

Summary of Results for the Second AIAA Stability and Control Prediction Workshop

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AIAA SciTech Forum

06–10 January 2025

*Presenters

Contents

- Workshop overview
- Comparison of CFD results and wind tunnel data
- Conclusions and next steps
- Questions
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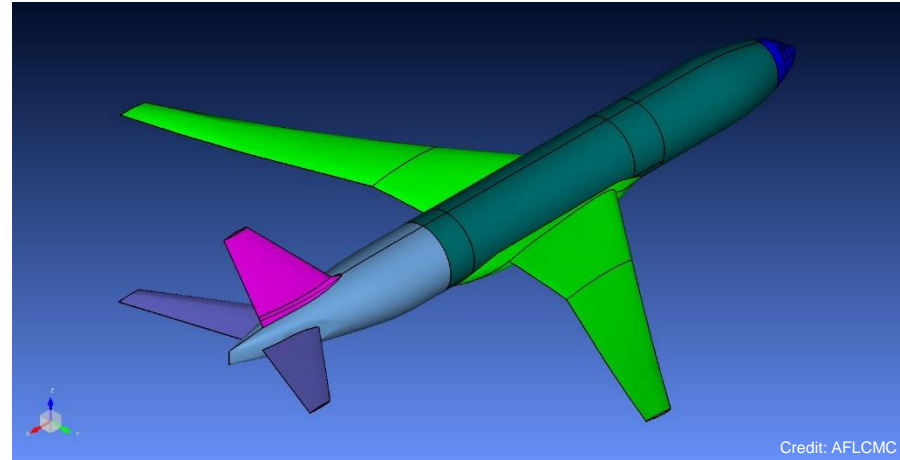
Introduction and Objectives

- Workshop series to establish best-practices for CFD prediction of S&C derivatives and assess limitations of CFD predictions
- 2nd S&CPW focuses on static and dynamic stability derivatives of high-speed version of NASA/Boeing CRM
- Static and dynamic data (forced oscillation) were taken in NASA Langley 12-Foot Low-Speed Tunnel in Fall 2023, using a 2.4% scale model
- Computational results are blind (wind tunnel data were not publicly released before the workshop)



Model Geometry and Reference Quantities

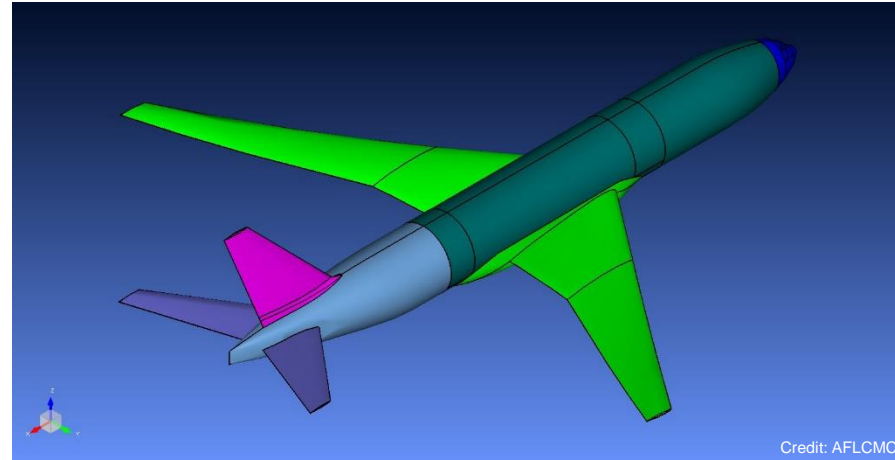
- Geometry is full scale
- Reynolds numbers are wind tunnel scale
- MAC = 275.8 inches (\bar{c})
- Wingspan = 2313.5 inches (b)
- Ref. Area = 594,720 inches² (S)
- Body-axis coord. sys. (xByRzU)
- Force and moment coefficients:
 - Normal force: $C_N = C_Z = \frac{F_Z}{\bar{q}S}$
 - Axial force: $C_A = C_X = \frac{F_X}{\bar{q}S}$
 - Side force: $C_S = C_Y = \frac{F_Y}{\bar{q}S}$



- Pitching moment: $C_m = C_{M_y} = \frac{M_y}{\bar{q}S\bar{c}}$
- Yawing moment: $C_n = -C_{M_z} = \frac{-M_z}{\bar{q}Sb}$
- Rolling moment : $C_l = -C_{M_x} = \frac{-M_x}{\bar{q}Sb}$

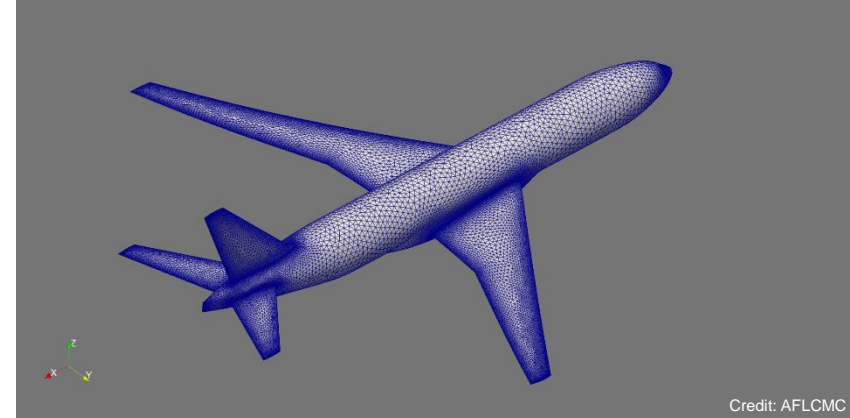
Model Geometry and Reference Quantities (cont.)

- Angle of attack (AoA, α) positive nose-up
- Sideslip (AoS, β) positive nose to port
- Roll angle (ϕ) positive right wing down
- Pitch angle (θ) positive nose-up
- Yaw angle (ψ) positive nose to starboard
- Force accounting: include only CRM model surfaces (not sting)



Computational Meshes

- Use at least 3 levels of increasing resolution to evaluate mesh independence
- Workshop meshes were provided by AFLCMC and Bihrlle



Mesh	Num. Nodes	Num. Cells
AFLCMC Mesh A	~3.4M	~10M
AFLCMC Mesh B	~6.7M	~22M
AFLCMC Mesh C	~16M	~60M
AFLCMC Mesh D	~49M	~210M
Bihrlle (fine)	~30M	~72M

Test Case 1

➤ Test Case 1a, Longitudinal Static Stability Derivatives, CRM with Tails and Sting (required)

- AoA Sweep (Run 15); AoA in bold are required, others are optional
 - Mach = 0.052, Re = 200,000, T = 518°R
 - AoA = -5, **0**, 2, **4**, 6, **8**, 10, **12**, 14, **16**, 18, **20**, 22, 24, 26, 28, 30, 35, 40, 45
 - Report final values (or time-averages) of all six forces and moments
 - Report C_{N_α} and C_{m_α} at 4-deg AoA

➤ Test Case 1b, Lateral/Directional Static Stability Derivatives, CRM with Tails and Sting (optional)

- AoS Sweep at 0-deg AoA (Run 25); AoS in bold are recommended
 - Mach = 0.052, Re = 200,000, T = 518°R
 - AoS = **-10**, -8, **-4**, -2, **0**, 2, **4**, 8, **10**
 - Report final values (or time-averages) of all six forces and moments
 - Report C_{Y_β} , C_{l_β} , C_{n_β} at 0-deg AoA and AoS

➤ Test Case 1c, Lateral/Directional Static Stability Derivatives, CRM with Tails and Sting (required)

- AoS sweep at 4-deg AoA (Run 26); AoS in bold are required, others are optional
 - Mach = 0.052, Re = 200,000, T = 518°R
 - AoS = **-10**, -8, **-4**, -2, **0**, 2, **4**, 8, **10**
 - Report final values (or time-averages) of all six forces and moments
 - Report C_{Y_β} , C_{l_β} , C_{n_β} at 0-deg AoS

➤ Test Case 1d, Longitudinal Static Stability Derivatives, CRM with Sting no Tails (optional)

- AoA Sweep (Run 7); AoA in bold are recommended
 - Mach = 0.052, Re = 200,000, T = 518°R
 - AoA = -5, **0**, 2, **4**, 6, **8**, 10, **12**, 14, **16**, 18, **20**, 22, 24, 26, 28, 30, 35, 40, 45
 - Report final values (or time-averages) of all six forces and moments
 - Report C_{N_α} and C_{m_α} at 4-deg AoA

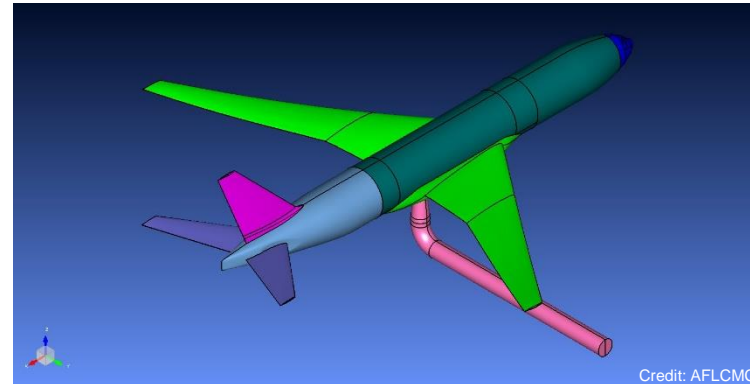
Test Case 2a

Test Case 2a, Dynamic Longitudinal Derivatives with Tails and Sting (required)

- Pitching Oscillation (Run 68)
 - Mach = 0.0358, Re = 140,000, T = 518°R
 - AoA = 3-deg, +/- 5-deg (sinusoidal oscillation between +8-deg and -2-deg)
 - Reduced frequency is 0.04, where $f_r = \frac{\omega \bar{c}}{2V}$ (ω is the oscillation frequency in rad/sec, \bar{c} is the MAC, V is the freestream velocity). For the full-scale model, the oscillation frequency is 0.0222 Hz.
 - **Report time histories of forces and moment coefficients in body axes**
 - **Enough time steps should be run to report results over 3 converged oscillation cycles**
 - Report C_{N_q} and C_{m_q} (where q is the pitch rate in **radians** per second)
- Optional
 - Repeat Test Case 2a for reduced frequencies of 0.06, 0.08 and 0.10 or 0.0332, 0.0443 and 0.0554 Hz for the full-scale model (Runs 69, 70 and 71)



Credit: NASA



Credit: AFLCMC

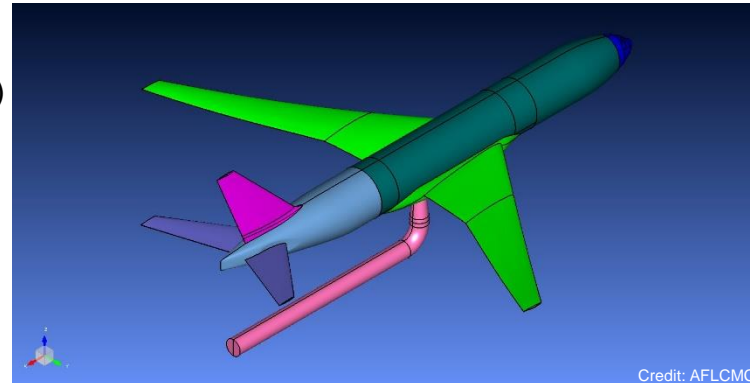
Test Case 2b

➤ Test Case 2b, Dynamic Lateral/Directional Derivatives with Tails and Sting (required)

- Rolling Oscillation (Run 2)
 - Mach = 0.0358, Re = 140,000, T = 518°R
 - AoA = 3-deg
 - Roll angle = sinusoidal oscillation between +/- 5-deg
 - Reduced frequency is 0.4, where $f_r = \frac{\omega b}{2V}$ (ω is the oscillation frequency in rad/sec, b is the span, V is the freestream velocity). For the full-scale model, the oscillation frequency is 0.0264 Hz.
 - **Report time histories of forces and moment coefficients in body axes**
 - **Enough time steps should be run to report results over 3 converged oscillation cycles**
 - Report C_{l_p} and C_{n_p} (where p is the roll rate in **radians** per second)
- Optional
 - Repeat Test Case 2b for reduced frequencies of 0.2, 0.6 and 0.8, or 0.0132, 0.0396 and 0.0528 Hz for the full-scale model (Runs 5, 3 and 4)



Credit: NASA

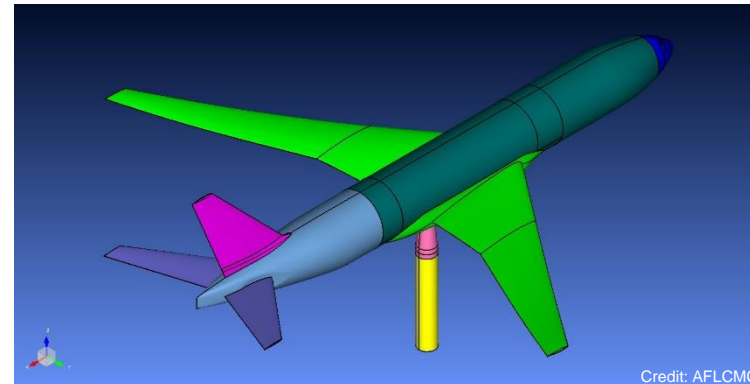


Credit: AFLCMC

Test Case 2c

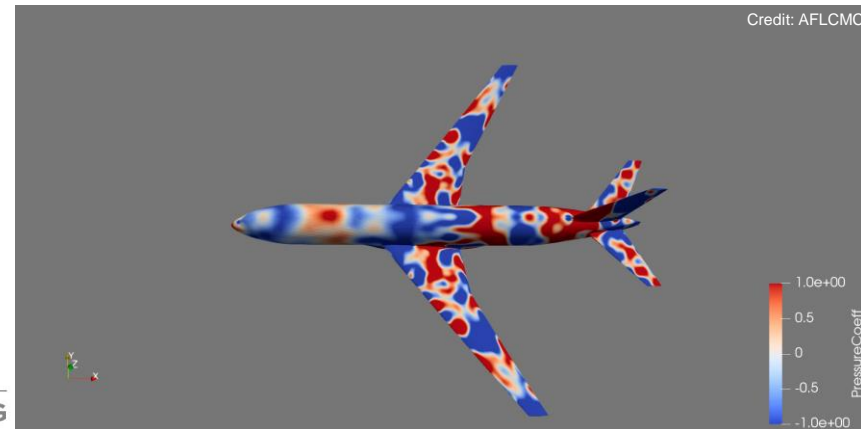
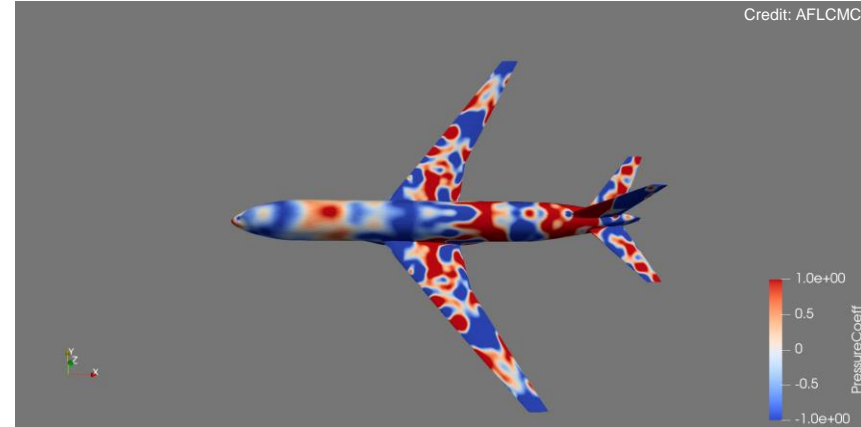
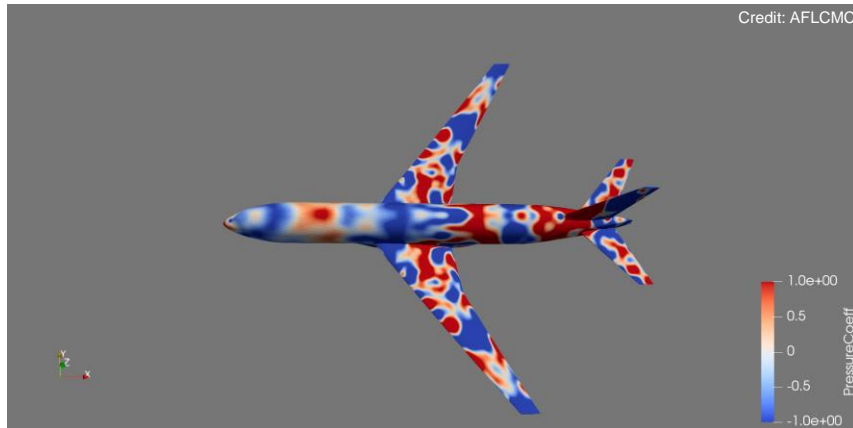
Test Case 2c, Dynamic Lateral/Directional Derivatives with Tails and Sting (required)

- Yawing Oscillation (Run 52)
 - Mach = 0.0358, Re = 140,000, T = 518°R
 - AoA = 3-deg
 - Yaw angle = sinusoidal oscillation between +/- 5-deg
 - Reduced frequency is 0.4, where $f_r = \frac{\omega b}{2V}$ (ω is the oscillation frequency in rad/sec, b is the span, V is the freestream velocity). For the full-scale model, the oscillation frequency is 0.0264 Hz.
 - **Report time histories of forces and moment coefficients in body axes**
 - **Enough time steps should be run to report results over 3 converged oscillation cycles**
 - Report C_{l_r} and C_{n_r} (where r is the yaw rate in **radians** per second)
- Optional
 - Repeat Test Case 2c for reduced frequencies of 0.2, 0.6 and 0.8 or 0.0132, 0.0396 and 0.0528 Hz for the full-scale model (Runs 51, 53 and 54)



Optional Test Cases

- Test Case 3: Use other methods available (such as custom training maneuvers) to determine the static and dynamic stability derivatives at 3-deg AoA.
- Test Case 4: Repeat Test Case 1 with CRM and no Sting
- Test Case 5: Repeat Test Case 2 with CRM and no Sting



Comparison of Results

S&CPW2 Participants

Authors (*Presenter)	Organization	Method
Dan. D. Vicroy, Benjamin M. Simmons*	Adaptive Aerospace Group and NASA Langley	Wind Tunnel
Mehdi Ghoreyshi*, Pooneh Aref	US Air Force Academy	Kestrel
Daniel E. Enriquez*	Altair Engineering	FlightStream
Andrew J. Lofthouse*, William Vogel	Air Force Life Cycle Management Center	Kestrel
Kelly R. Laflin*, Steven M. Klausmeyer	Textron Aviation	FUN3D
Zhuoneng Li, Andrea Da Ronch*, Xupeng Sui	University of Southampton	STAR-CCM+
Seung Yoo*	NASA Armstrong Flight Research Center	STAR-CCM+
Wei Liao, Collin Strassburger*	Bihrlle Applied Research	FUN3D

- Participant ID numbers have been removed for public release of this presentation
- Participants are not ordered by their ID number on this slide

Stability Derivative Calculation Approach

Static stability derivatives

- Central difference approximation
- Differentiation of local polynomial fit

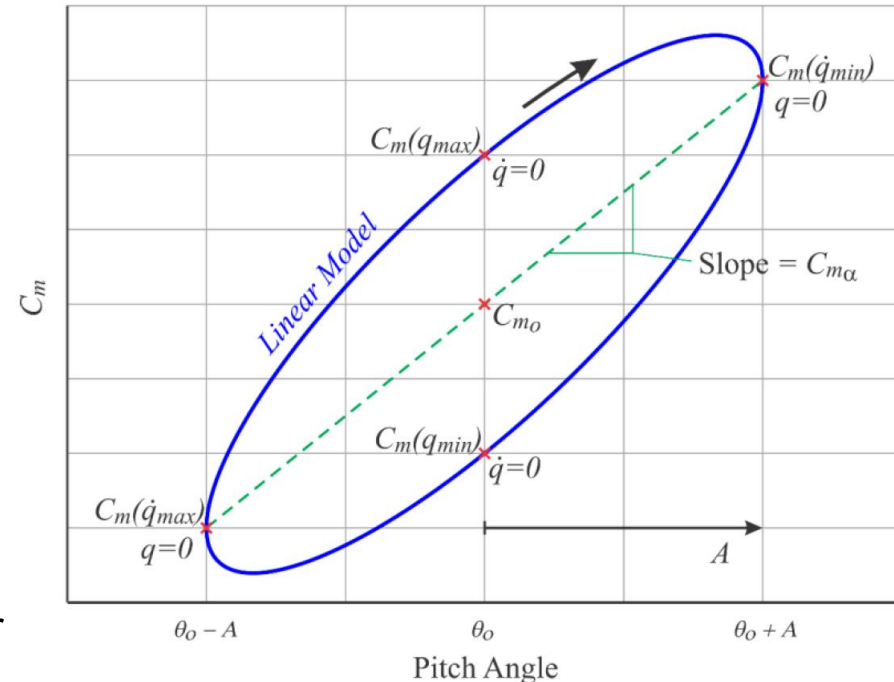
Dynamic stability derivatives

- Integration method
 - $\overline{C_{m_q}}(\alpha_o) = \frac{4V}{\bar{c}\omega AT} \int_0^T C_m(t) \cos(\omega t) dt$
 - Legacy method; only valid in linear regions
- Specific point method
 - $\overline{C_{m_q}}(\alpha_o) = \frac{V}{\bar{c}A\omega} [C_m(q_{max}) - C_m(q_{min})]$
 - Preferred method; valid in nonlinear regions

CFD forced oscillation data processing

- Remove initial transients (if applicable)
- Resample to 5 Hz
- Apply a zero phase-shift digital low-pass 6th order Butterworth filter ($f_c = 5f_{osc}$)
- Trim data to include full cycles for analysis

Vicroy, D. D., "A Guide to Forced Oscillation Data Processing and Analysis," NASA TP-20210023569.



Example linear model hysteresis loop.

