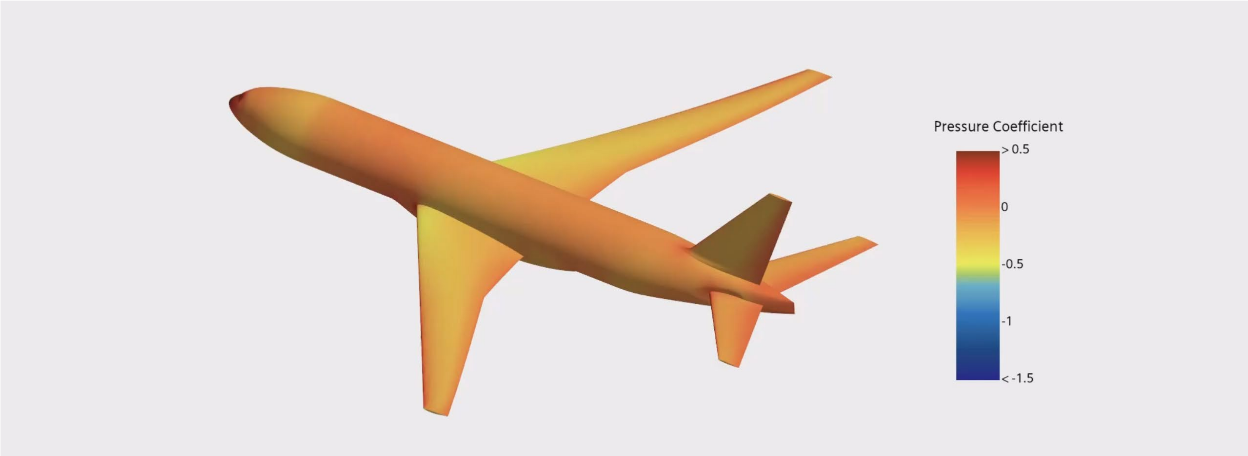
- AoA = 3° ± 5°, Beta = 0°
- Reynolds number 140000
- Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.04, Oscillation Freq 0.0222 Hz
  - 1000 steps per cycle -> 0.045 sec
- 128 million cells mesh
  - Based on mesh setting of 81 million steady-state mesh



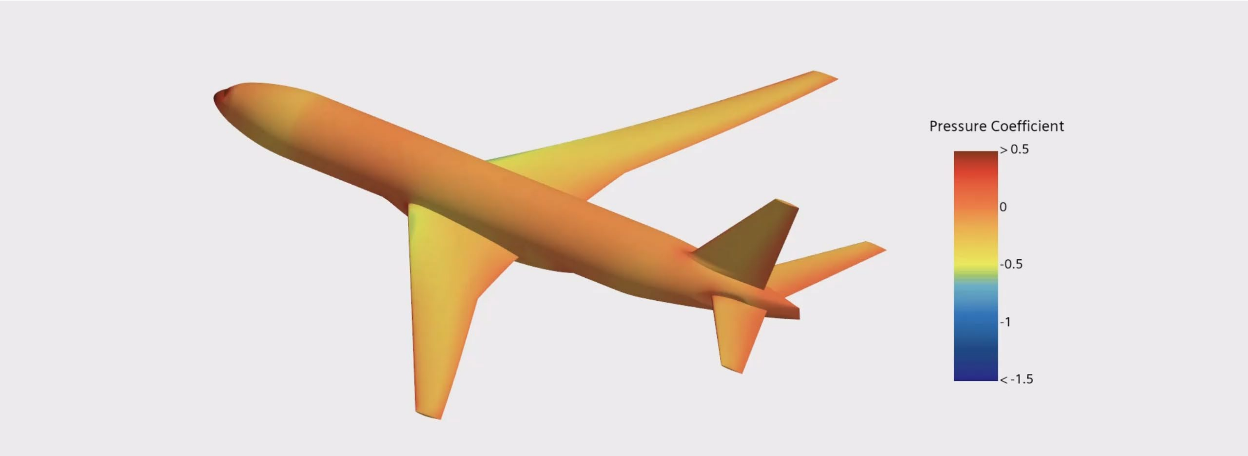
RESULTS: UNSTEADY PITCH OSCILLATION

- Both turbulence models show asymmetric pressure coefficient at upper surface of right wing at high AoA
- Suspect this phenomena is due to the sting extending to RHS of the model