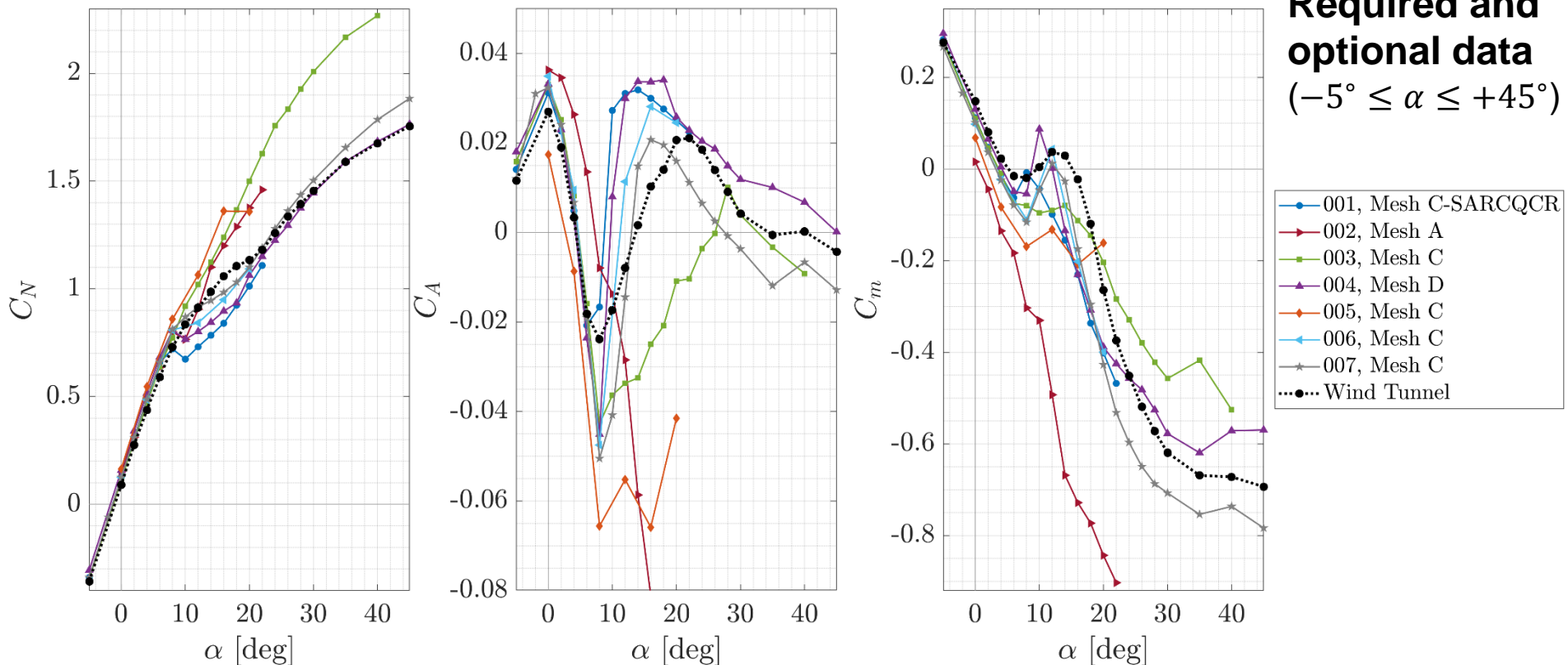
Comparison Notes

- One dataset was selected per participant per test case for the overall comparison
 - Easier viewing of data from all participants
 - Selected based on best judgment (e.g., convergence of results)
- Sign corrections were applied to match the expected trends
- Meshes were renamed coarsest to finest (e.g., A = coarse, B = medium, C = fine, etc.)
- Distinguishing information is provided in the plot legends to inform participants on which dataset is shown

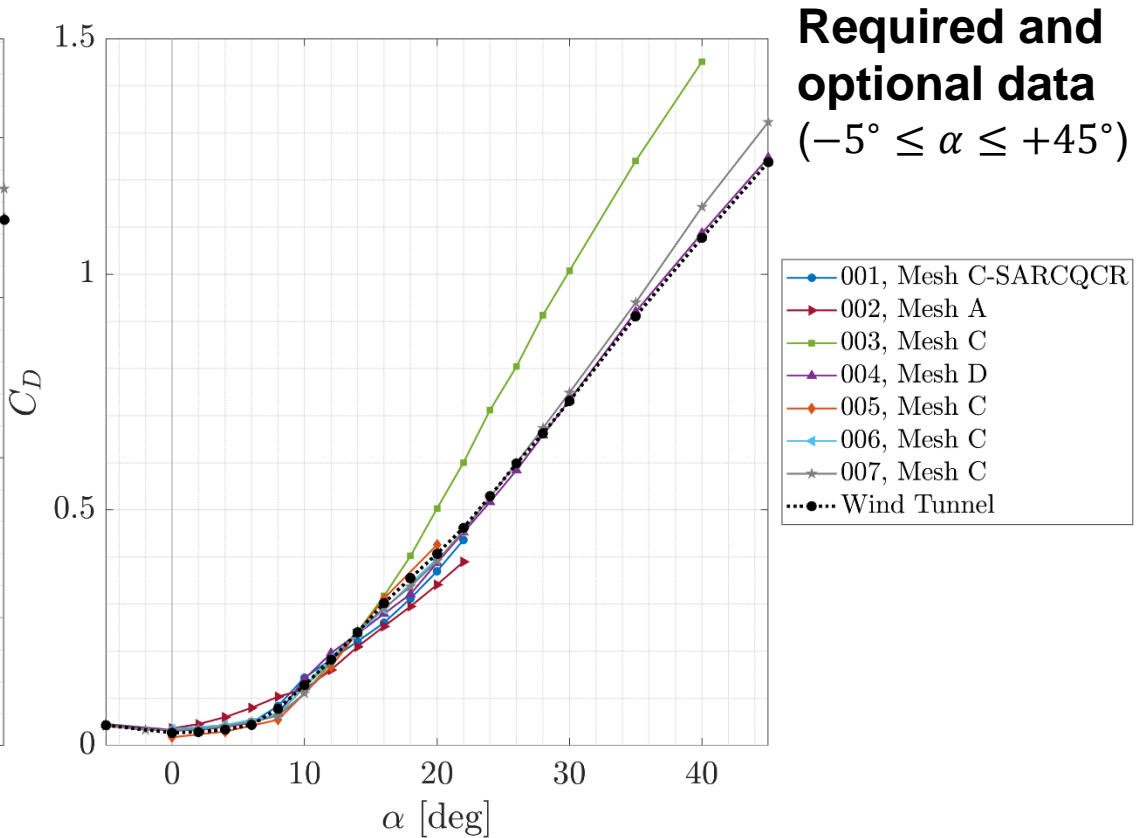
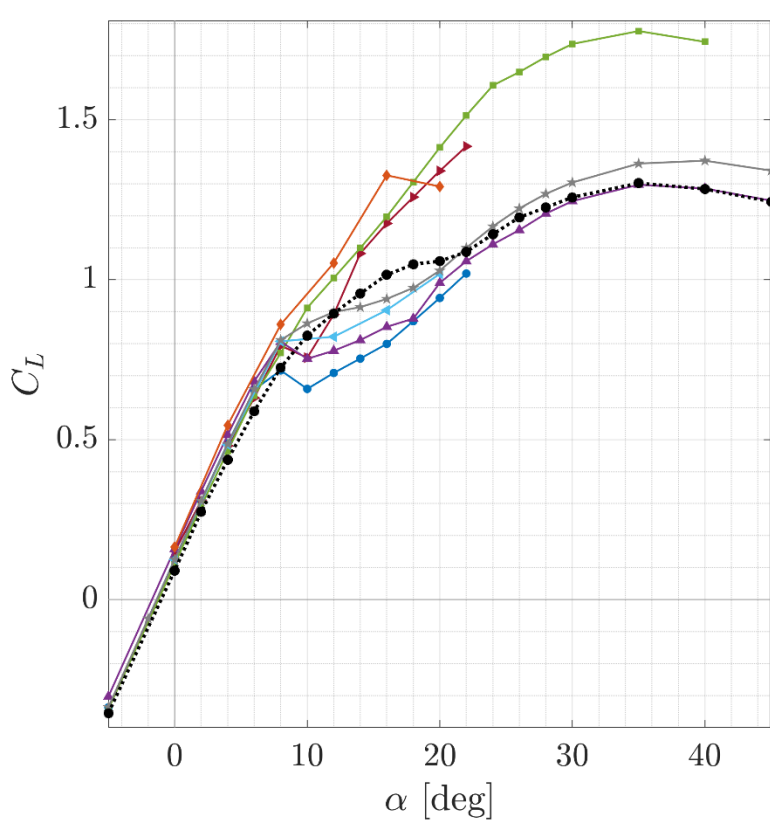
Case 1a Results

- Angle of attack (α) sweep
- $M = 0.052$; $Re = 200,000$; $T = 518^\circ\text{R}$
- CRM with sting and tail

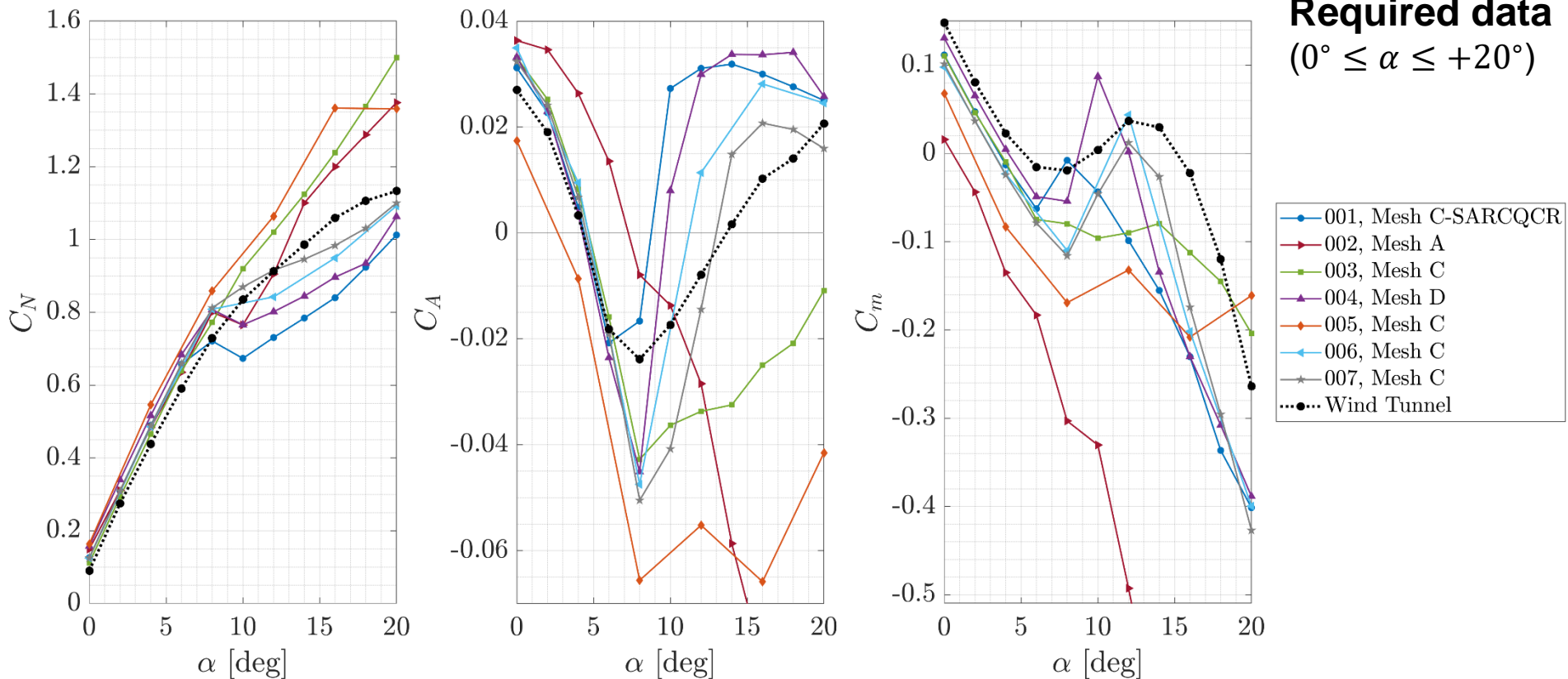
Case 1a: α -Sweep with Sting and Tail



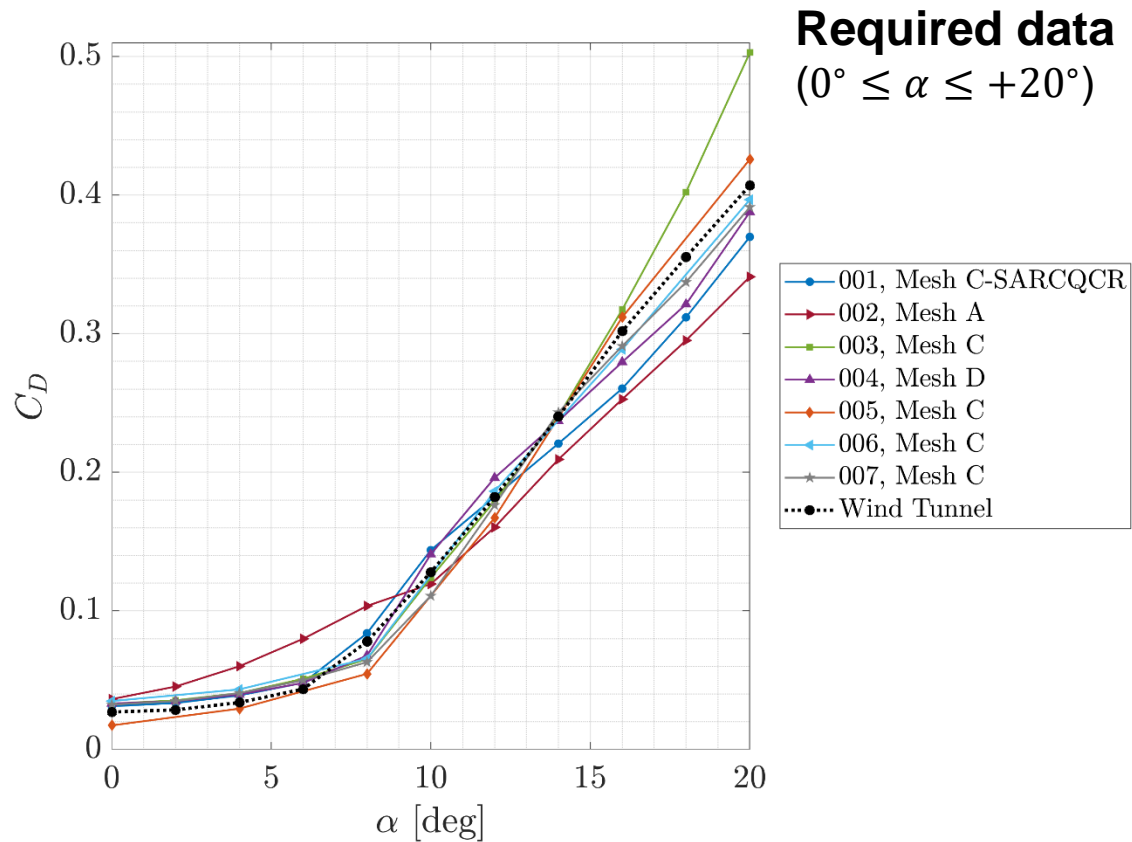
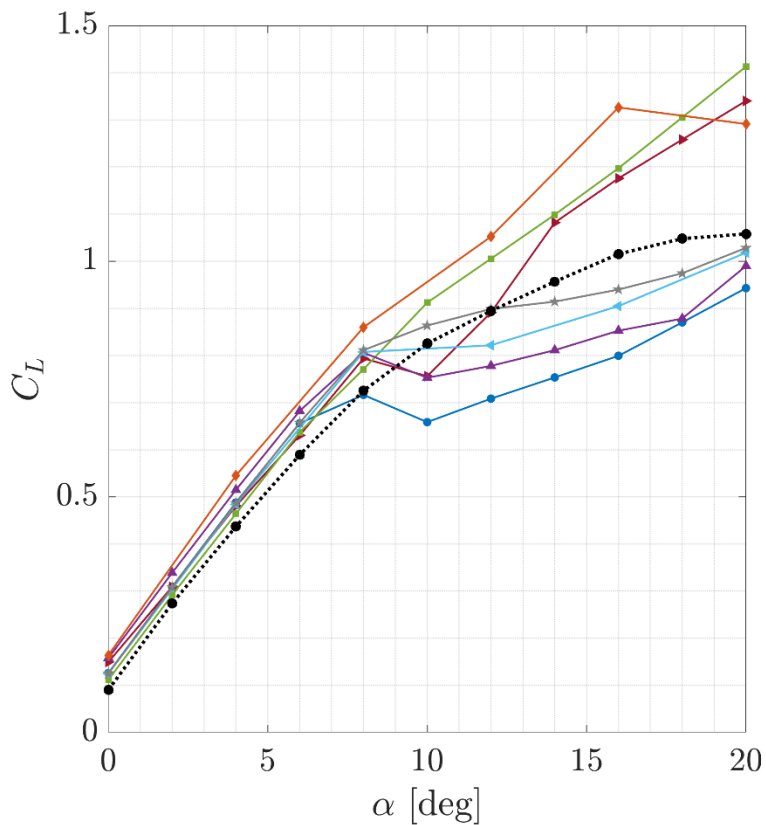
Case 1a: α -Sweep with Sting and Tail



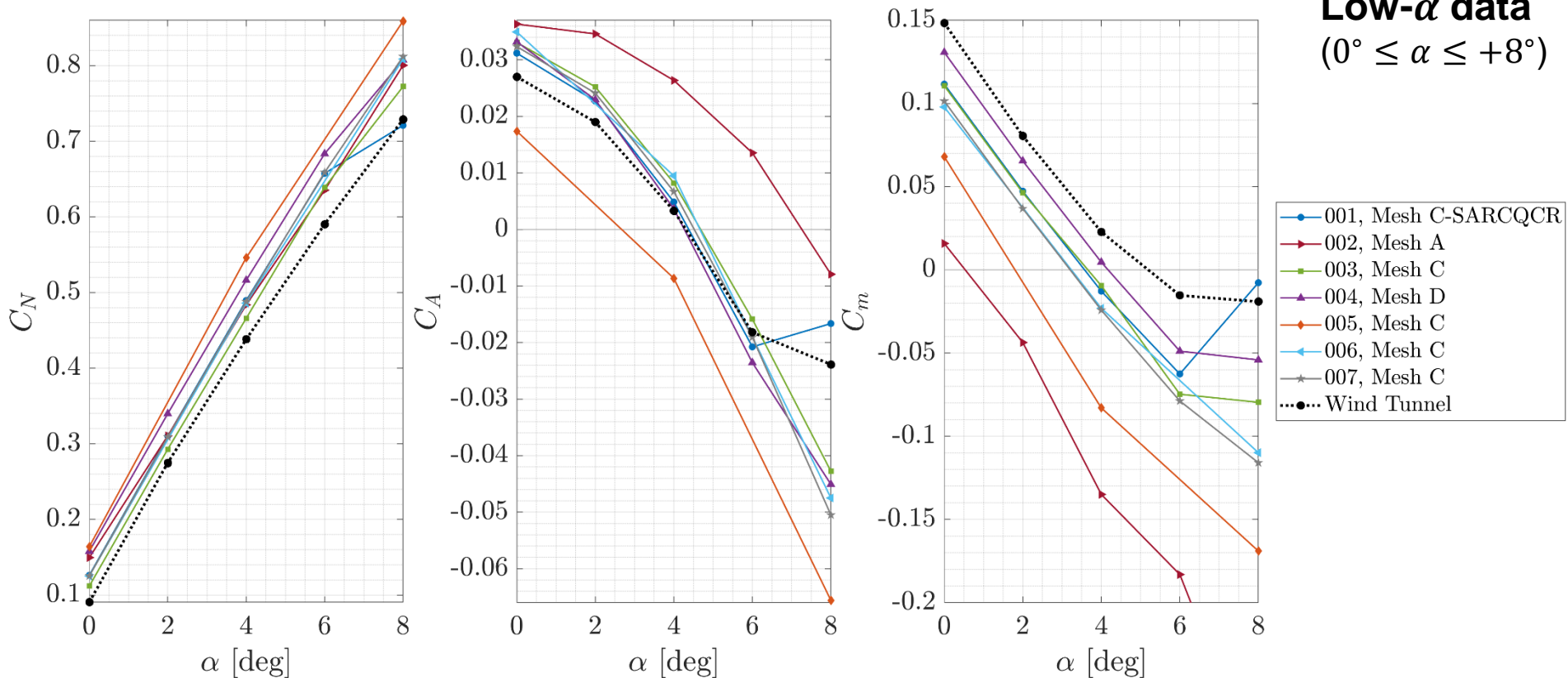
Case 1a: α -Sweep with Sting and Tail



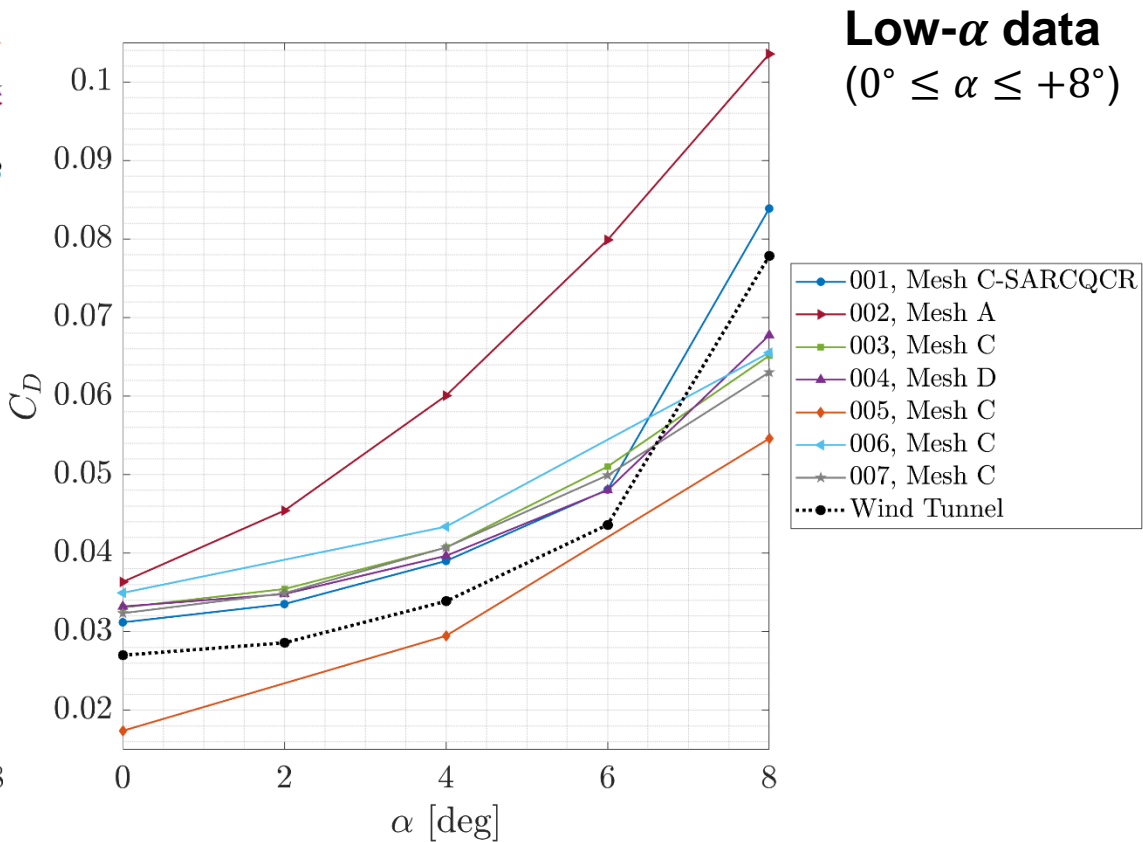
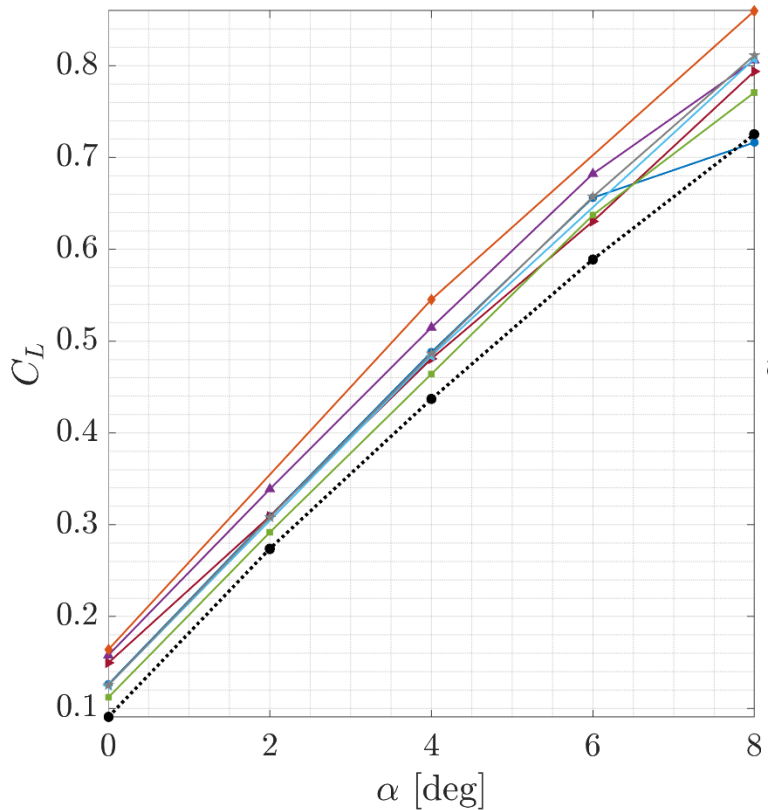
Case 1a: α -Sweep with Sting and Tail



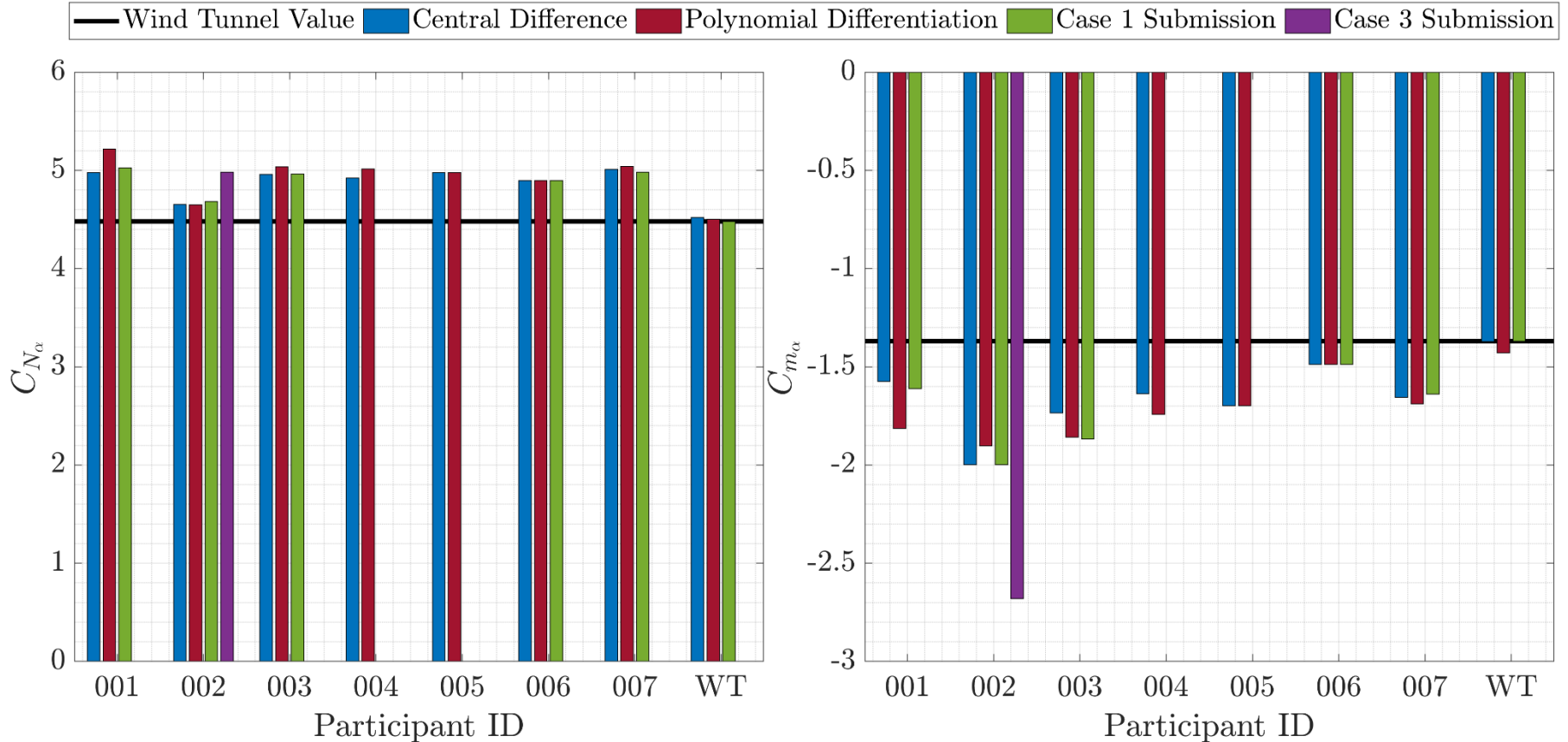
Case 1a: α -Sweep with Sting and Tail



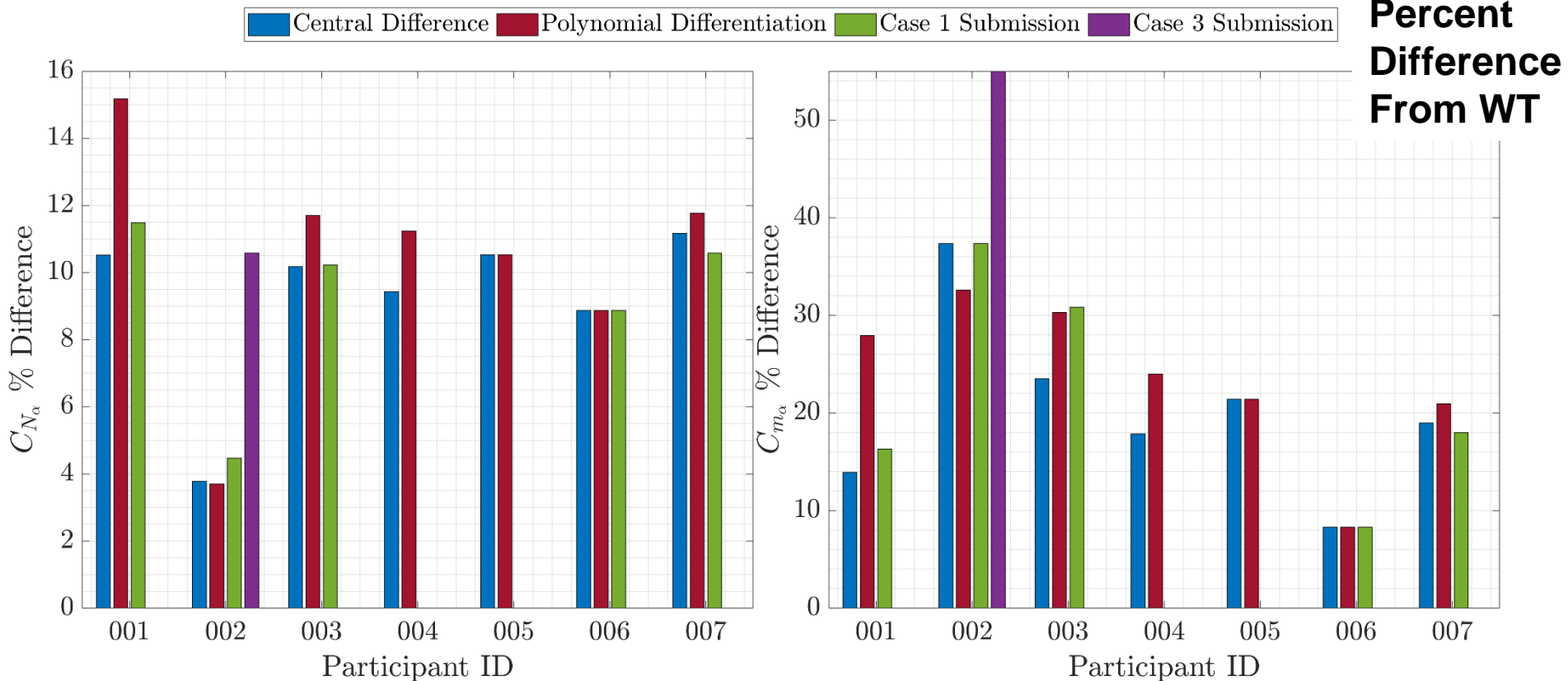
Case 1a: α -Sweep with Sting and Tail



Case 1a: Static Stability Derivatives ($\alpha = 4^\circ$)



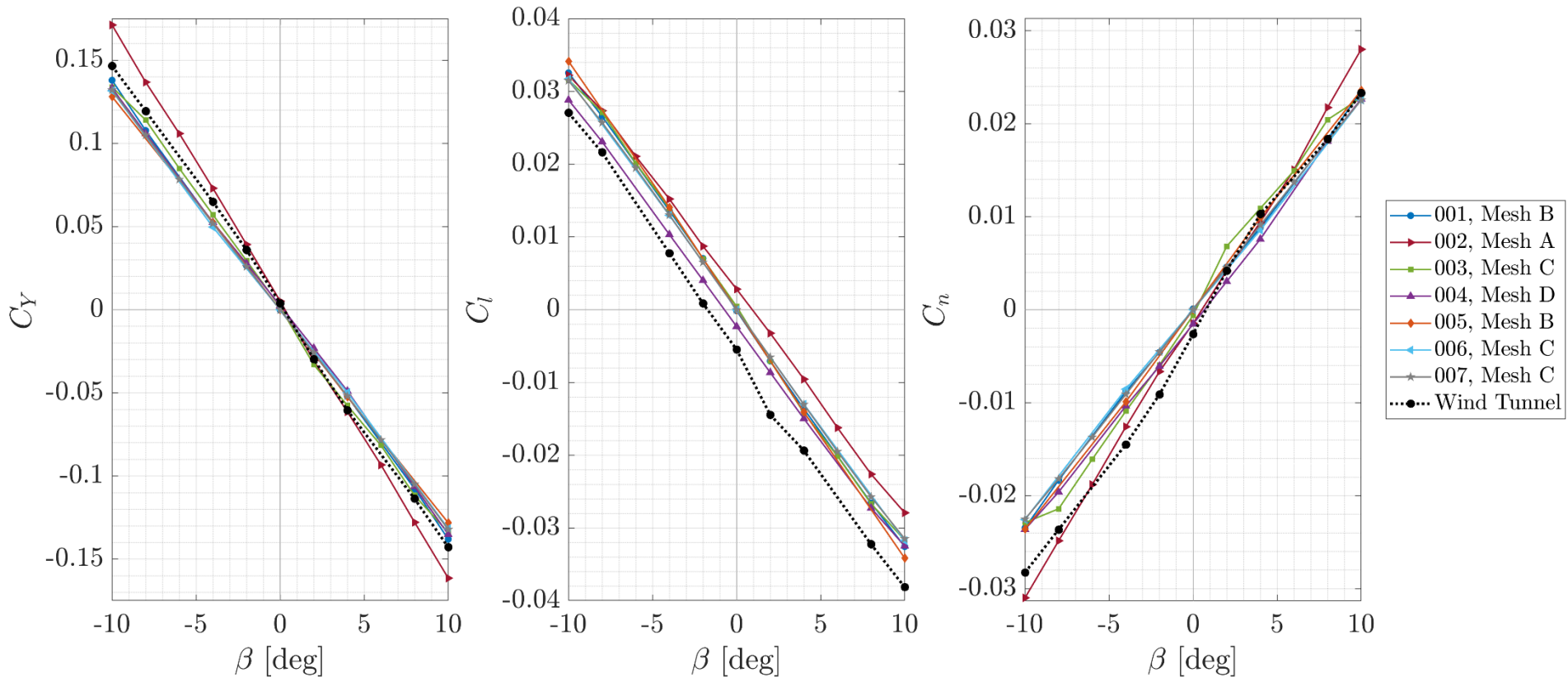
Case 1a: Static Stability Derivatives ($\alpha = 4^\circ$)



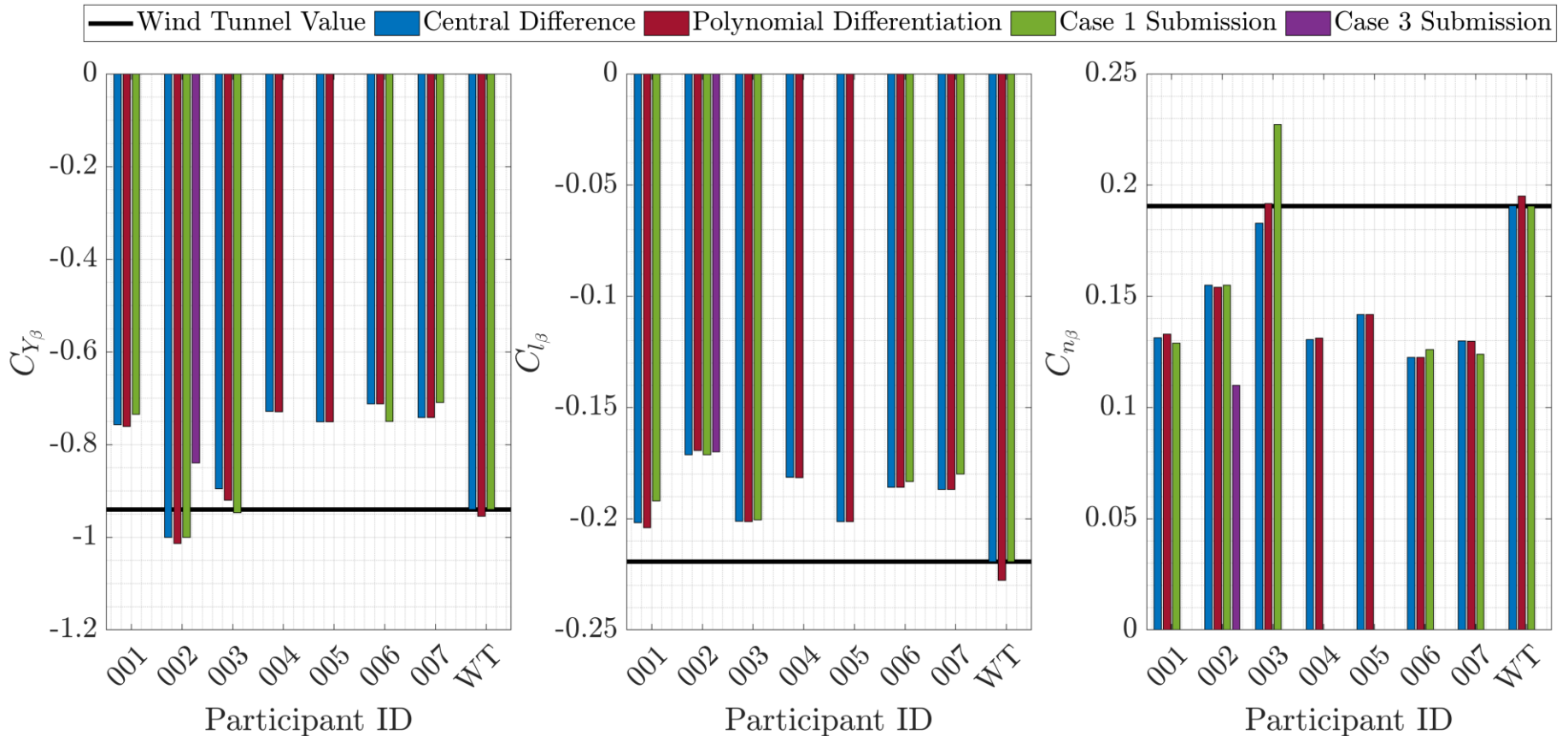
Case 1c Results

- Angle of sideslip (β) sweep at $\alpha = 4^\circ$
- $M = 0.052$; $Re = 200,000$; $T = 518^\circ R$
- CRM with sting and tail

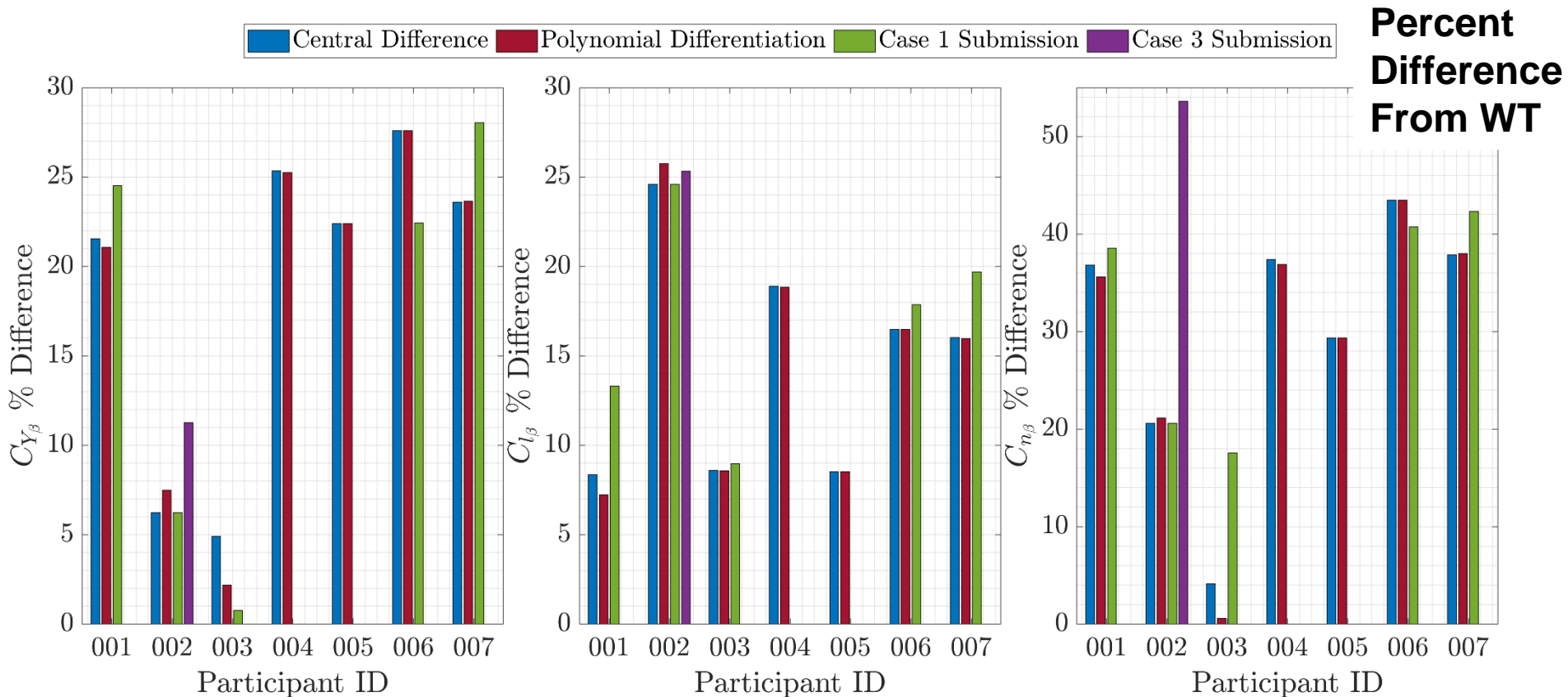
Case 1c: β -Sweep with Sting and Tail ($\alpha = 4^\circ$)



Case 1c: Static Stability Derivatives ($\alpha = 4^\circ$)



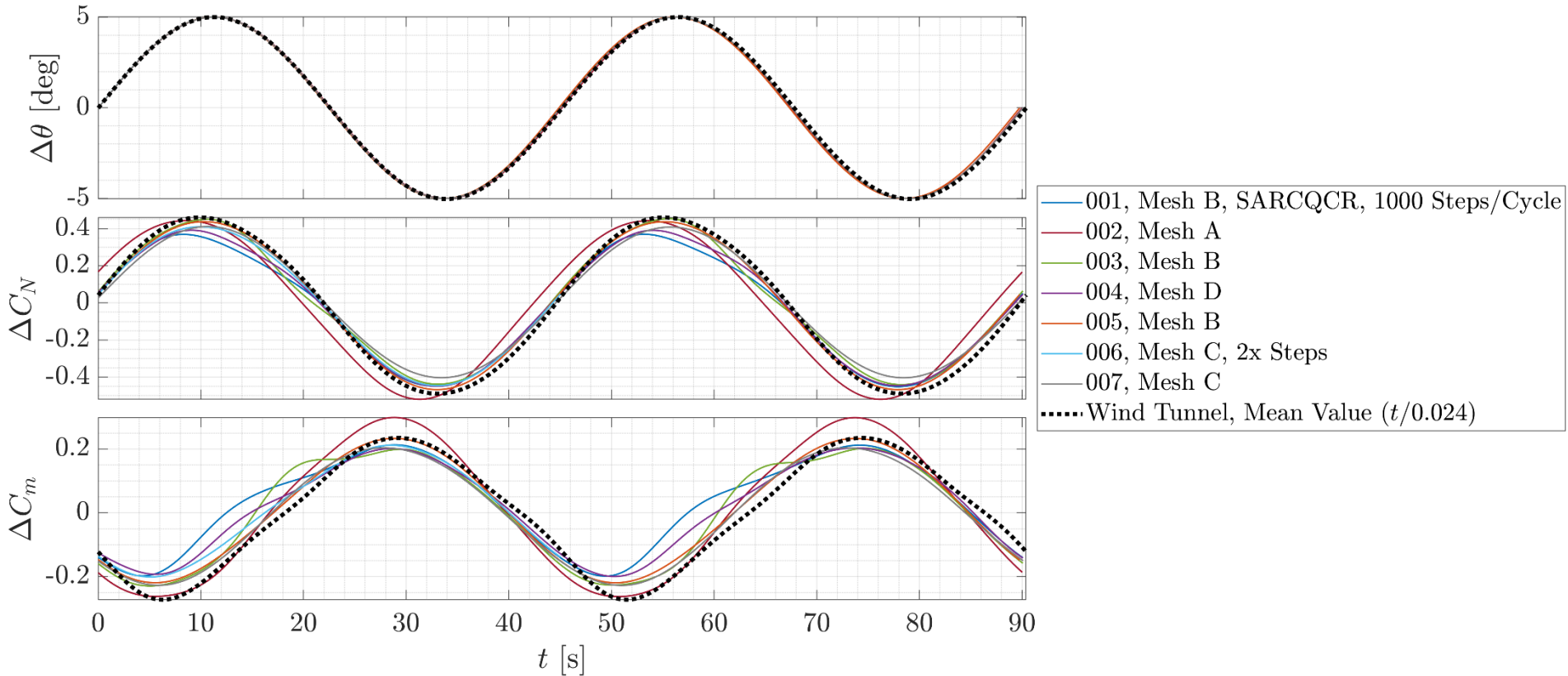
Case 1c: Static Stability Derivatives ($\alpha = 4^\circ$)