SA-RC-QCR



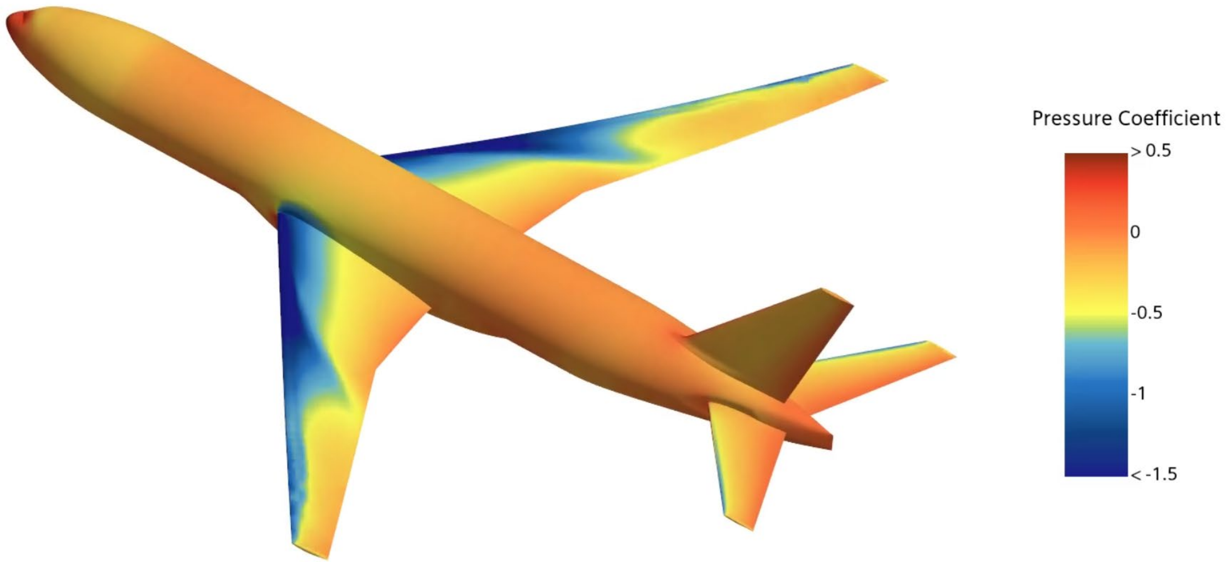
SA



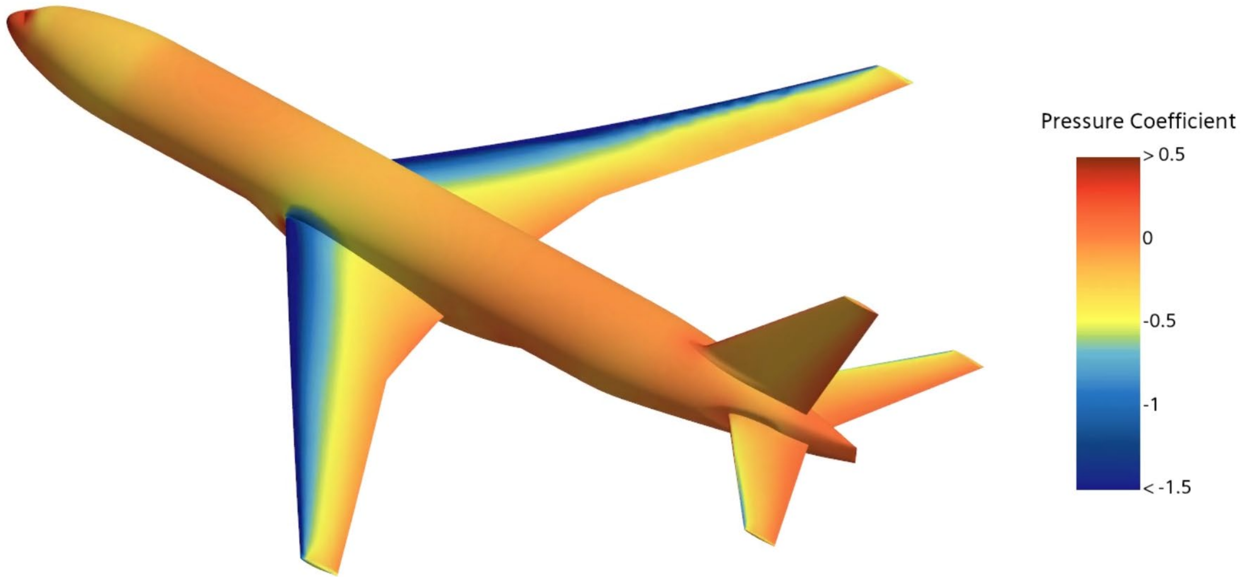
RESULTS: UNSTEADY PITCH OSCILLATION

- Both turbulence models show asymmetric pressure coefficient at upper surface of right wing at high AoA
- Suspect this phenomena is due to the sting extending to RHS of the model

SA-RC-QCR



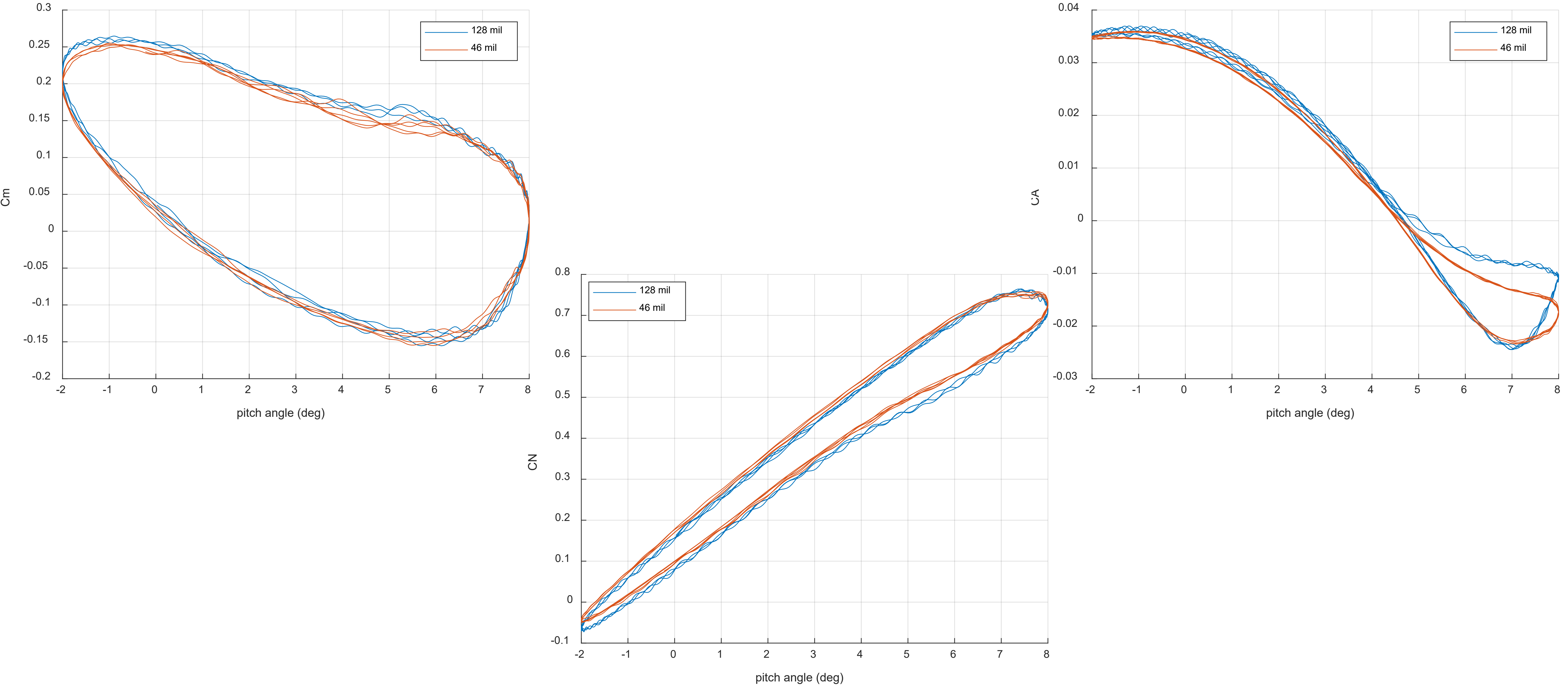
SA



RESULTS: UNSTEADY PITCH OSCILLATION

MESH RESOLUTION STUDY (SA-RC-QCR)

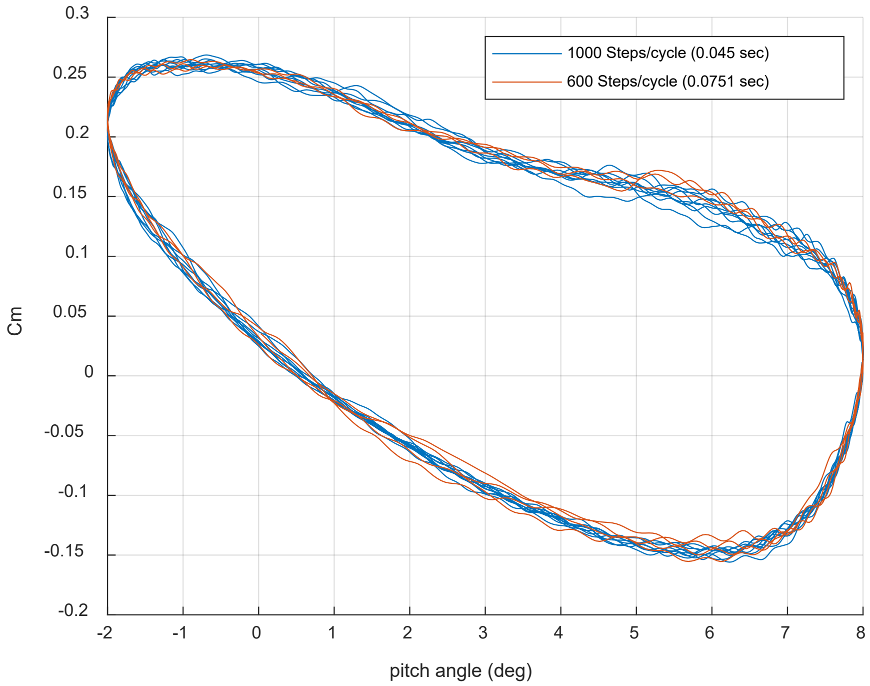
- 1000 Steps/Cycle

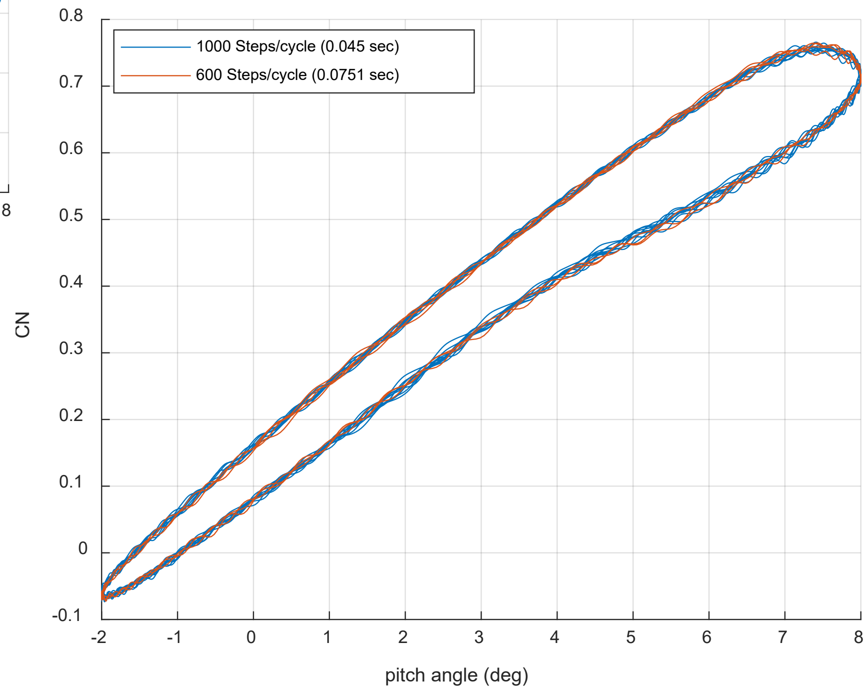


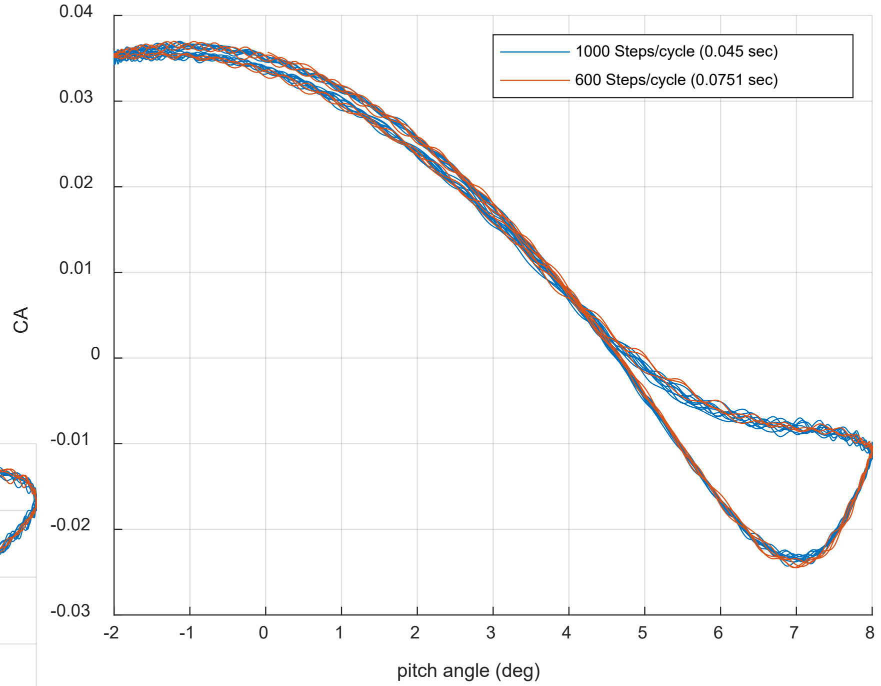
RESULTS: UNSTEADY PITCH OSCILLATION

TIME RESOLUTION STUDY (SA-RC-QCR)