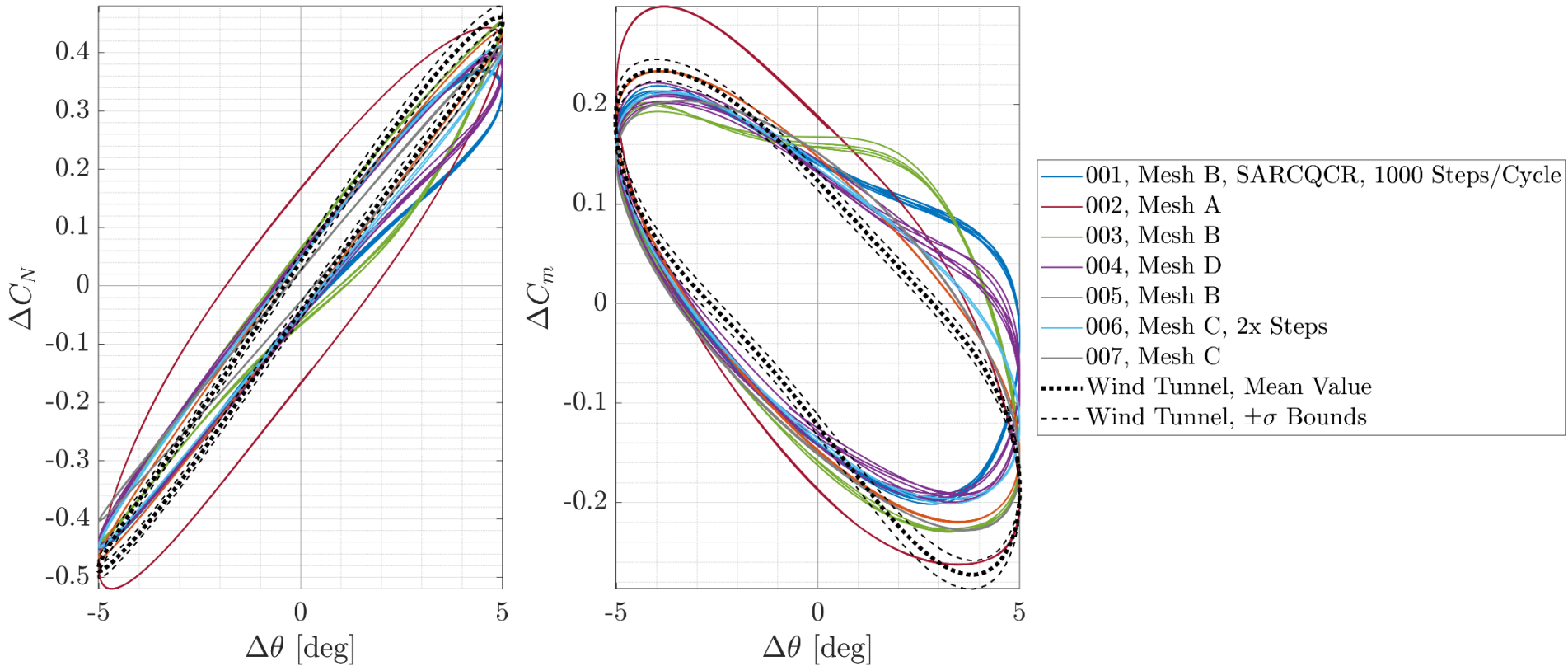
Case 2a Results

- Pitch forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\theta \leq +5^\circ$
- $f_r = \frac{\omega \bar{c}}{2V} = 0.04$ (optional: 0.06, 0.08, 0.10)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ\text{R}$
- CRM with sting and tail

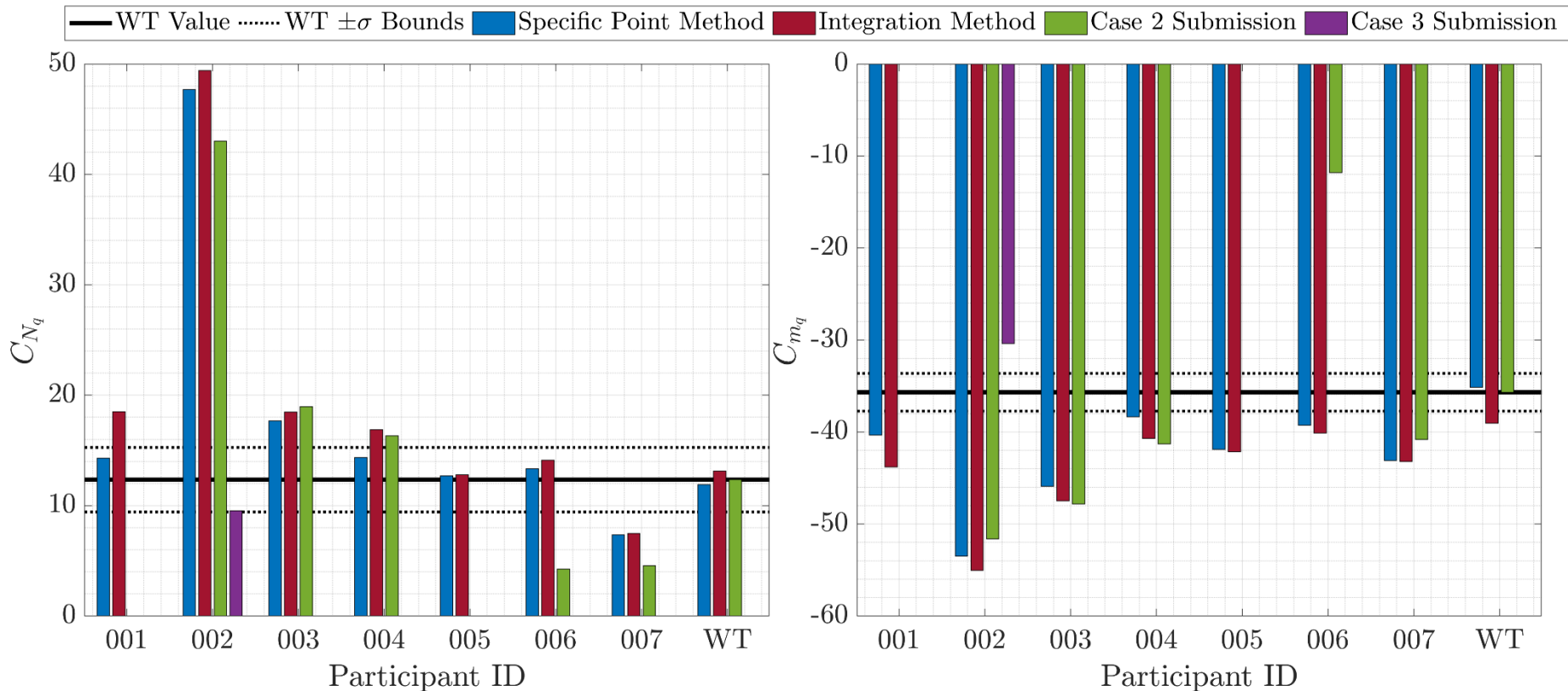
Case 2a: Time Histories ($f_r = 0.04$)



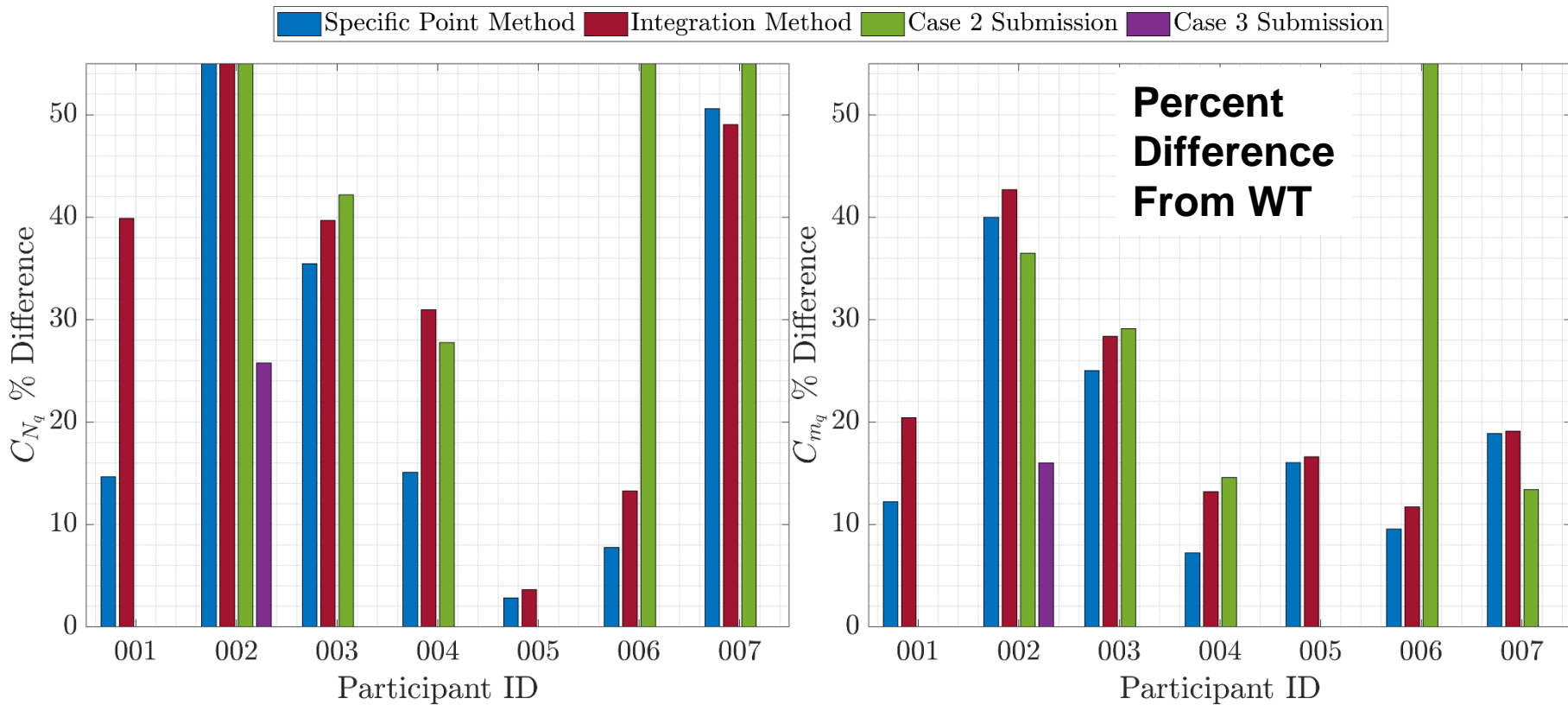
Case 2a: Hysteresis Loops ($f_r = 0.04$)



Case 2a: Dynamic Stability Derivatives ($f_r = 0.04$)



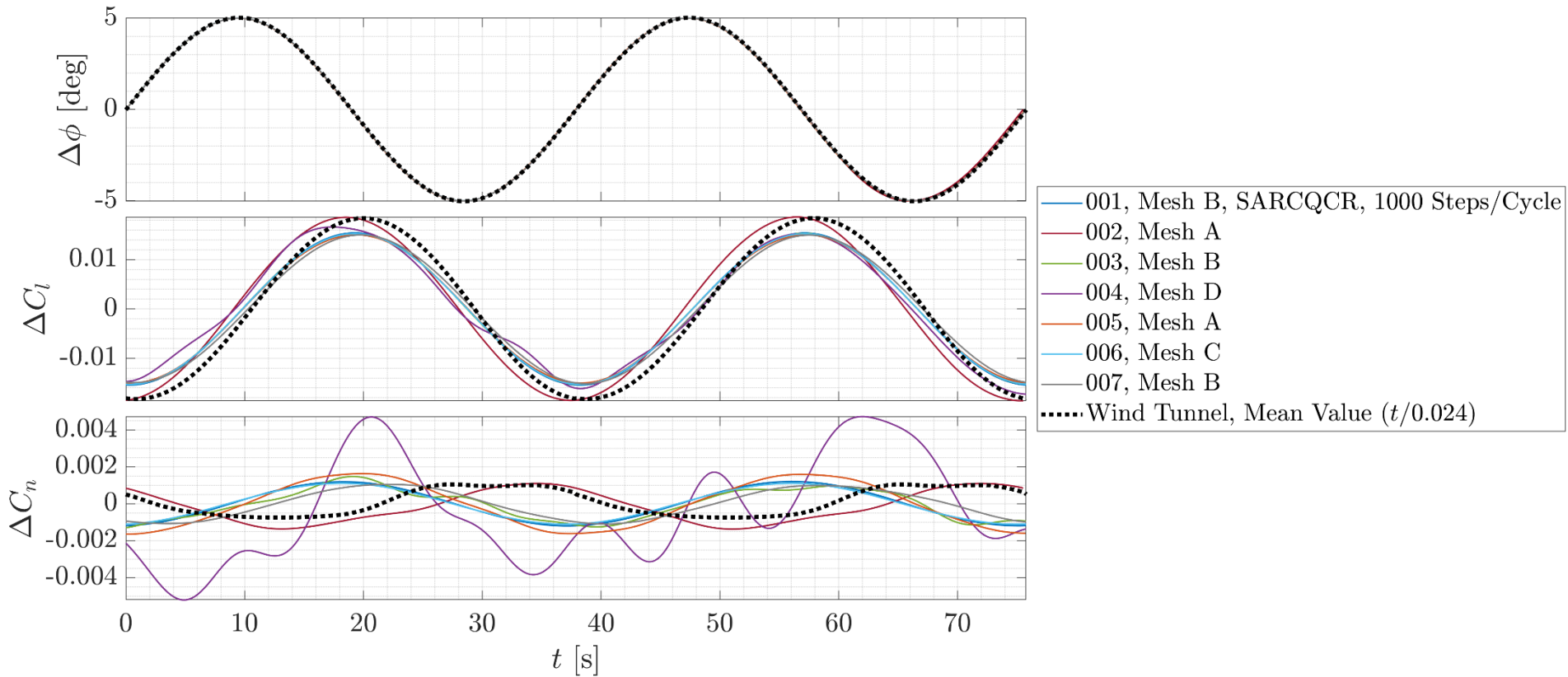
Case 2a: Dynamic Stability Derivatives ($f_r = 0.04$)



Case 2b Results

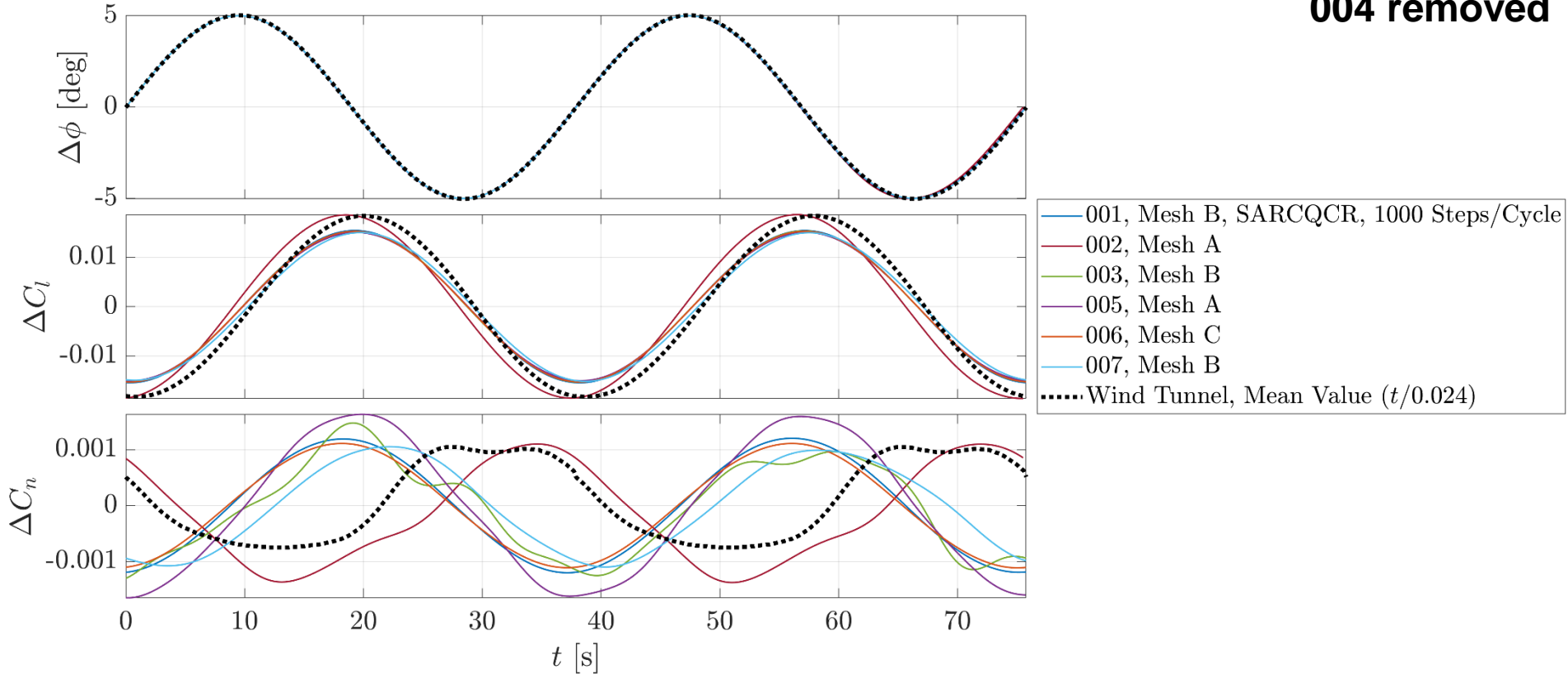
- Roll forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\phi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ\text{R}$
- CRM with sting and tail

Case 2b: Time Histories ($f_r = 0.4$)

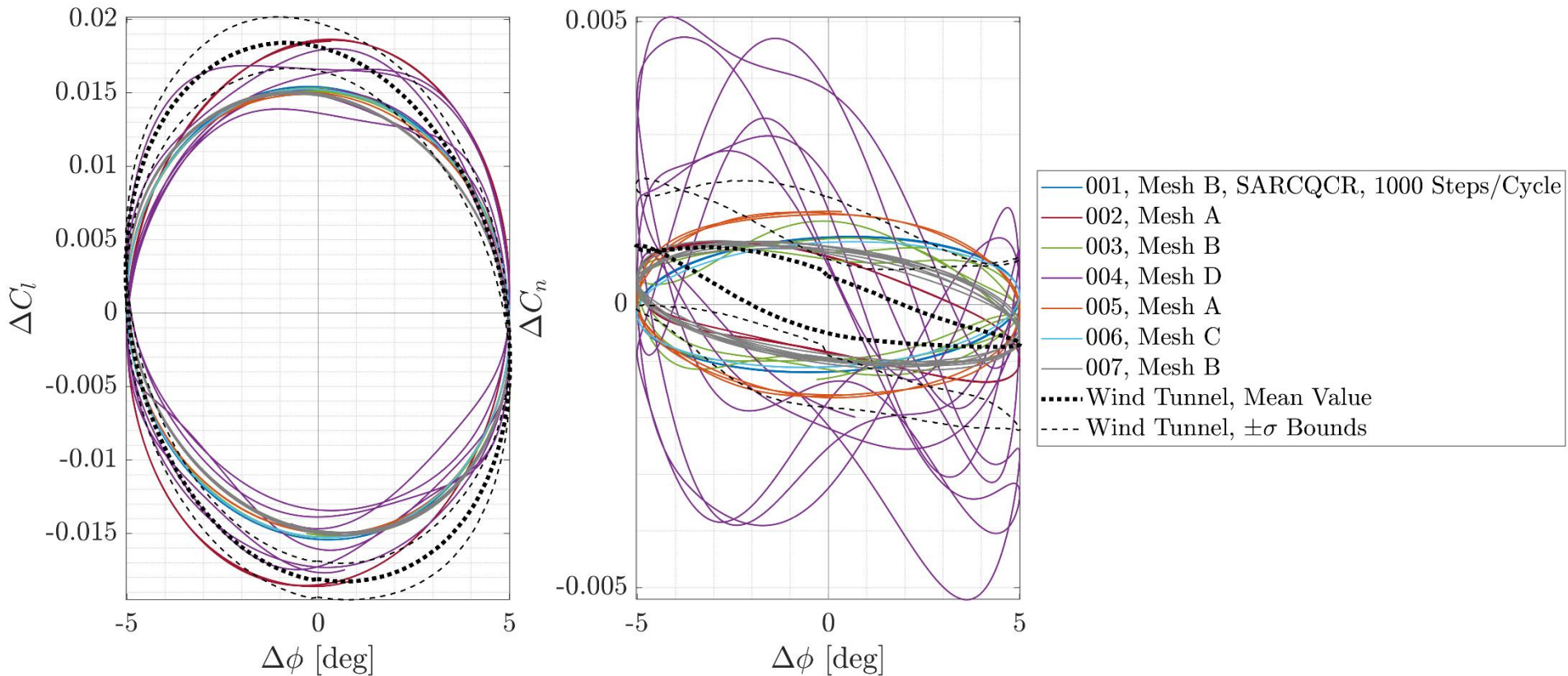


Case 2b: Time Histories ($f_r = 0.4$)