- 128 mil mesh



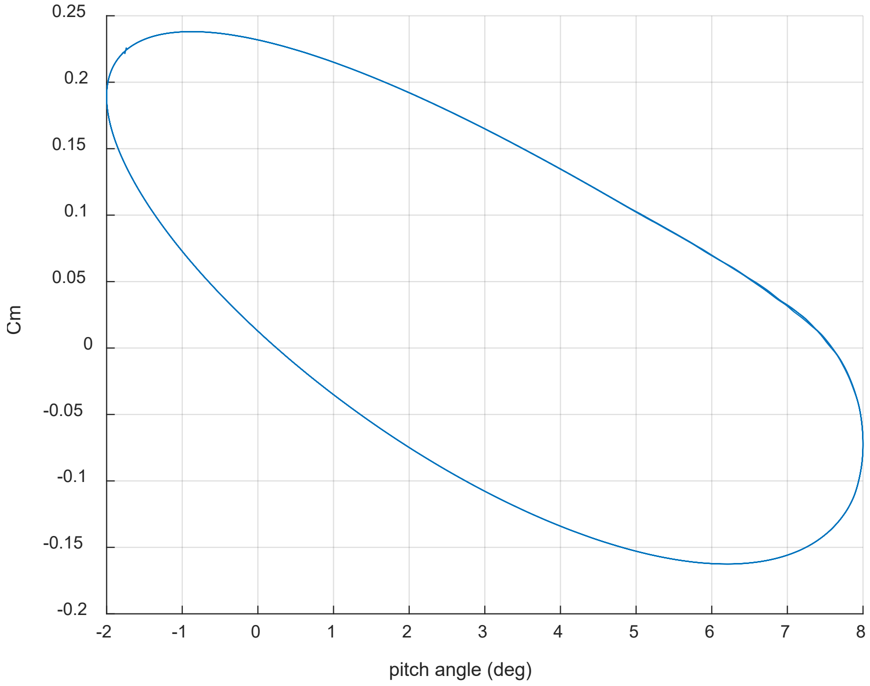


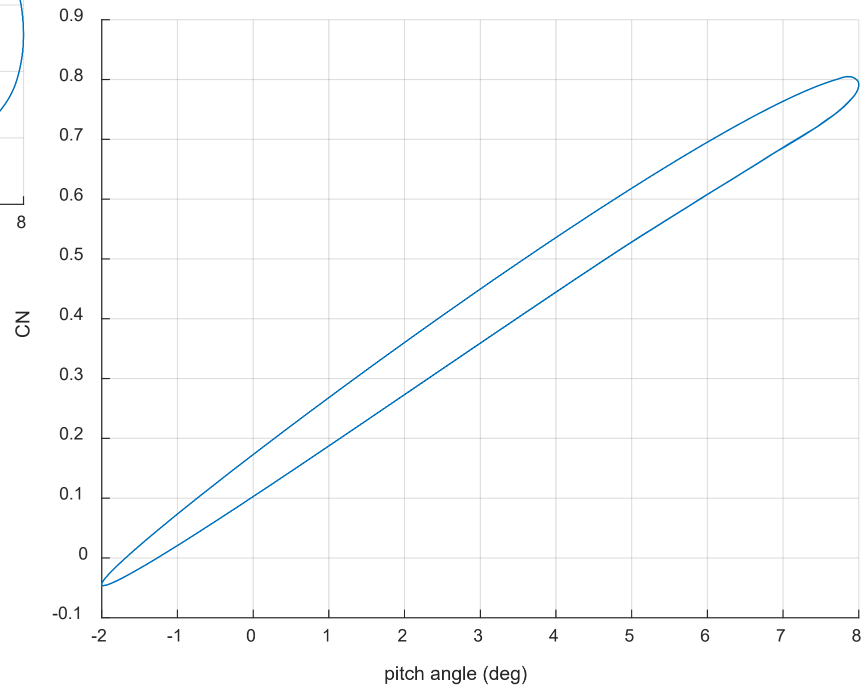


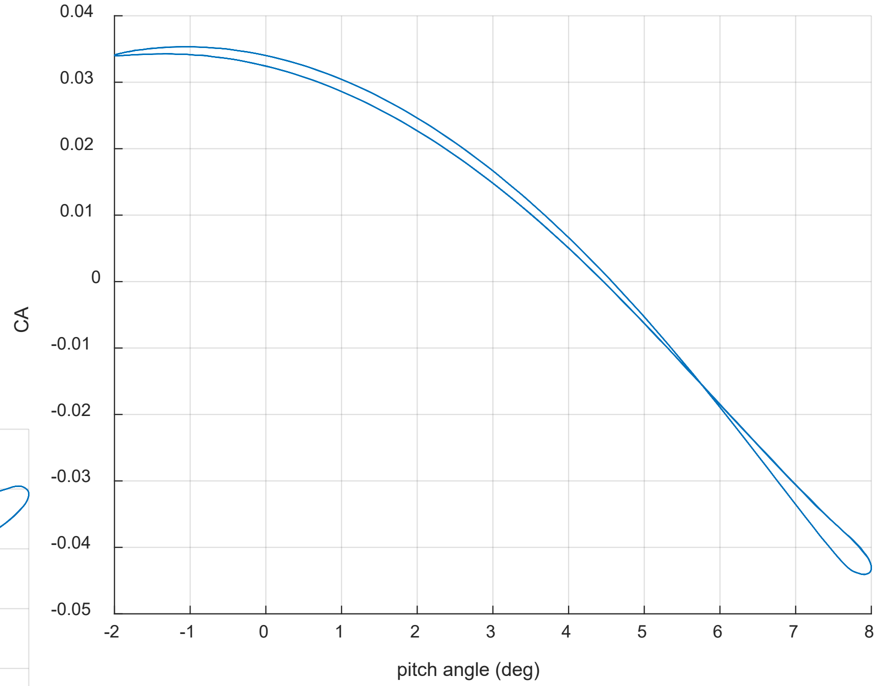
RESULTS: UNSTEADY PITCH OSCILLATION

CLEANEST RESULTS (DOESN'T MEAN MOST ACCURATE)

- 48 mil mesh, 600 Steps/cycle, SA

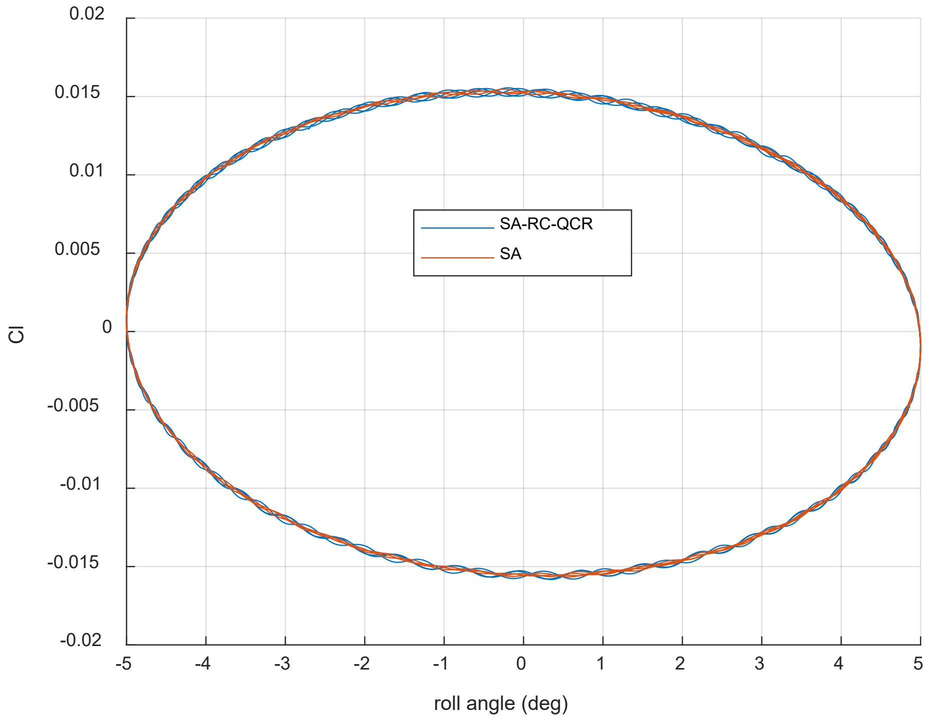


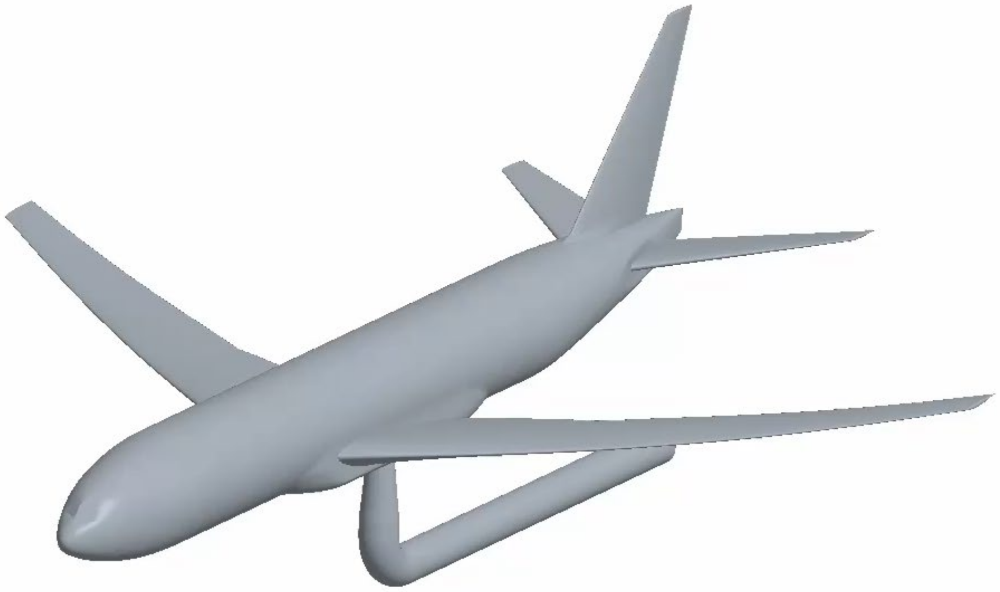




RESULTS: UNSTEADY ROLL OSCILLATION

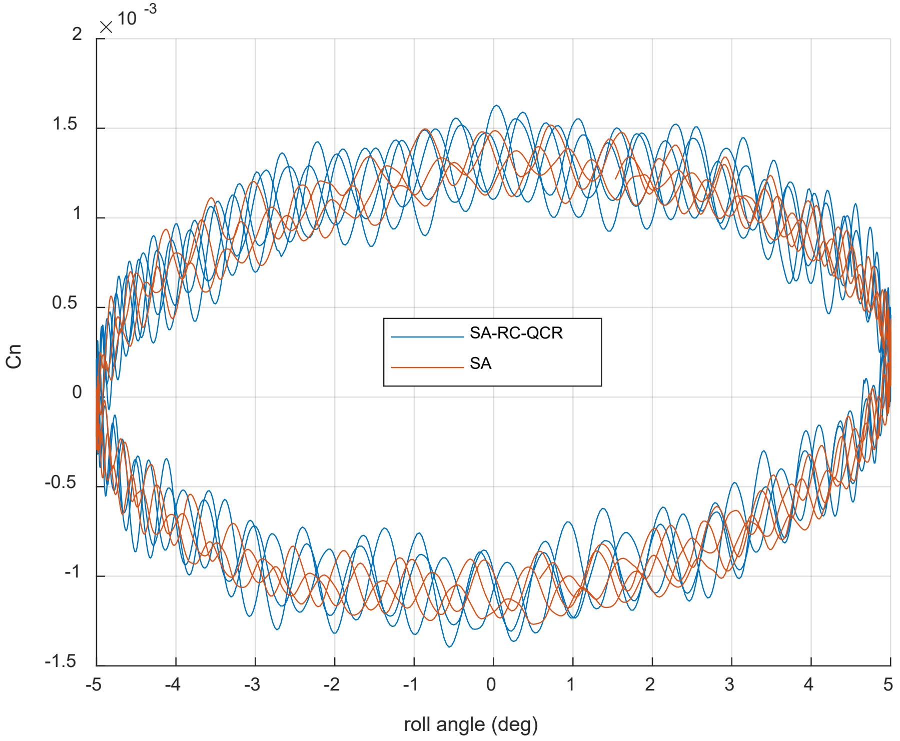
- AoA = 4°, Roll angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh





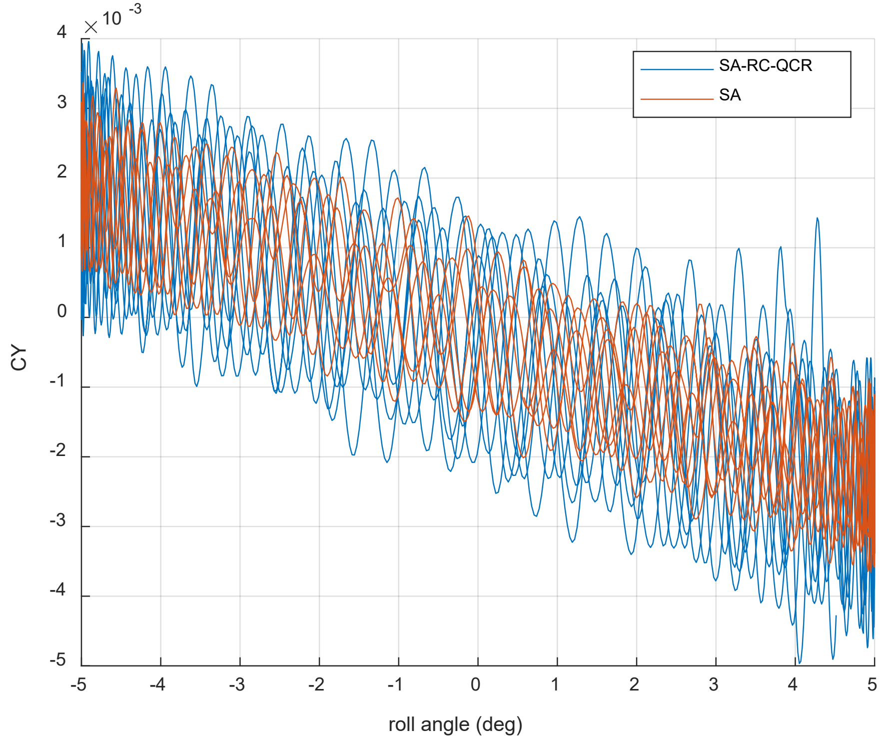
RESULTS: UNSTEADY ROLL OSCILLATION

- AoA = 4°, Roll angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh



RESULTS: UNSTEADY ROLL OSCILLATION

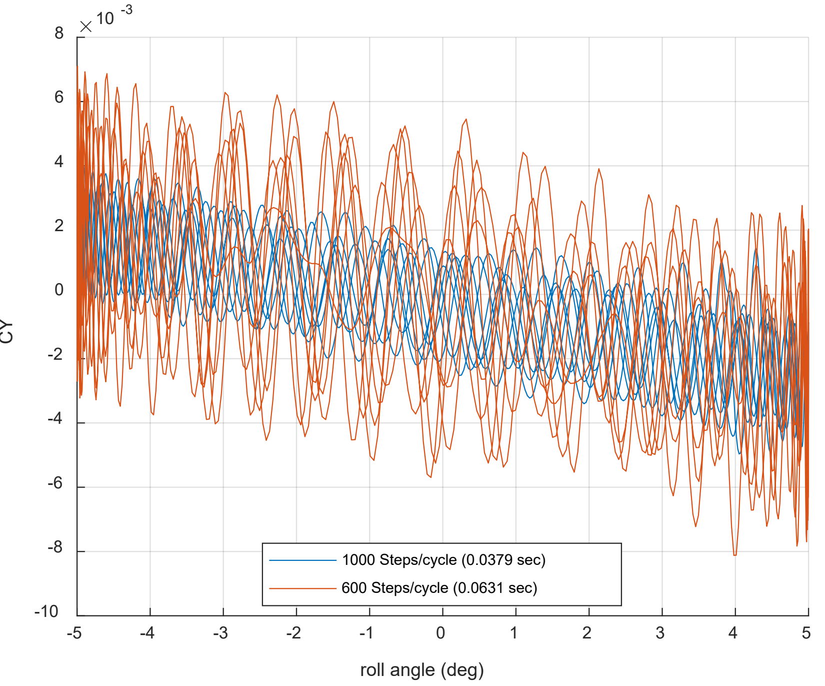
- AoA = 4°, Roll angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh