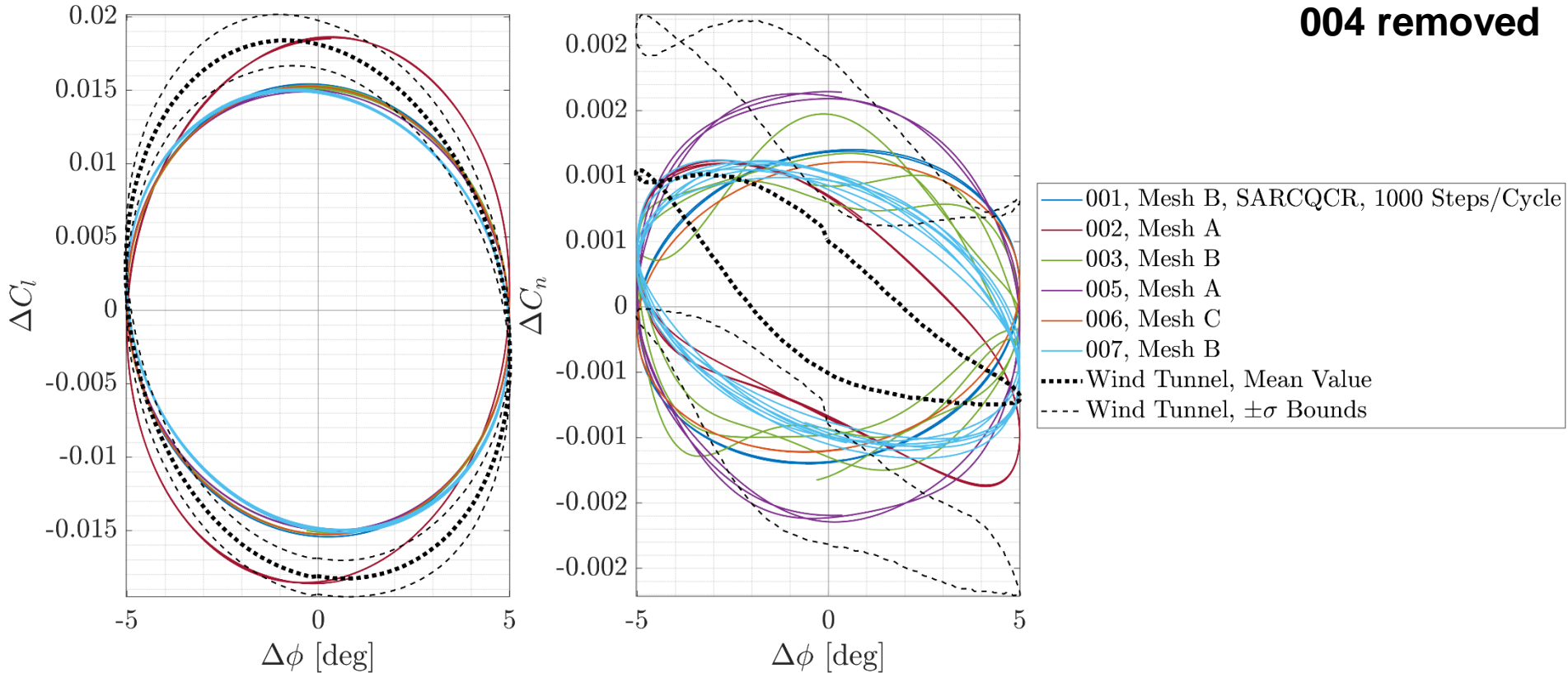
004 removed



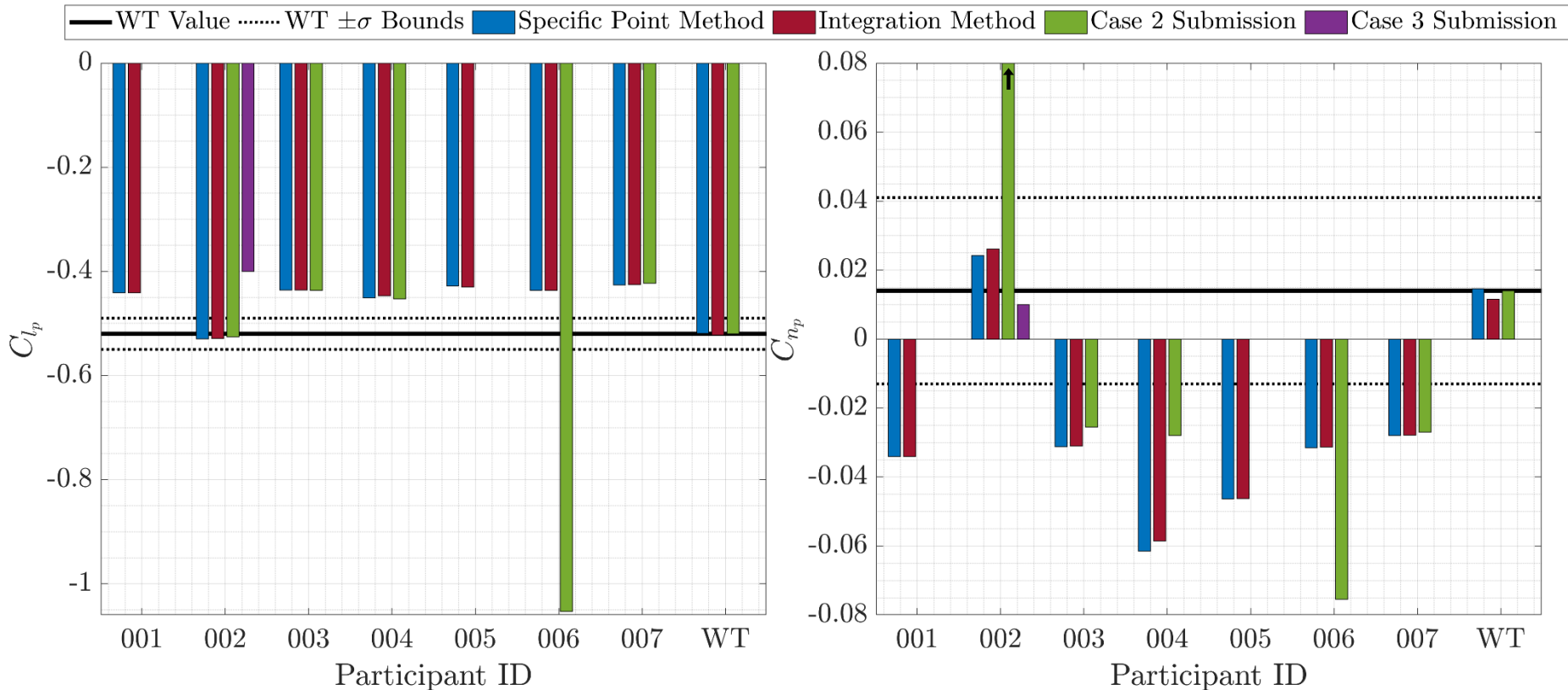
Case 2b: Hysteresis Loops ($f_r = 0.4$)



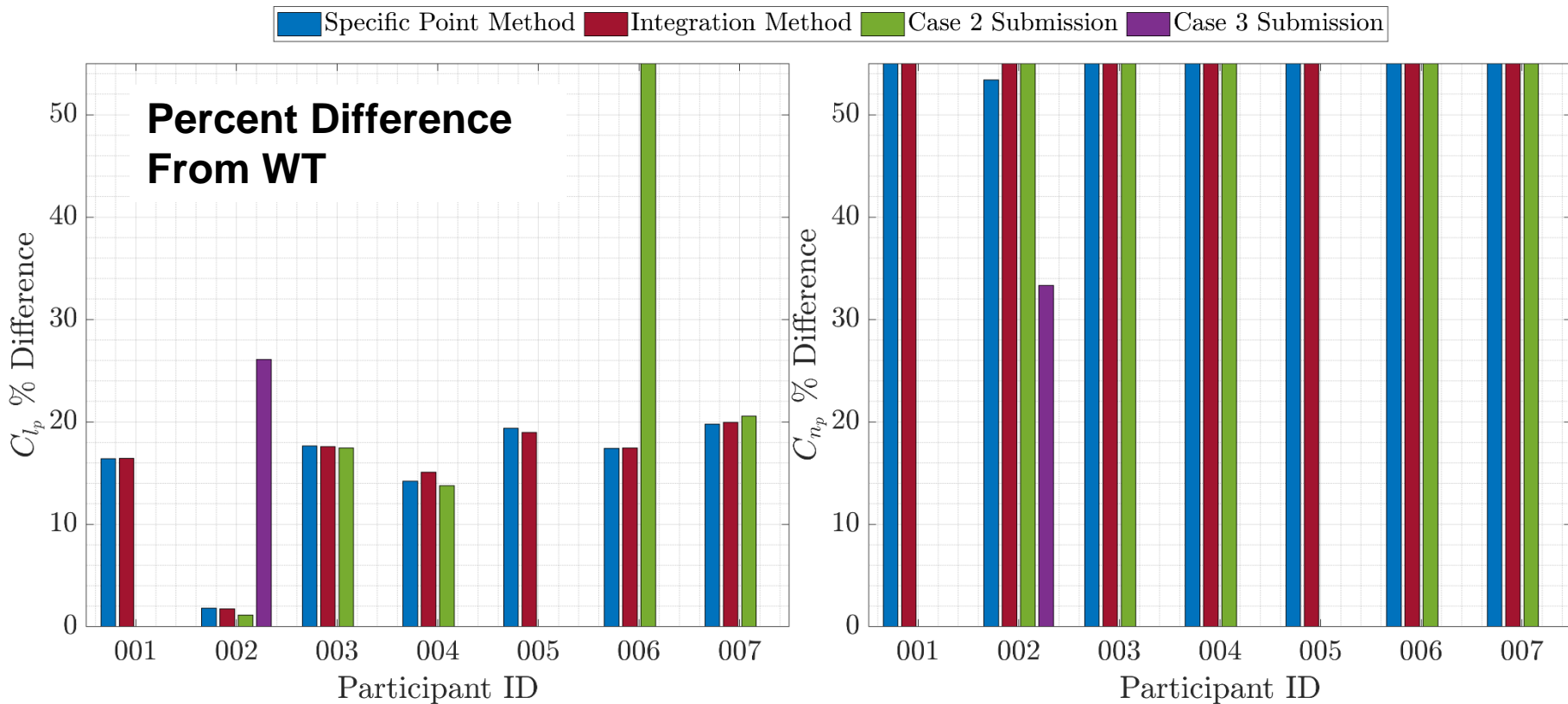
Case 2b: Hysteresis Loops ($f_r = 0.4$)



Case 2b: Dynamic Stability Derivatives ($f_r = 0.4$)



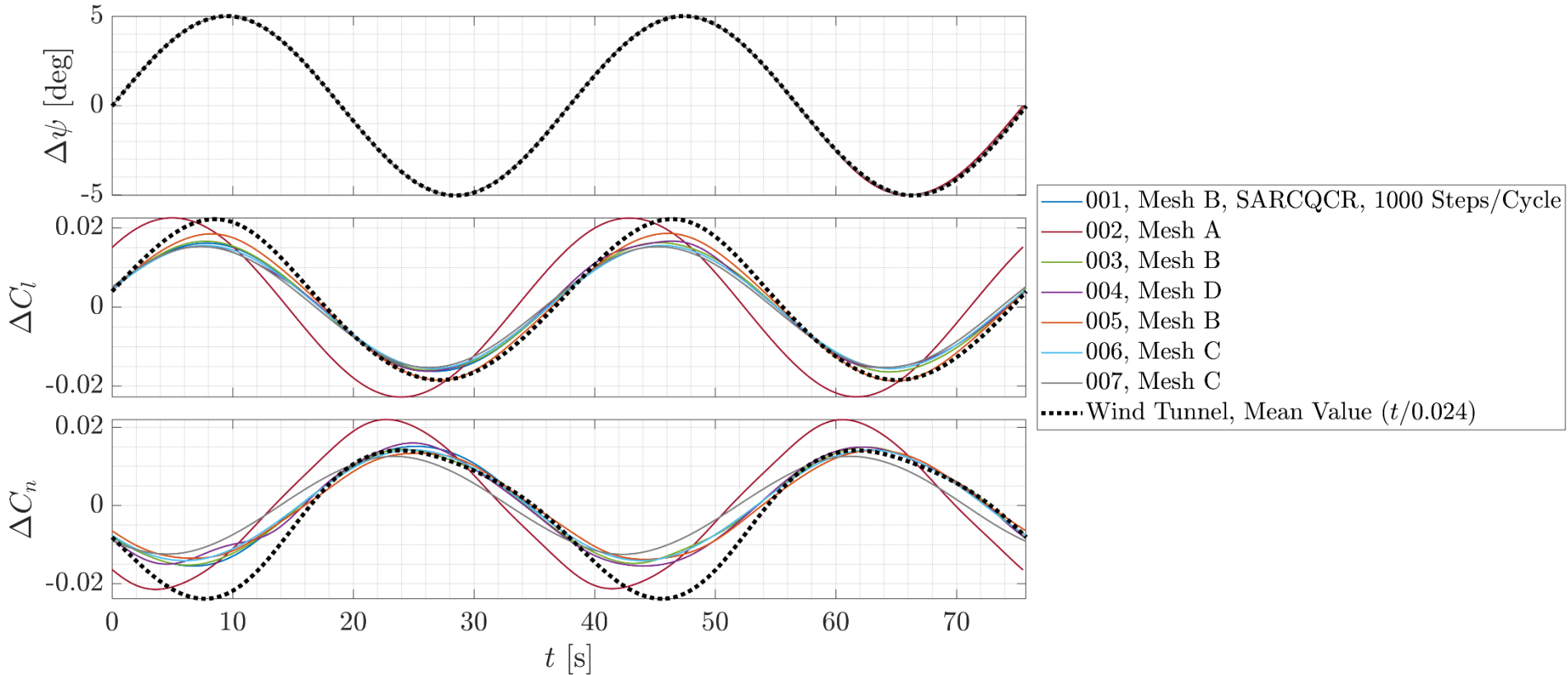
Case 2b: Dynamic Stability Derivatives ($f_r = 0.4$)



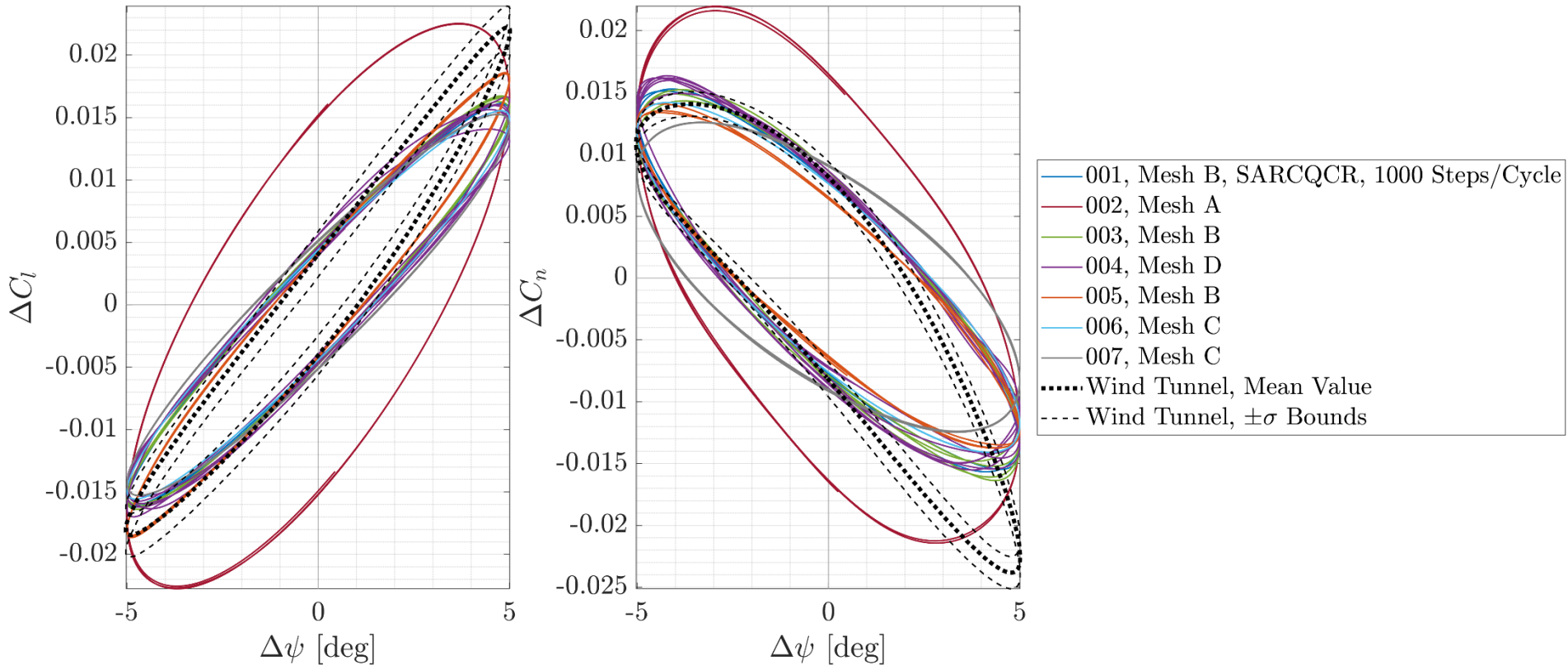
Case 2c Results

- Yaw forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\psi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ\text{R}$
- CRM with sting and tail

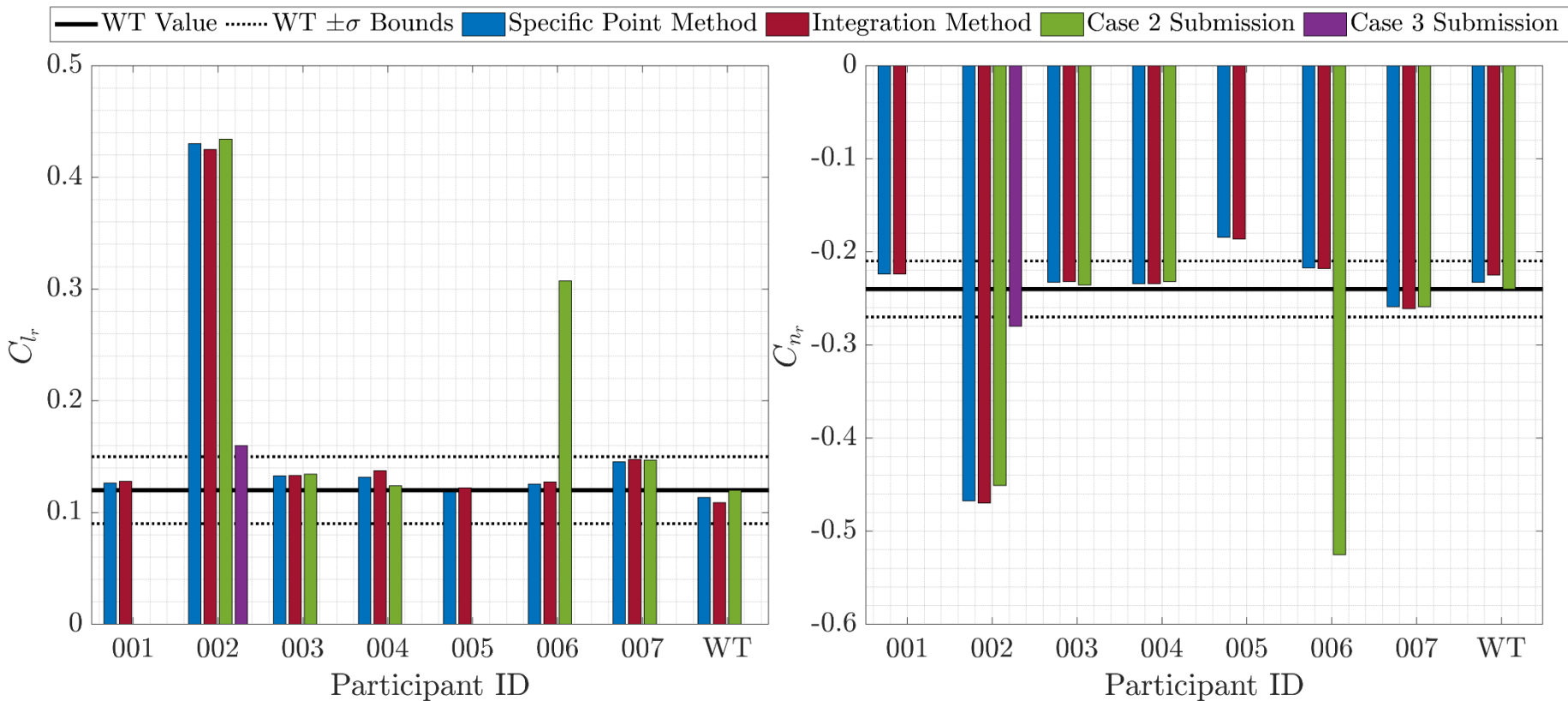
Case 2c: Time Histories ($f_r = 0.4$)



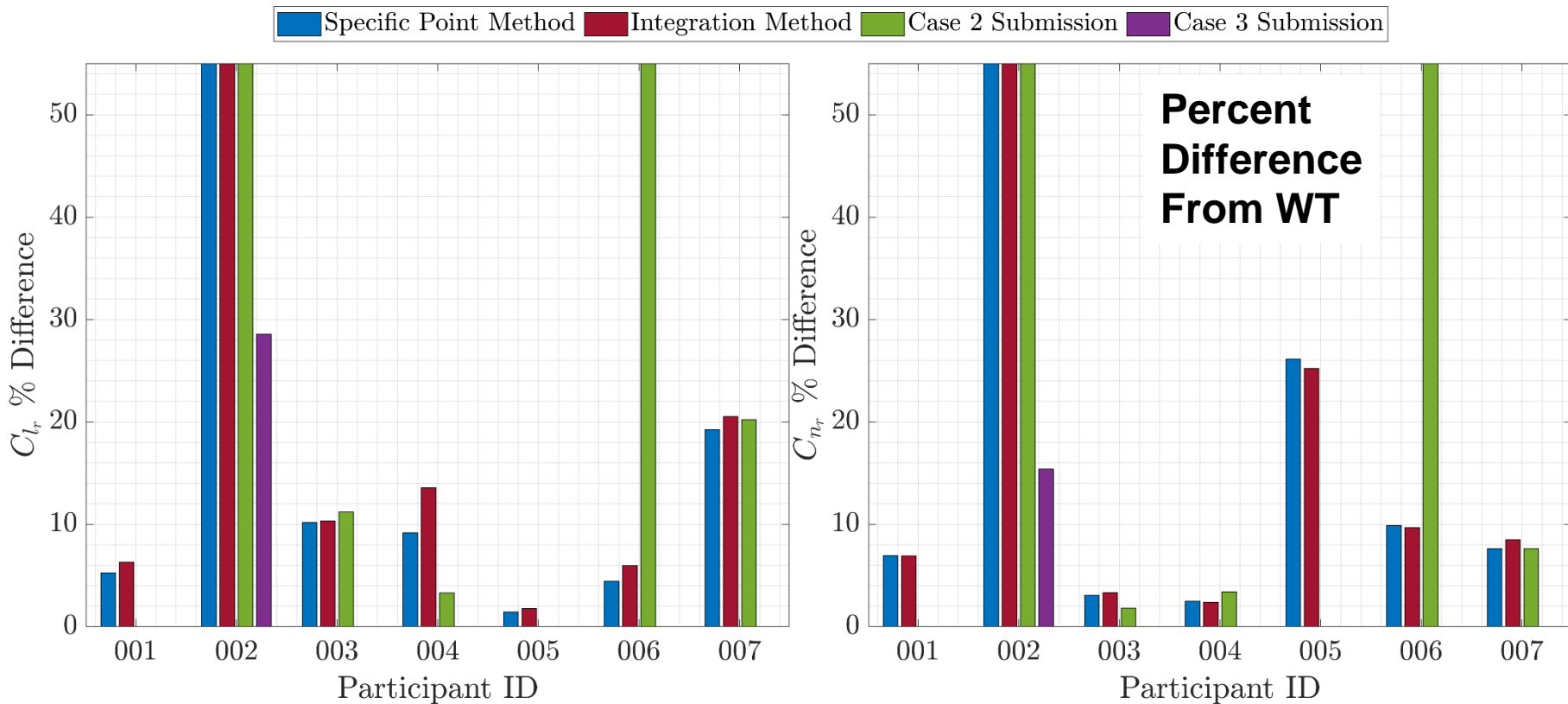
Case 2c: Hysteresis Loops ($f_r = 0.4$)