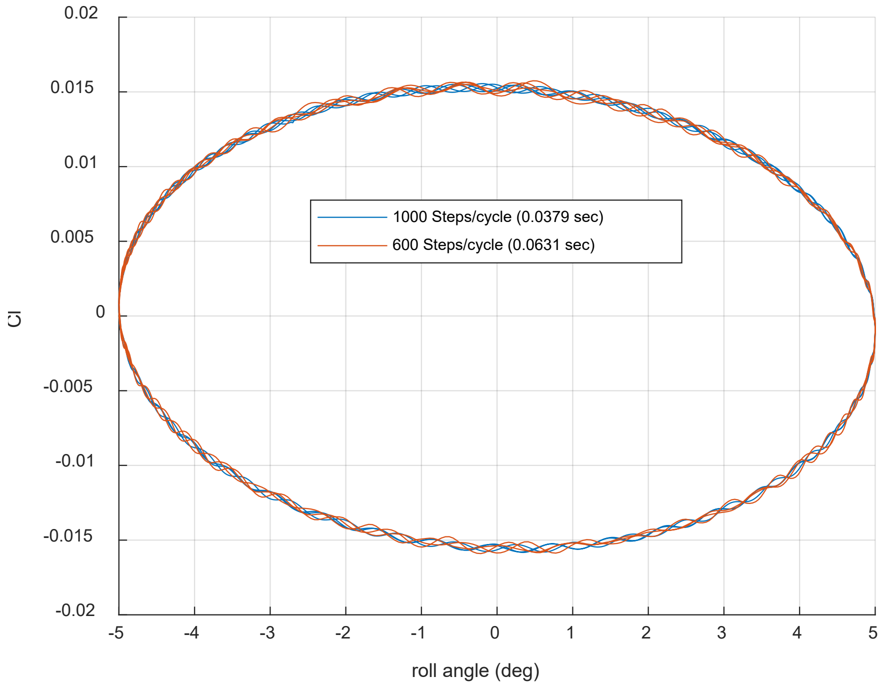


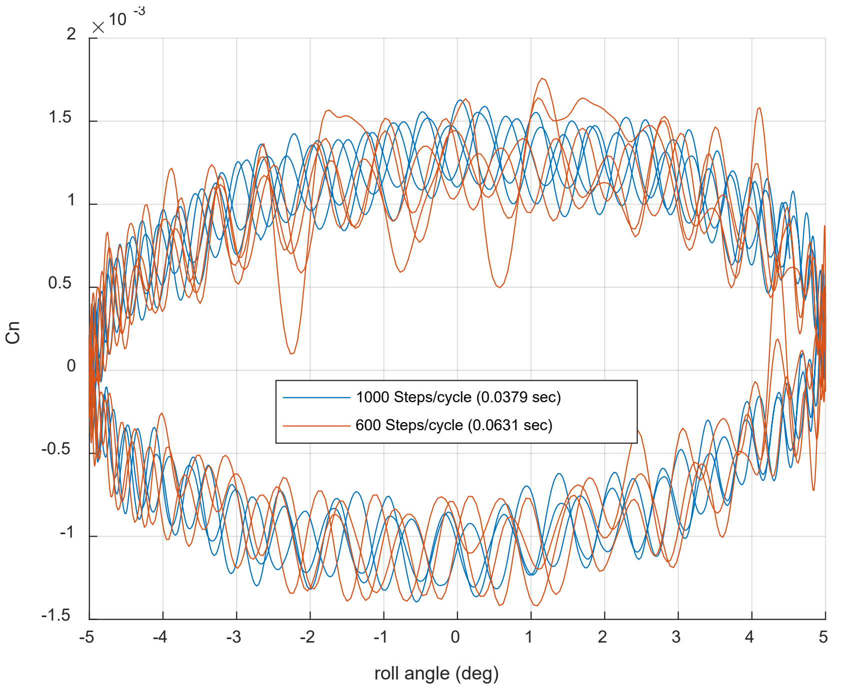
RESULTS: UNSTEADY ROLL OSCILLATION

TIME RESOLUTION STUDY (SA-RC-QCR)