Case 2c: Dynamic Stability Derivatives ($f_r = 0.4$)



Case 2c: Dynamic Stability Derivatives ($f_r = 0.4$)



Optional Test Cases

- β -sweep at $\alpha = 0^\circ$ (Case 1b)
- α -sweep without tail (Case 1d)
- Reduced frequency effects (Case 2)
- Sting effects (Case 4 and 5)

Available for discussion

Conclusions and Next Steps

Workshop Lessons Learned/Recommendations

- Provide an example of expected data character (shape, magnitude, sign), while retaining a blind comparison
- Hold pre-workshop comparison studies among participants
- Encourage exploration of approaches (turbulence models, meshes, time steps, etc.) but designate one “final” submission for each case
- Create a way to quickly verify format of submitted data files (consider providing a way for participants to check files)
- Standardize key attributes in data file name and submission files (ID, case, mesh, frequency, time steps, turbulence models, etc.)
- Request extra cycles for forced oscillation data processing

Concluding Remarks

- S&CPW2: CRM static/dynamic stability derivative prediction
 - Static angle of attack and sideslip sweeps
 - Roll, pitch, and yaw forced oscillation maneuvers
 - Blind comparison of CFD results to wind tunnel data
- Reasonable overall agreement, but room for improvement
- Best practices for dynamic derivative predictions are needed
- Establish next steps to document findings
- Future S&C prediction workshops
- Website: www.sandcpw.com, Email: sandcpw@gmail.com

Acknowledgements

- **Stability and Control Prediction Workshop II Organizers**
 - Andrew Lofthouse, Air Force Lifecycle Management Center
 - Benjamin Simmons, NASA Langley Research Center
 - Dan Vicroy, Adaptive Aerospace Group, Inc.
 - William Vogel, Air Force Lifecycle Management Center
 - Norman Princen, The Boeing Company
 - Adam Clark, The Boeing Company
 - Brett Johnson, The Boeing Company
 - Matthew Prior, General Atomics – ASI
 - Steve Klausmeyer, Textron Aviation
 - Kelly Laflin, Textron Aviation
 - Charlie Harrison, Gulfstream Aerospace Corporation
- **Workshop Participants (see earlier slide)**
- **AIAA Stability and Control Prediction Discussion Group**
- **Applied Aerodynamics and Atmospheric Flight Mechanics TCs**

Website:

www.sandcpw.com



Email:

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Optional Test Cases

Optional Static Test Cases With Sting

53

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Optional Dynamic Test Cases With Sting

76

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Optional Static Test Cases Without Sting

58

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Optional Dynamic Test Cases Without Sting

104

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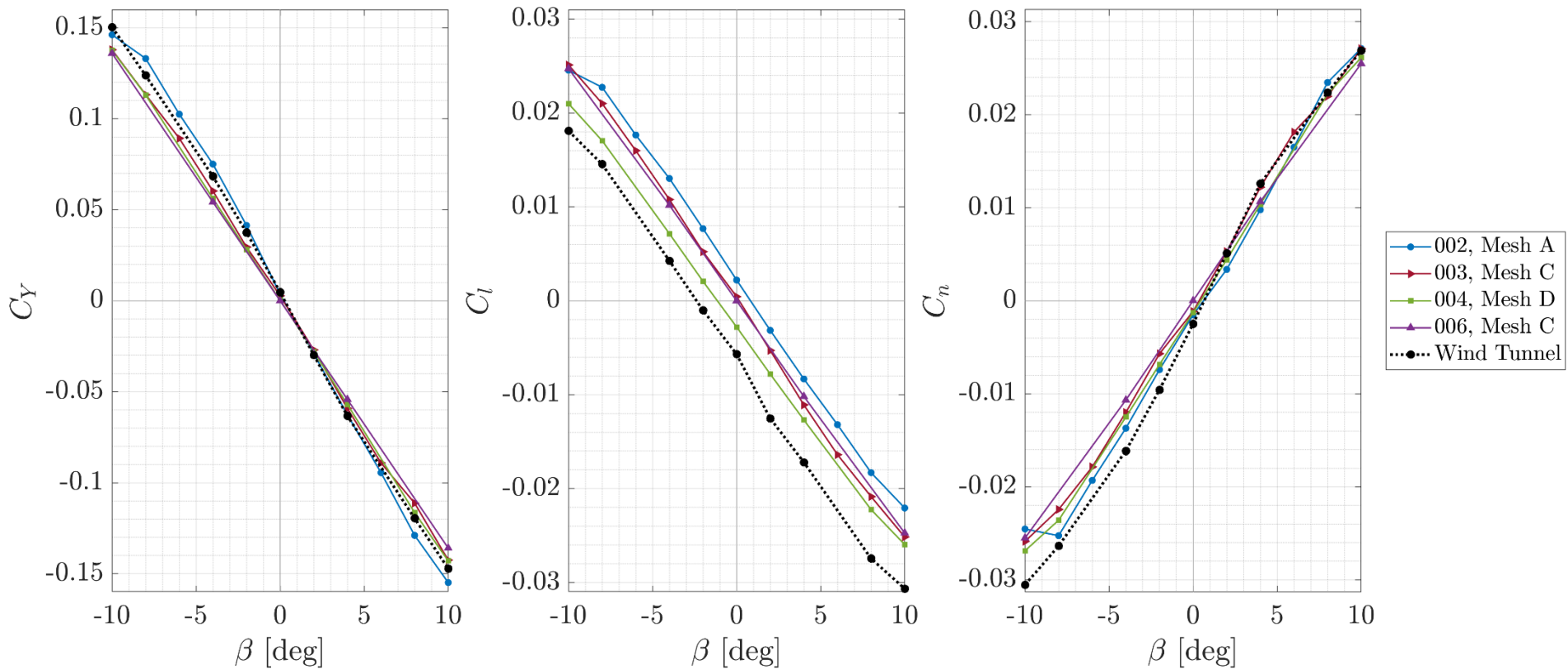


Optional Static Test Cases With Sting

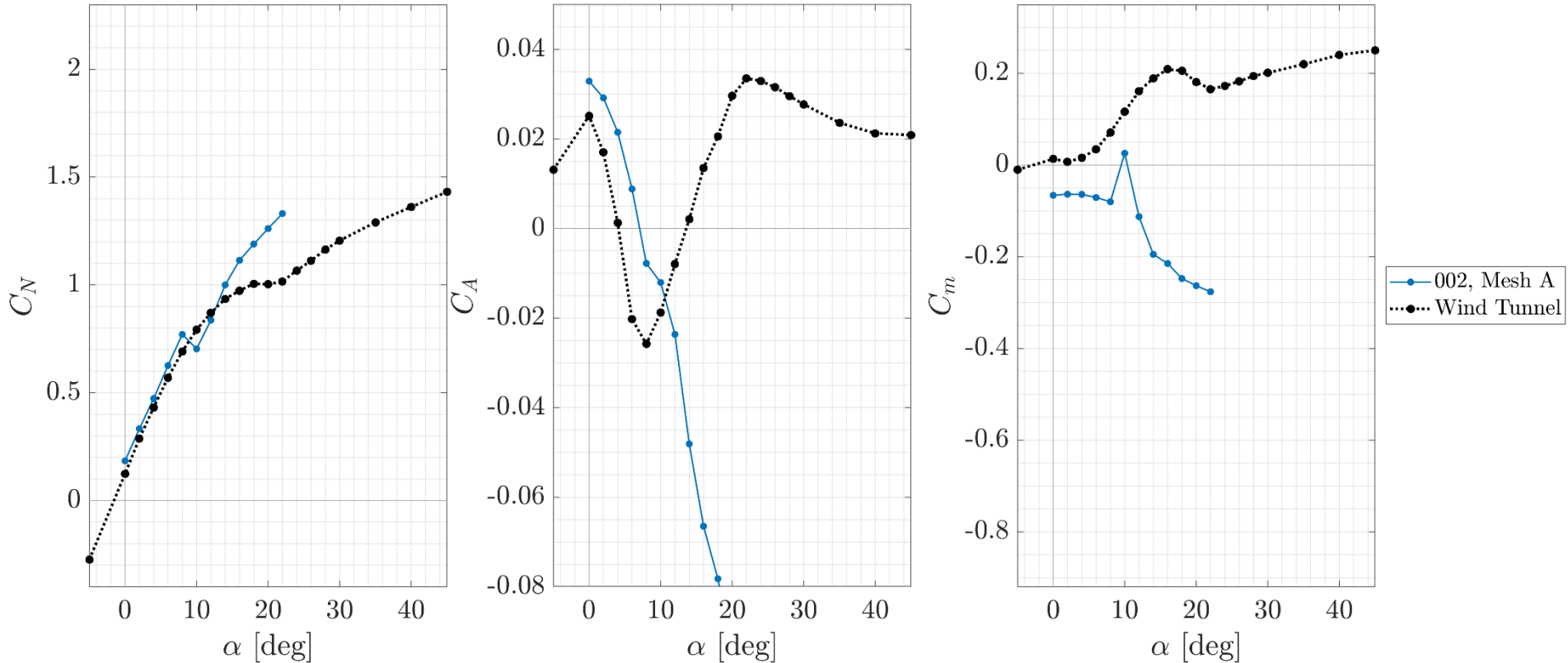
Case 1b and 1d

- **Case 1b:** angle of sideslip (β) sweep at $\alpha = 0^\circ$; CRM with sting and tail
- **Case 1d:** angle of attack (α) sweep; CRM with sting and no tail
- $M = 0.052$; $Re = 200,000$; $T = 518^\circ\text{R}$

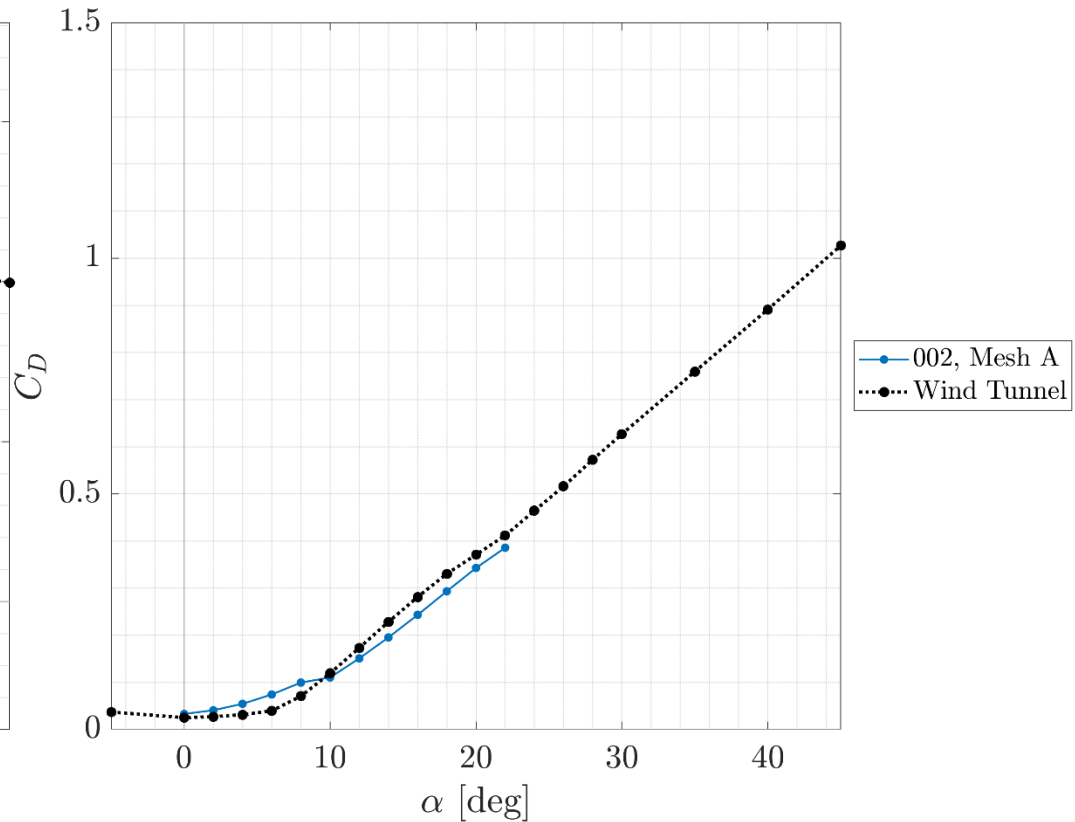
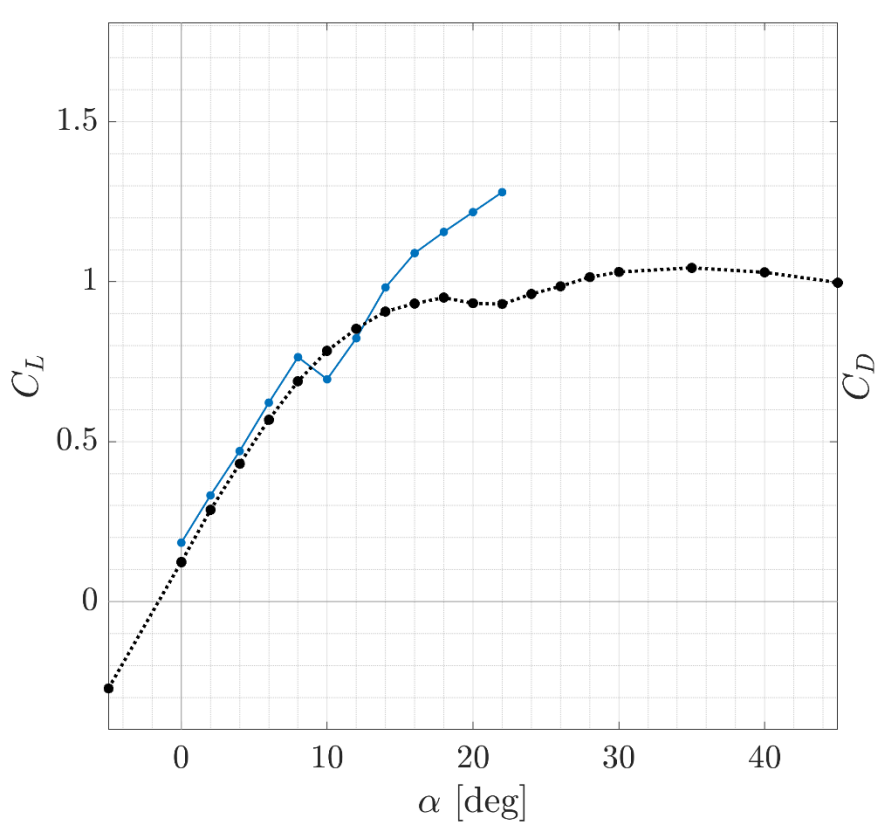
Case 1b: β -Sweep with Sting and Tail ($\alpha = 0^\circ$)



Case 1d: α -Sweep with Sting and No Tail



Case 1d: α -Sweep with Sting and No Tail



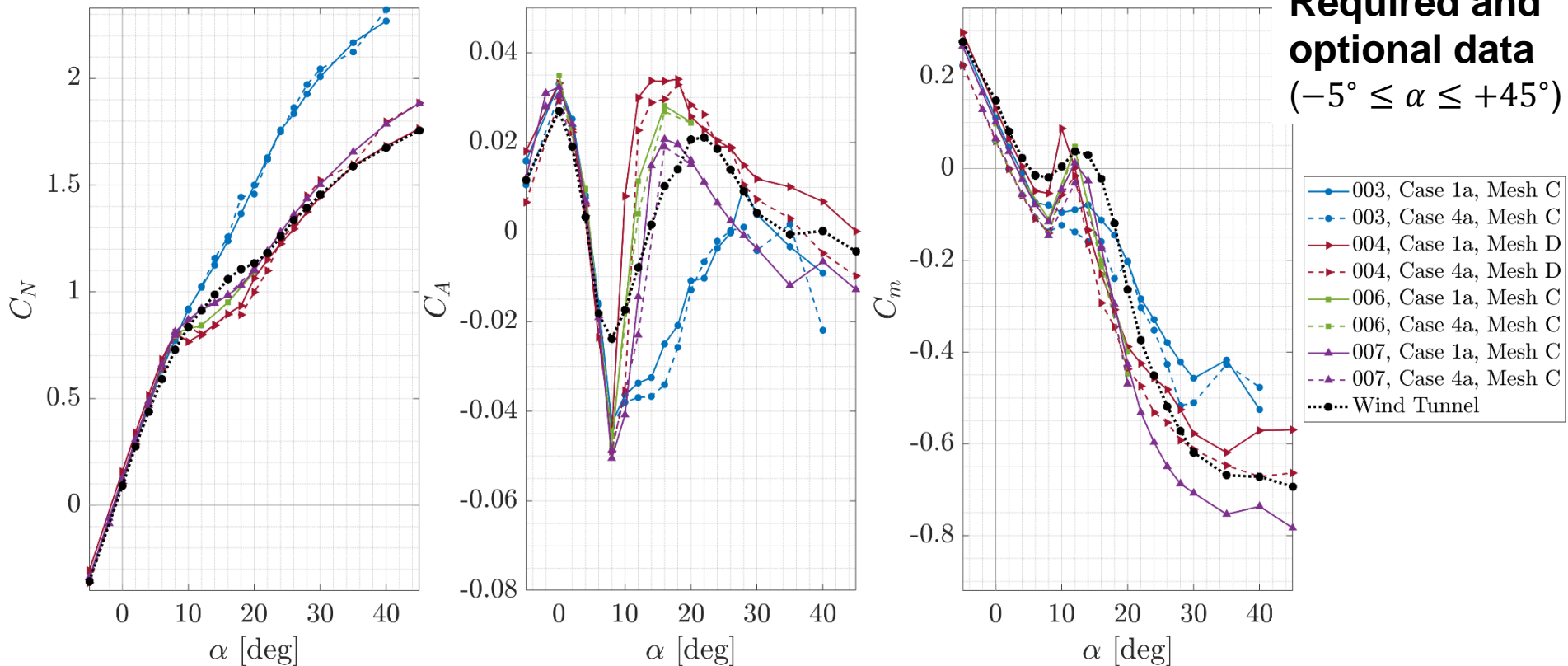
Optional Static Test Cases Without Sting

Case 4a Results

- Angle of attack (α) sweep
- $M = 0.052$; $Re = 200,000$; $T = 518^\circ\text{R}$
- CRM with tail and no sting

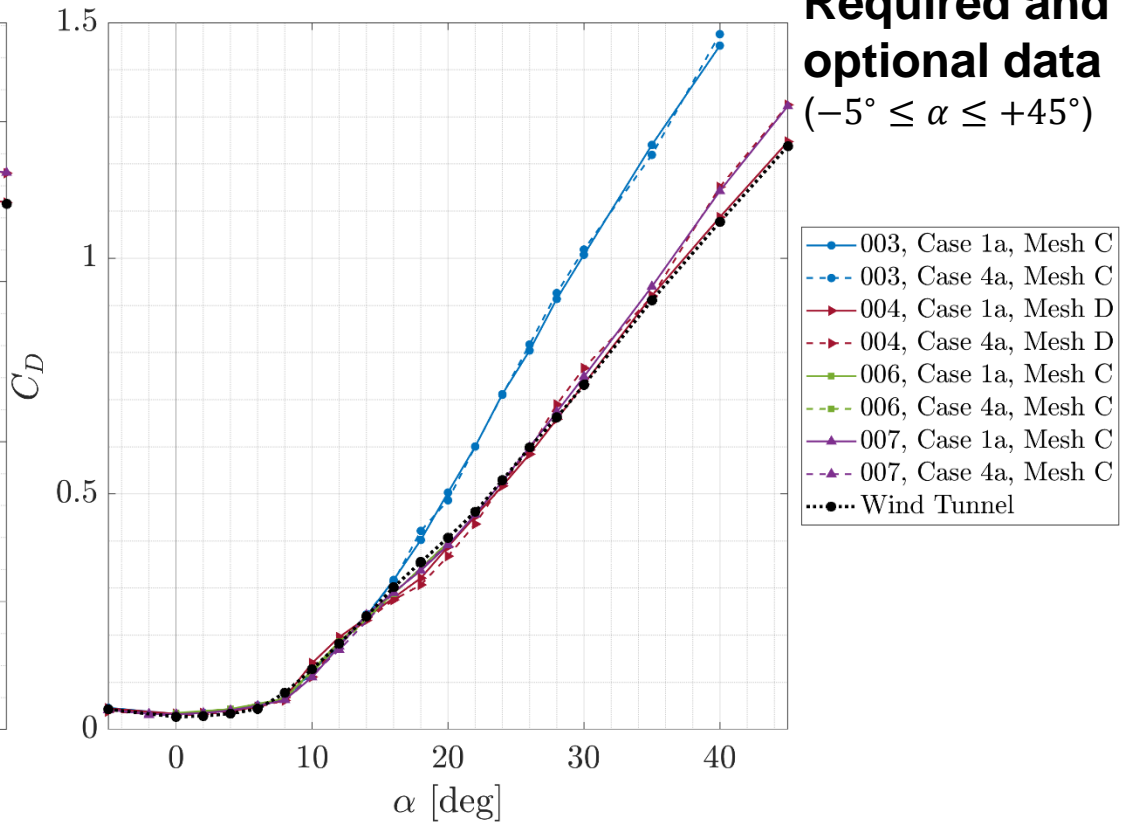
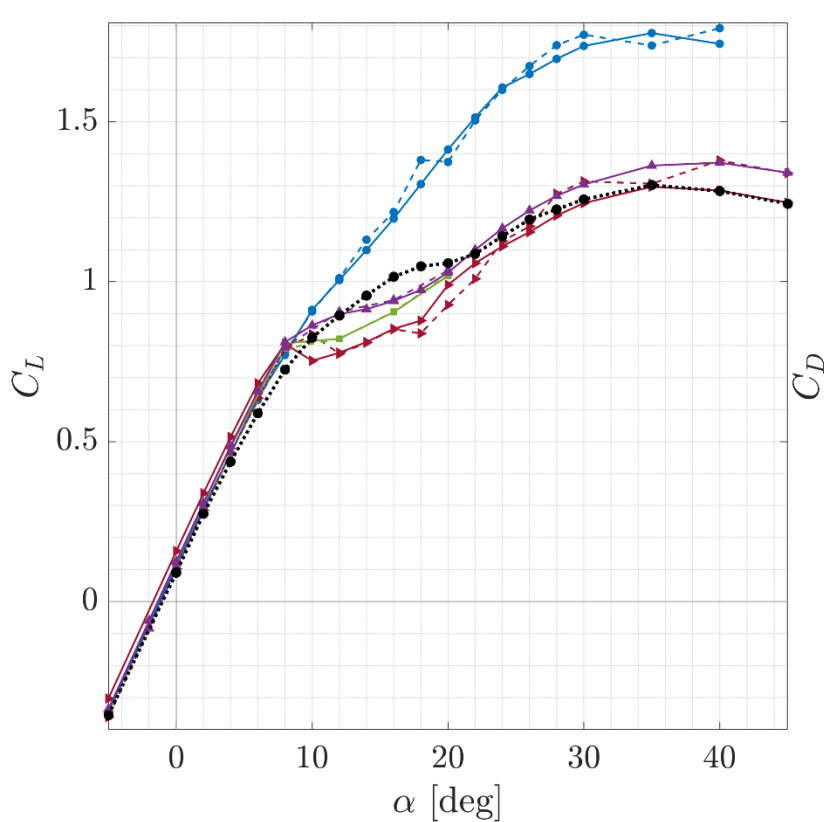
Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting



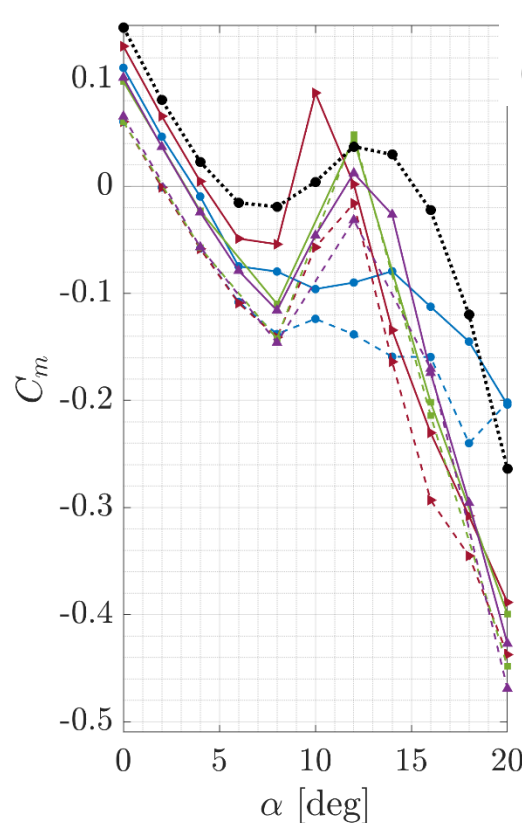
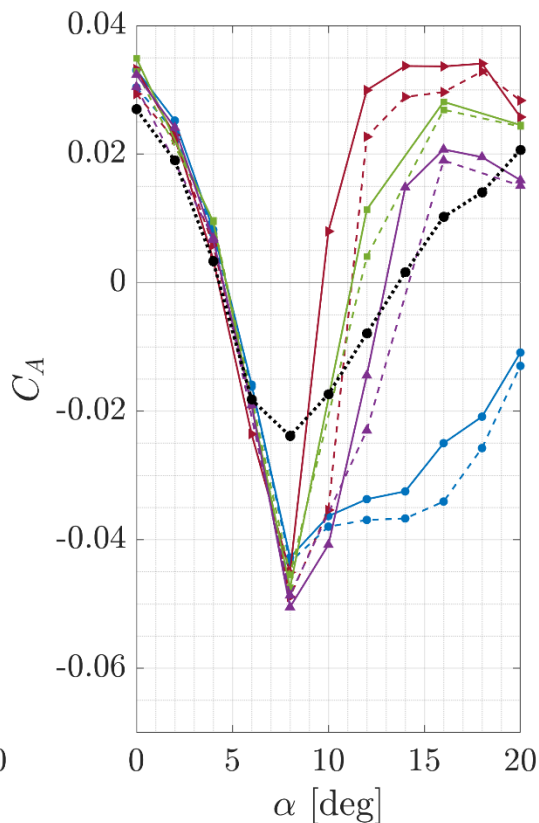
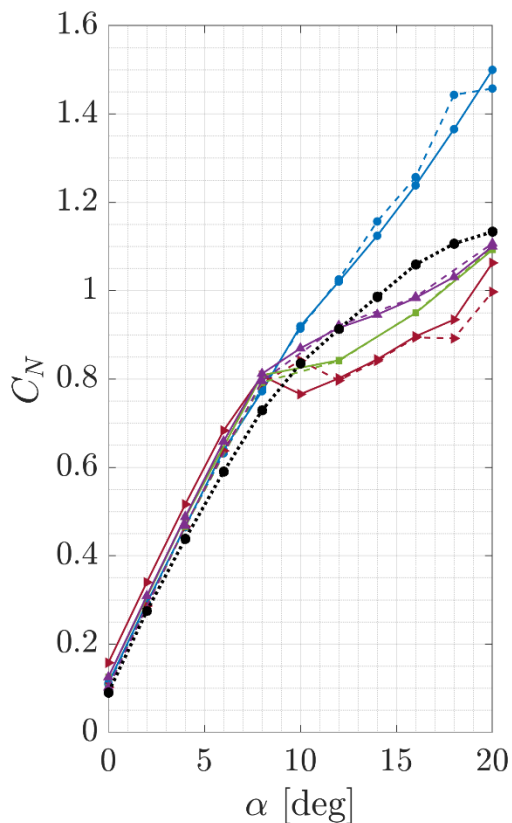
Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting



Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting

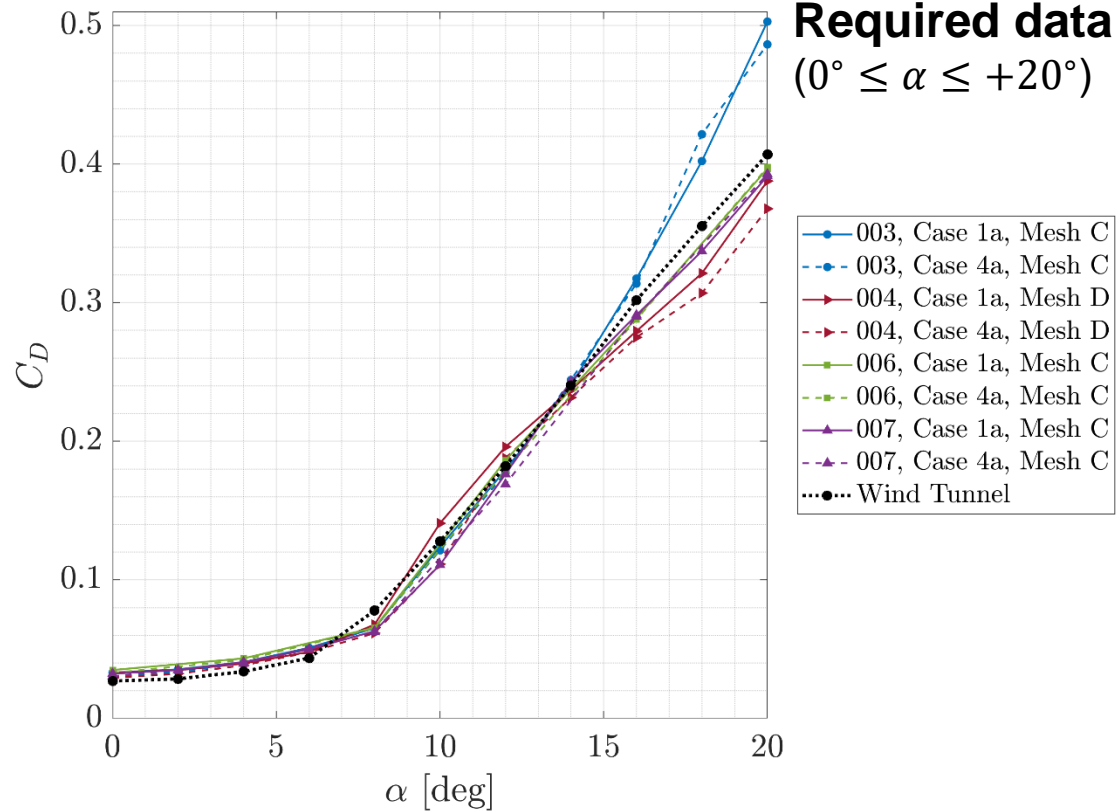
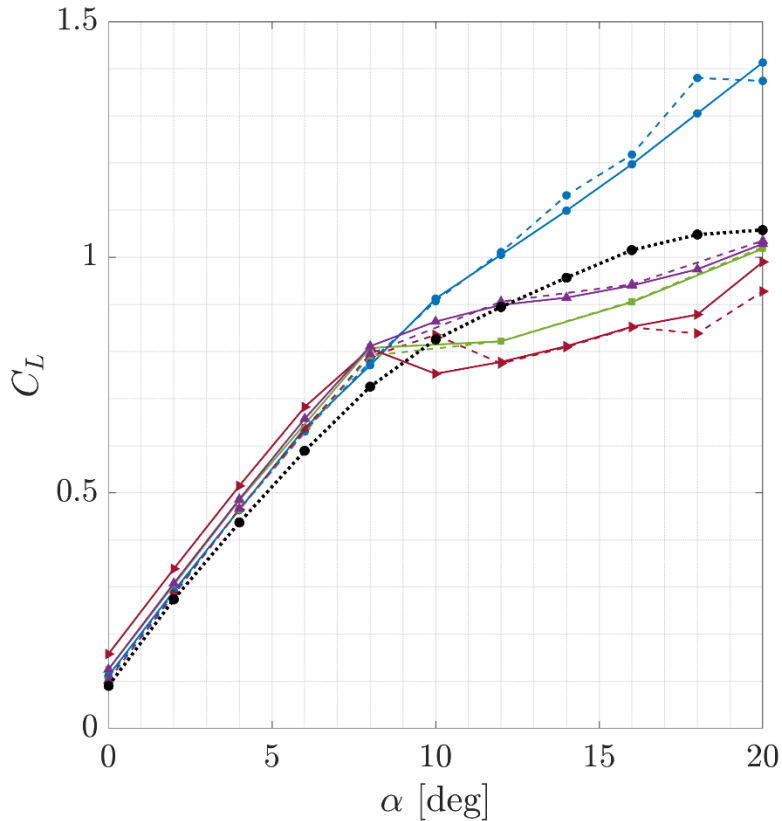


Required data
($0^\circ \leq \alpha \leq +20^\circ$)

- 003, Case 1a, Mesh C
- 003, Case 4a, Mesh C
- 004, Case 1a, Mesh D
- 004, Case 4a, Mesh D
- 006, Case 1a, Mesh C
- 006, Case 4a, Mesh C
- 007, Case 1a, Mesh C
- 007, Case 4a, Mesh C
- Wind Tunnel

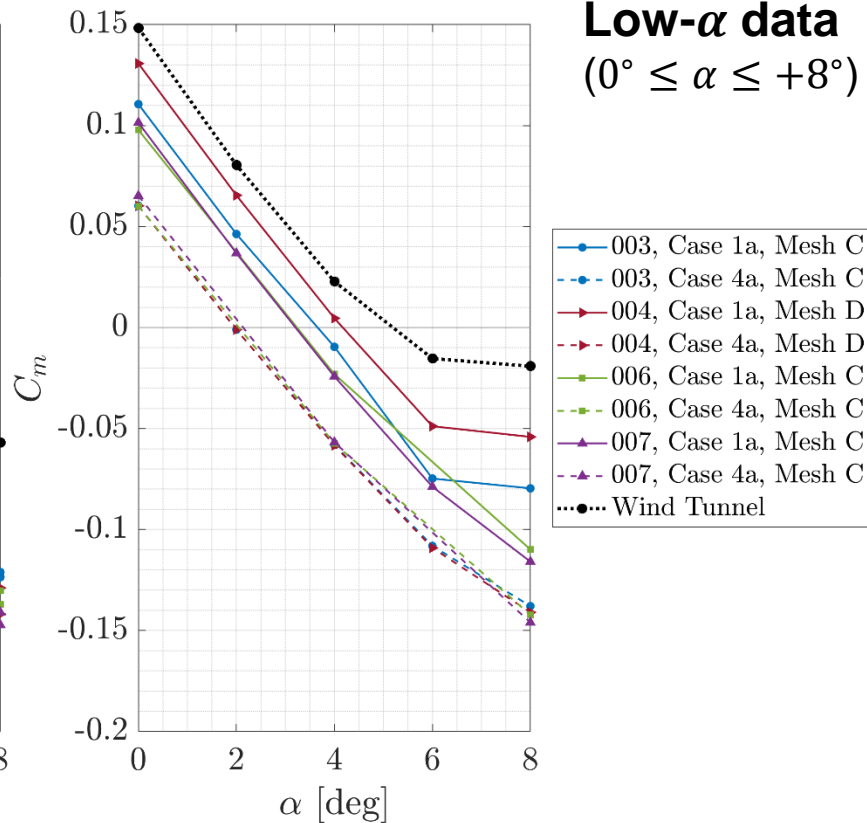
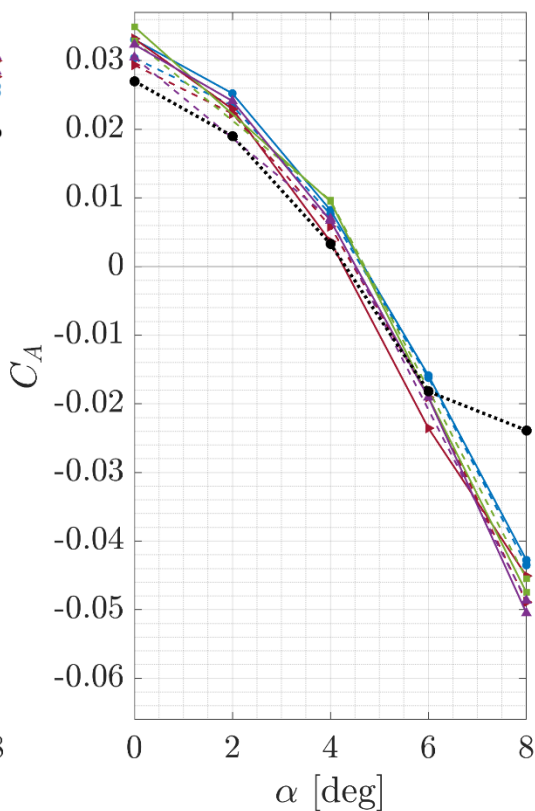
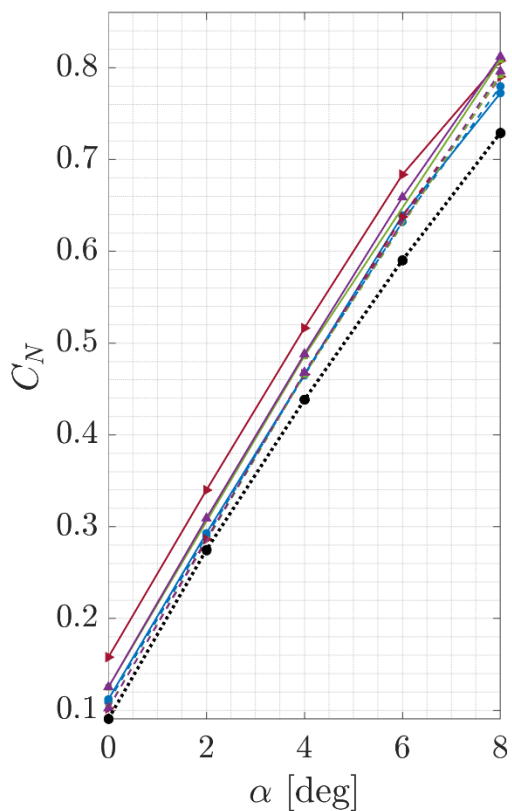
Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting



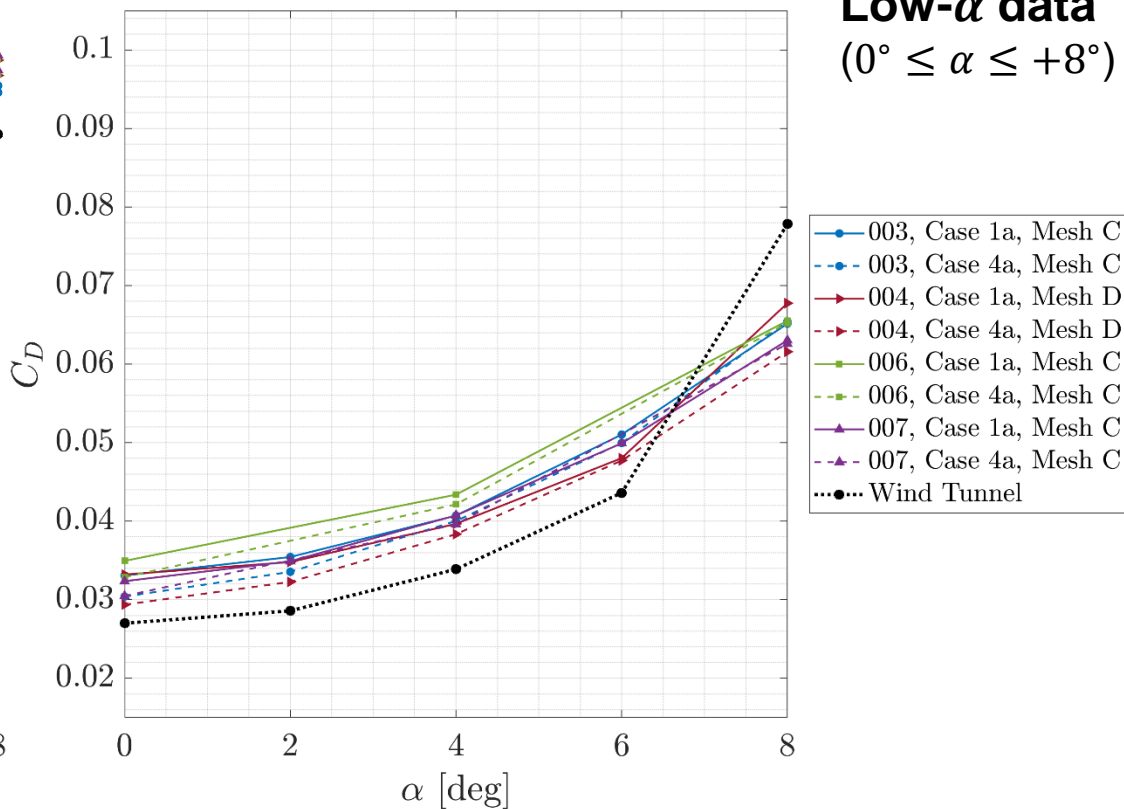
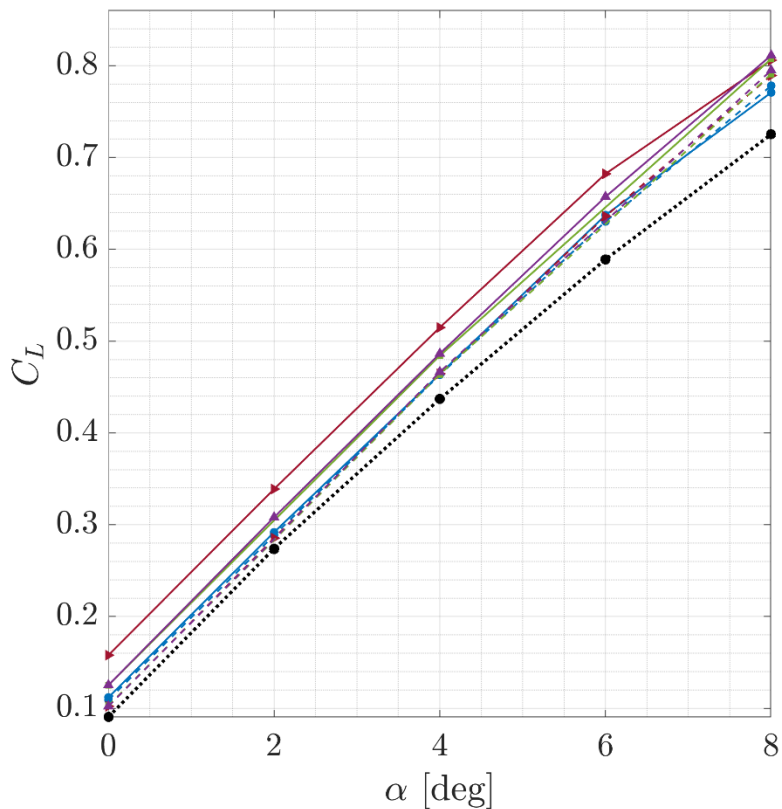
Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting



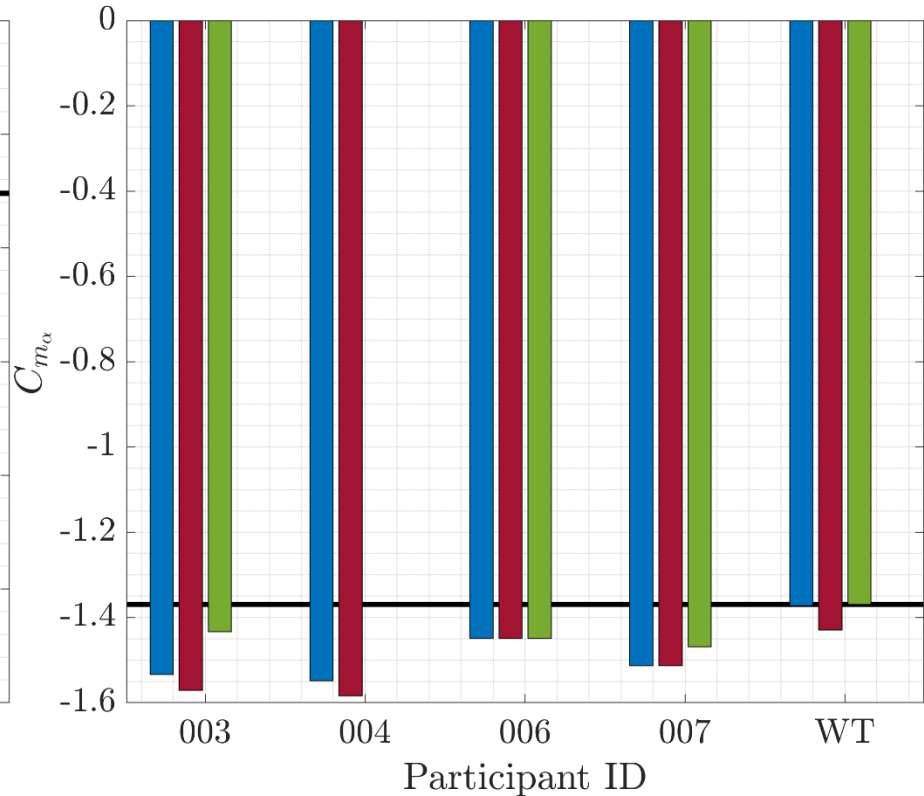
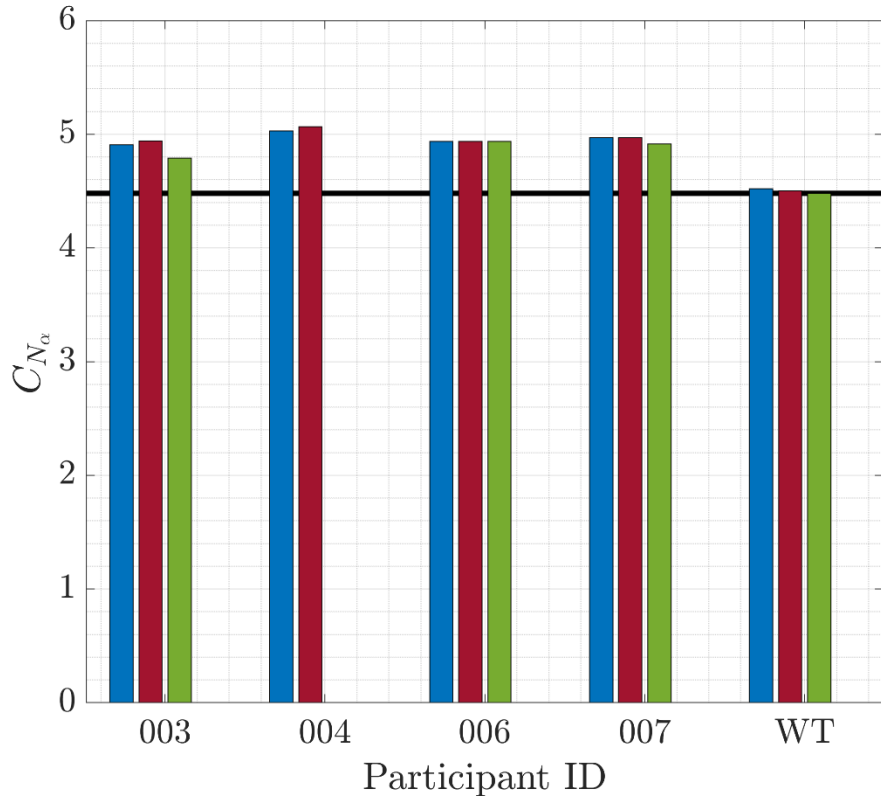
Case 1a/4a: α -Sweep with Tail