- 90 mil mesh

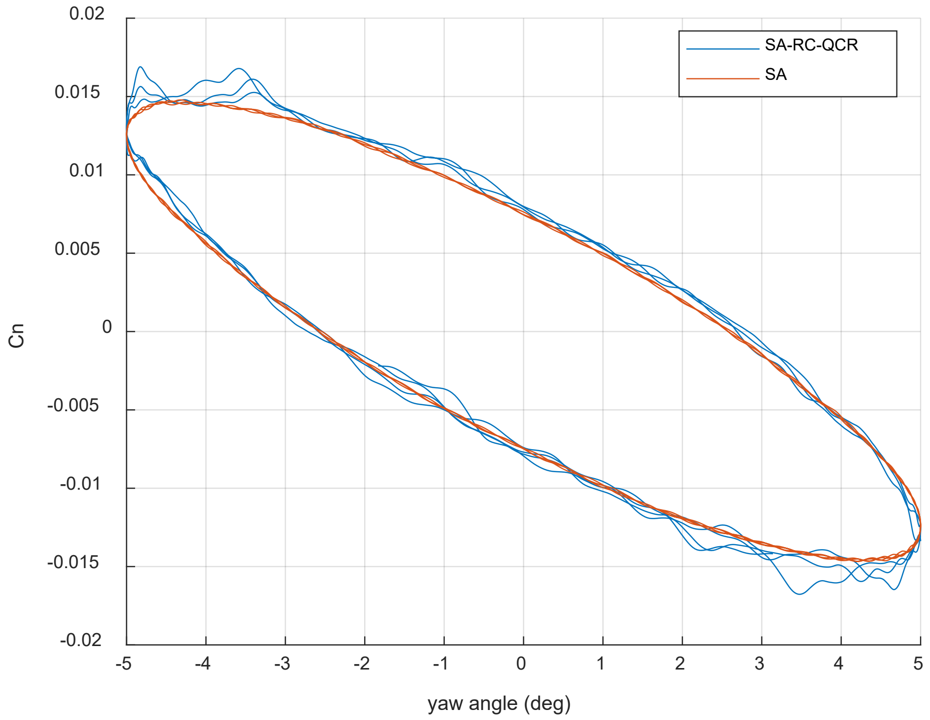


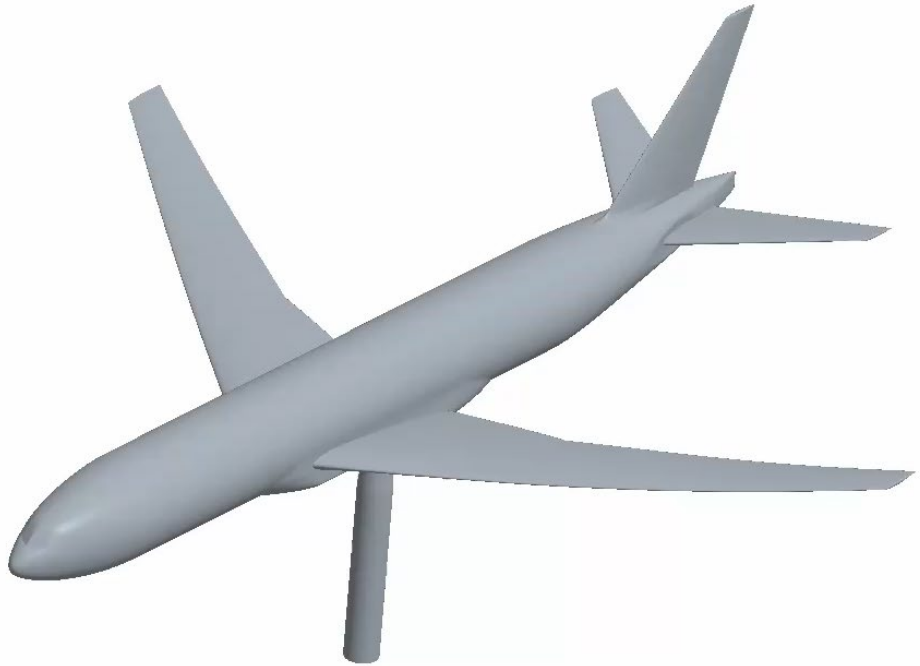




RESULTS: UNSTEADY YAW OSCILLATION

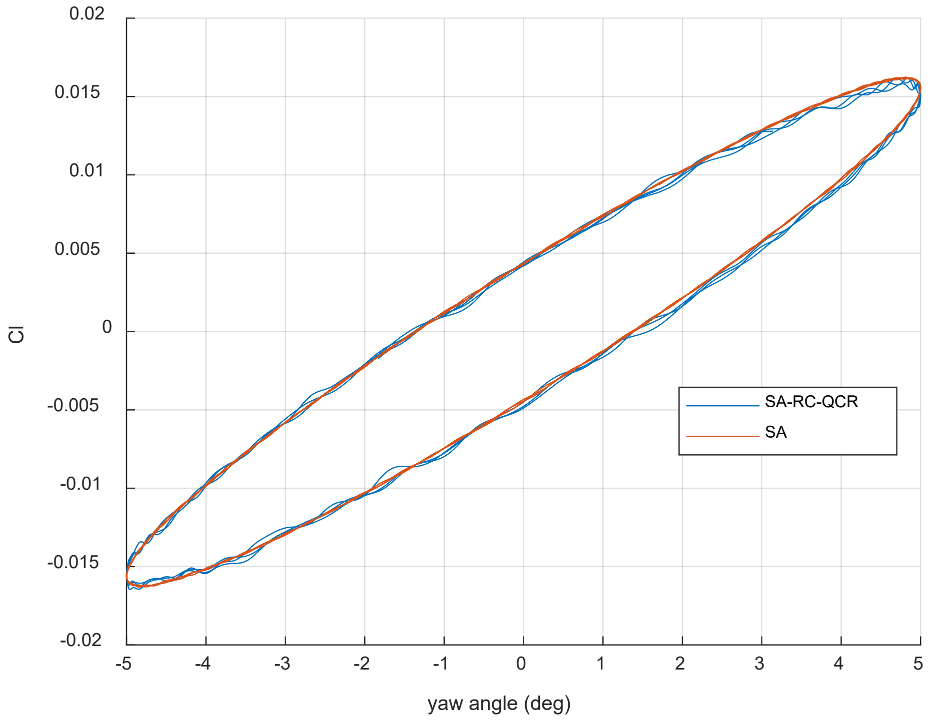
- AoA = 4°, Yaw angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh





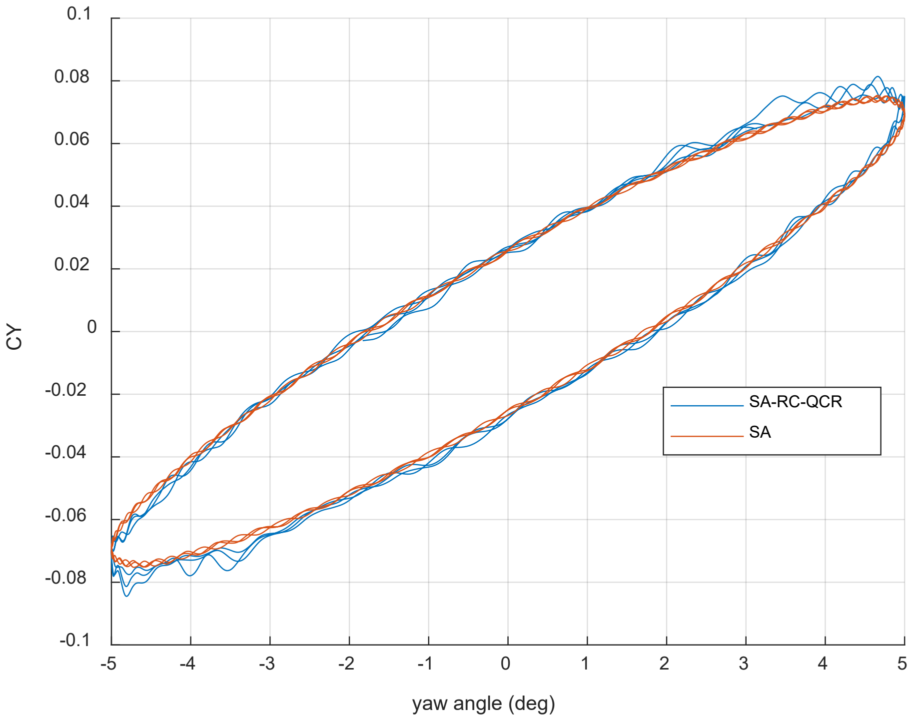
RESULTS: UNSTEADY YAW OSCILLATION

- AoA = 4°, Yaw angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh



RESULTS: UNSTEADY YAW OSCILLATION

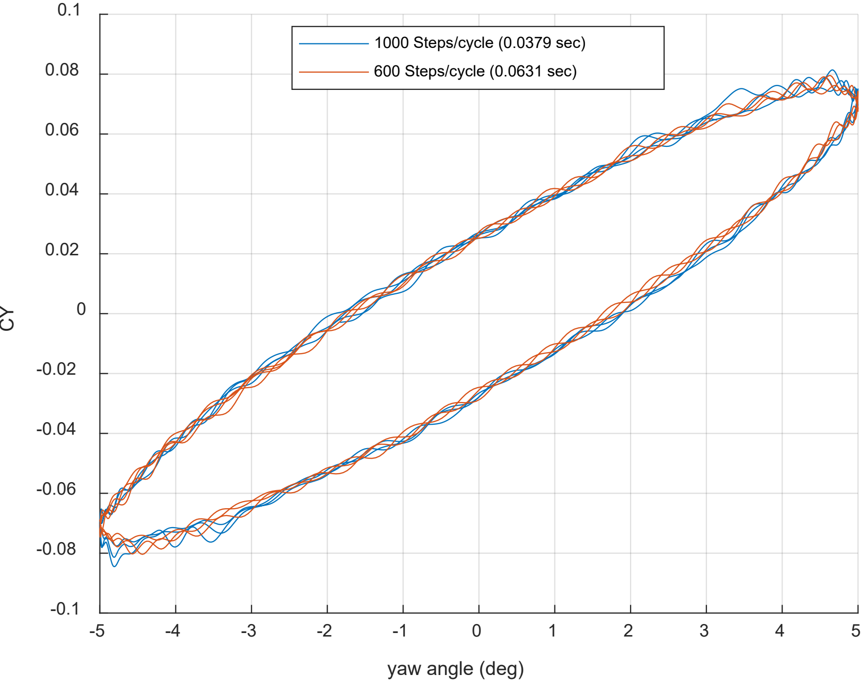
- AoA = 4°, Yaw angle = ± 5°
- Reynolds number 140000, Mach 0.0358, Static Temperature 518° R
- Oscillation Freq
  - Reduced Freq 0.4, Oscillation Freq 0.0262 Hz
  - 1000 steps per cycle -> 0.0379 sec
- 90 million cells mesh
  - Based on mesh setting of 90 million steady-state mesh

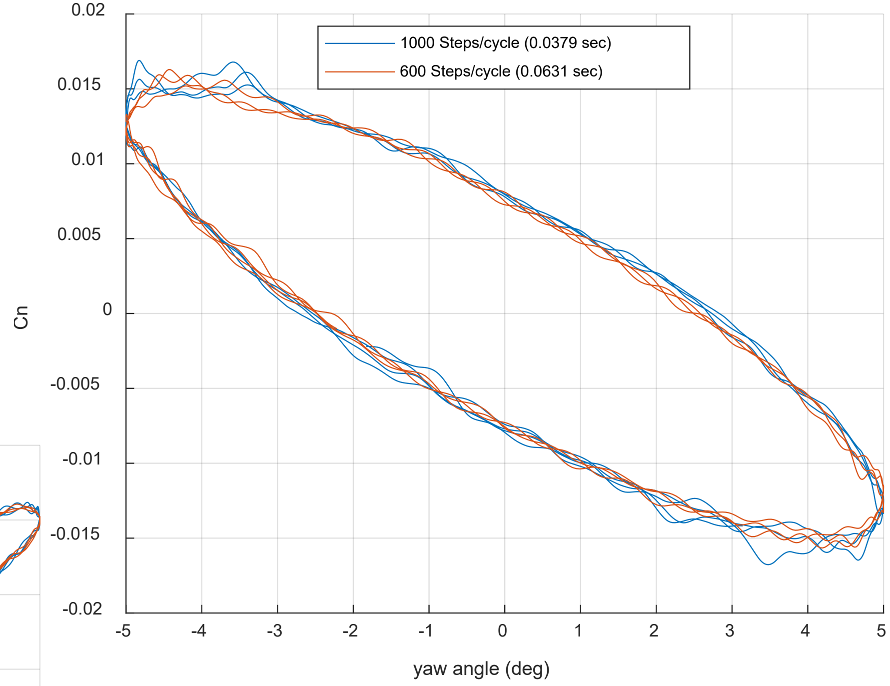


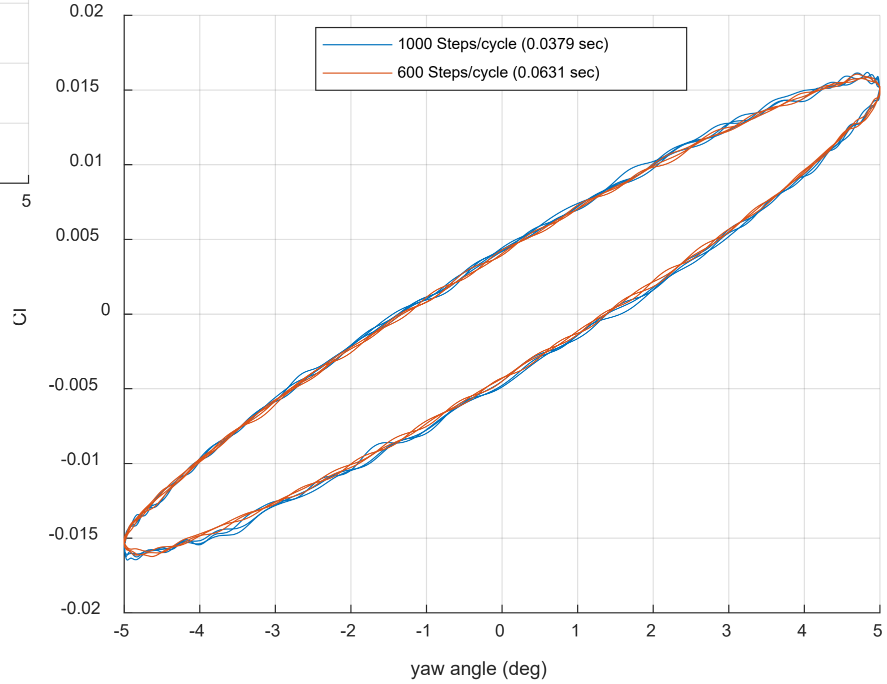
RESULTS: UNSTEADY YAW OSCILLATION

TIME RESOLUTION STUDY (SA-RC-QCR)

- 90 mil mesh







Conclusion

- Steady-state and unsteady conditions simulated using STAR-CCM+
- SA and SA-RC-QCR turbulence models evaluated
- Grid independence study performed to determine appropriate mesh setting

- Steady-state Results
  - AoA sweep shows discrepancy between SA and SA-RC-QCR increases for AoA higher than 6° for C_L, C_D, and C_m
  - SA-RC-QCR underpredicts $C_{m,aoa}$ by 3.1% compared to SA
  - SA-RC-QCR underpredicts $C_{N,aoa}$ by 1.1% compared to SA

  - Beta sweep shows discrepancy between SA and SA-RC-QCR increases for AoA higher than 4° for C_Y, C_l, and C_n
  - $C_{n,beta}$, $C_{l,beta}$, $C_{Y,beta}$ at beta 0° difference less than 4% between SA and SA-RC-QCR

Conclusion

- Unsteady Results
  - Pitch
    - larger discrepancy between SA and SA-RC-QCR at higher pitch angle as shown in state-state results
    - SA-RC-QCR hysteresis results show higher frequency contents
    - Influence of sting shown on the upper surface of the right wing
  - Roll
    - C_l hysteresis has negligible difference between SA and SA-RC-QCR
    - Both CY and Cn show high frequency content for both SA and SA-RC-QCR but amplitude of content in SA is smaller
    - Trends are same for both turbulence models
  - Yaw
    - Very similar results between turbulence models for C_Y, C_l, and C_n but SA-RC-QCR has less uniform results at yaw angle extremities
  - Time Step Study
    - Minor difference between 600 steps/cycle and 1000 steps/cycle for primary variables
  - Mesh
    - Some but no significant difference between 46 mil and 128 mil mesh based on pitch result
  - Cleanest hysteresis response, based on pitch result, was using 46 mil mesh, SA model, 600 steps/cycle
- Balance of simulation accuracy and simulation time by focusing on capturing 1st order effect by using coarser mesh?

QUESTIONS