1a = With Sting
4a = No Sting

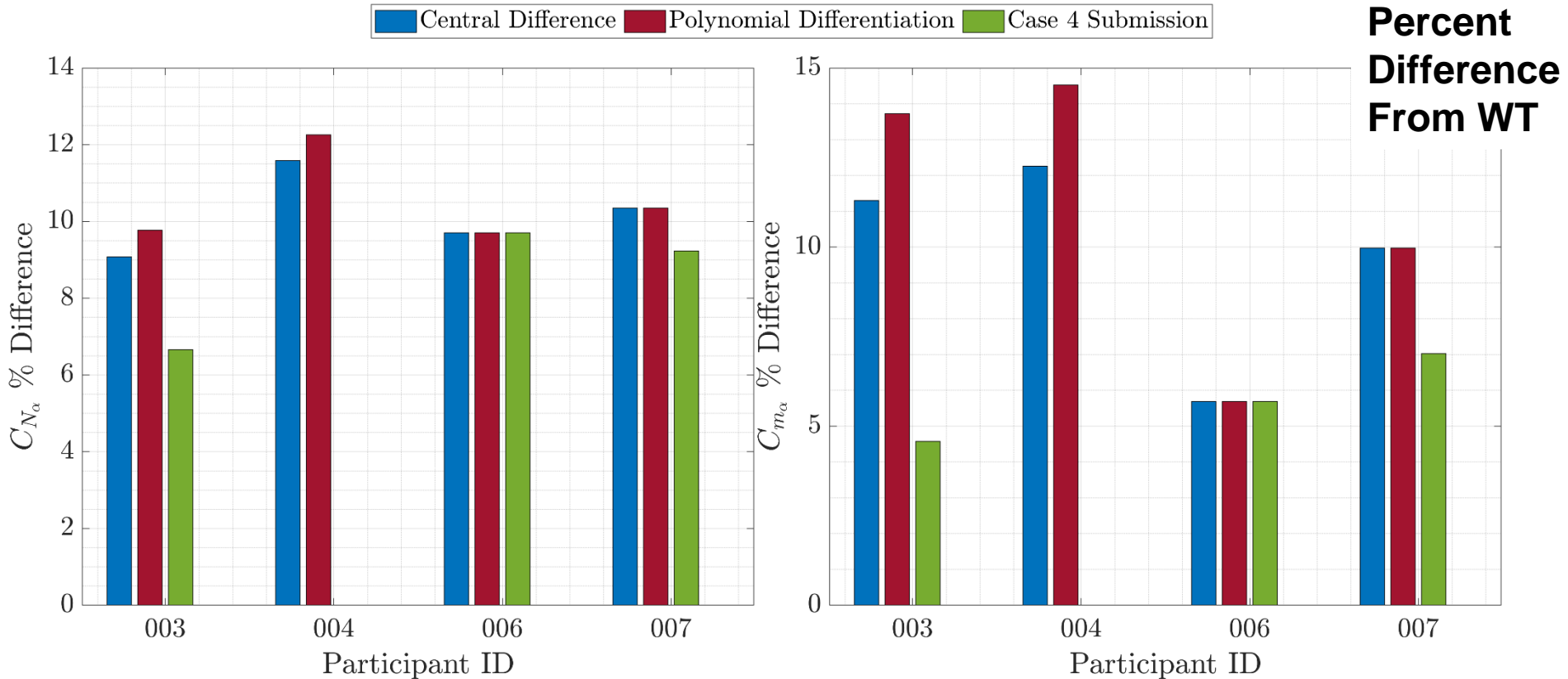


Case 4a: Static Stability Derivatives ($\alpha = 4^\circ$)

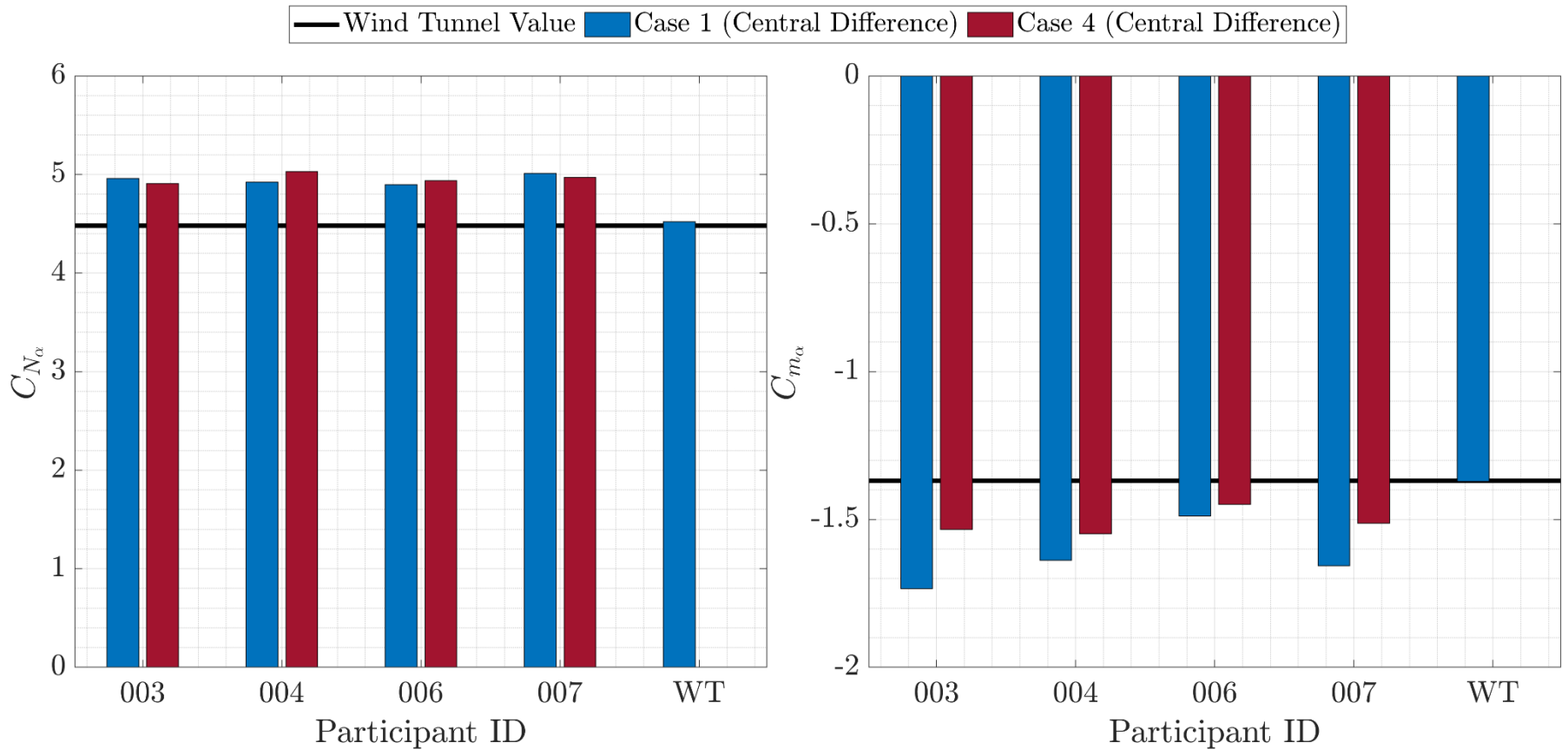
— Wind Tunnel Value Central Difference Polynomial Differentiation Case 4 Submission



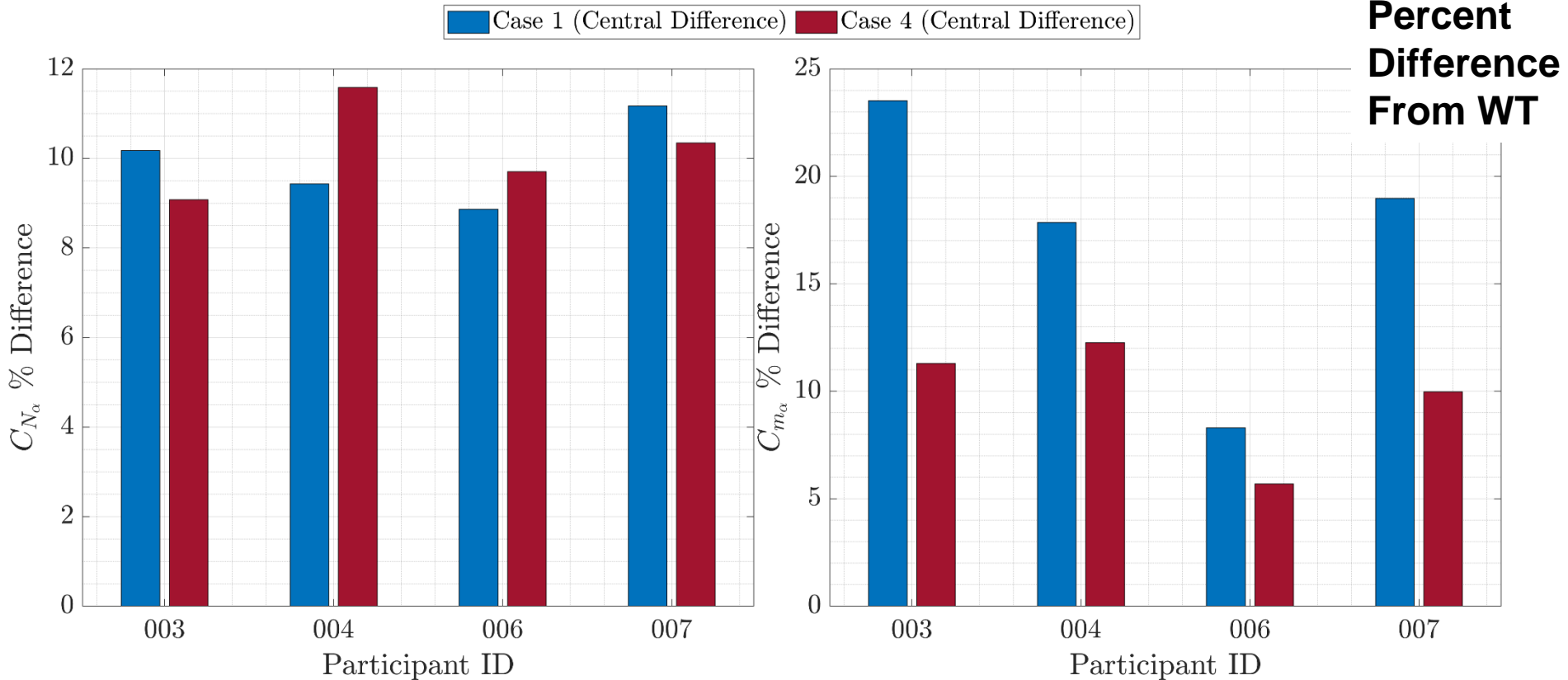
Case 4a: Static Stability Derivatives ($\alpha = 4^\circ$)



Case 1a/4a: Static Stability Derivatives ($\alpha = 4^\circ$)



Case 1a/4a: Static Stability Derivatives ($\alpha = 4^\circ$)

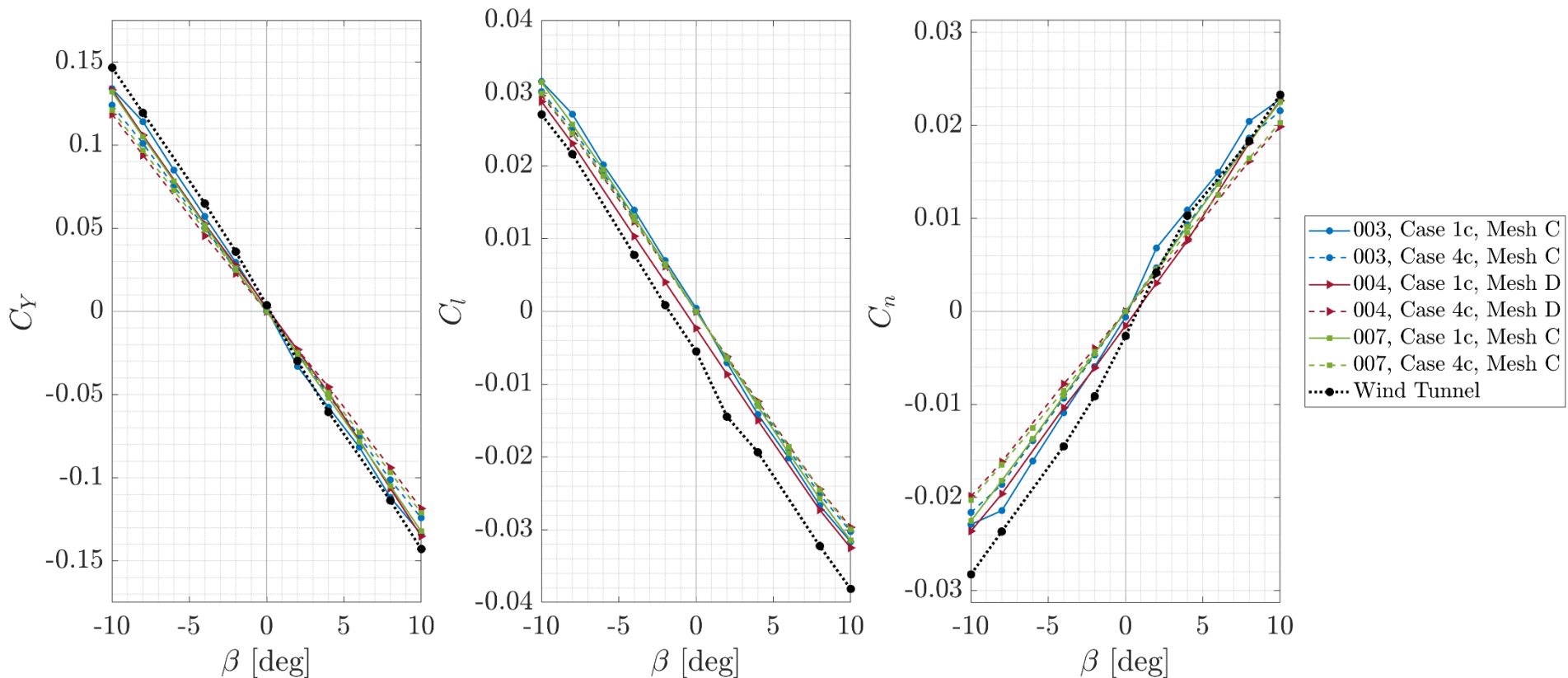


Case 4c Results

- Angle of sideslip (β) sweep at $\alpha = 4^\circ$
- $M = 0.052$; $Re = 200,000$; $T = 518^\circ R$
- CRM with tail and no sting

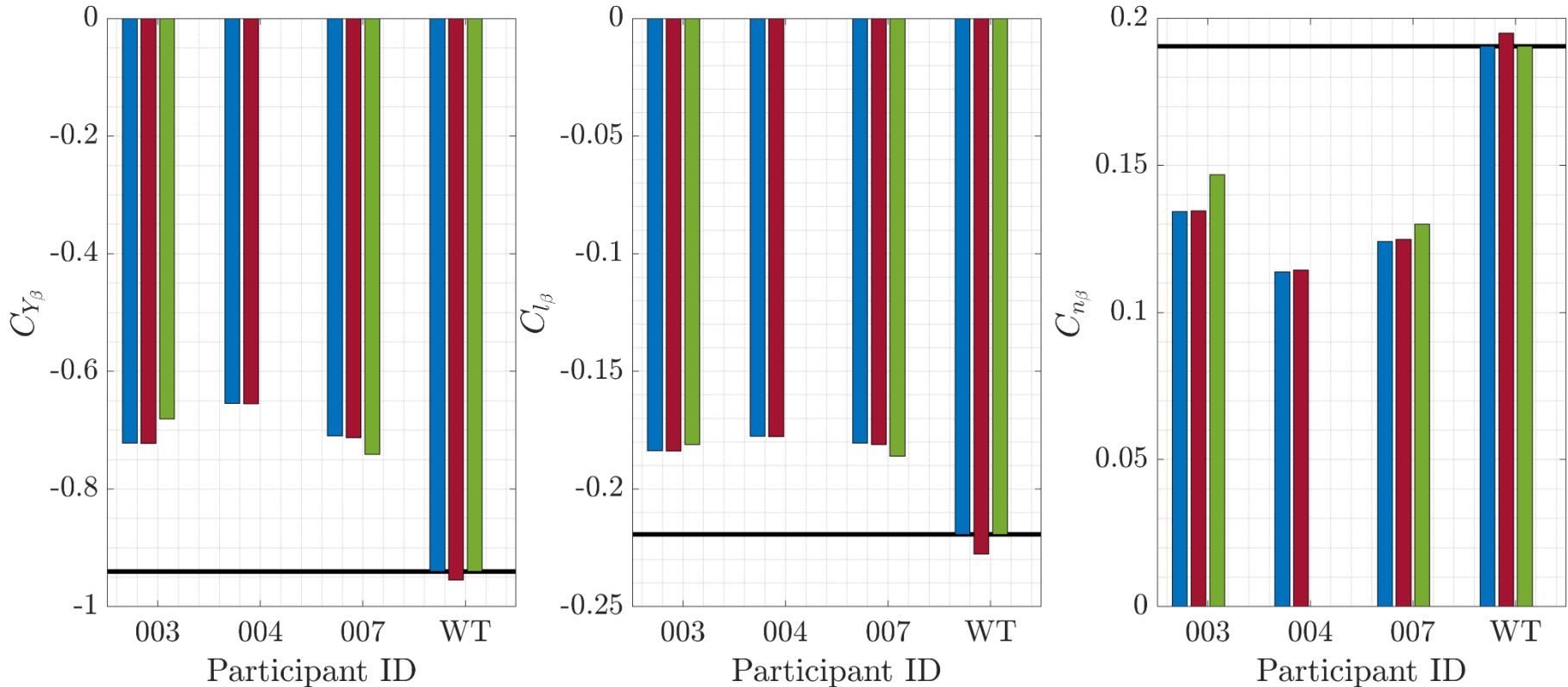
Case 1c/4c: β -Sweep with Tail ($\alpha = 4^\circ$)

1c = With Sting
4c = No Sting

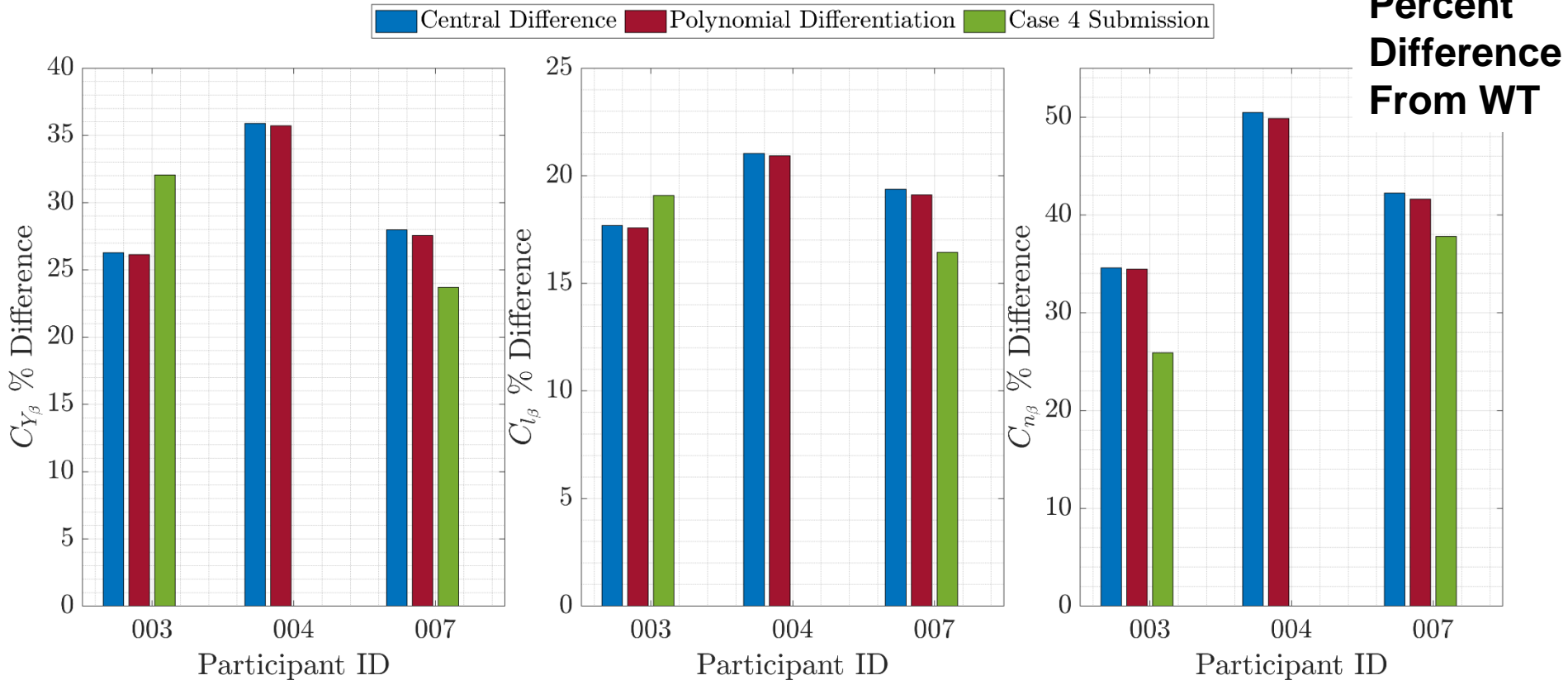


Case 4c: Static Stability Derivatives ($\alpha = 4^\circ$)

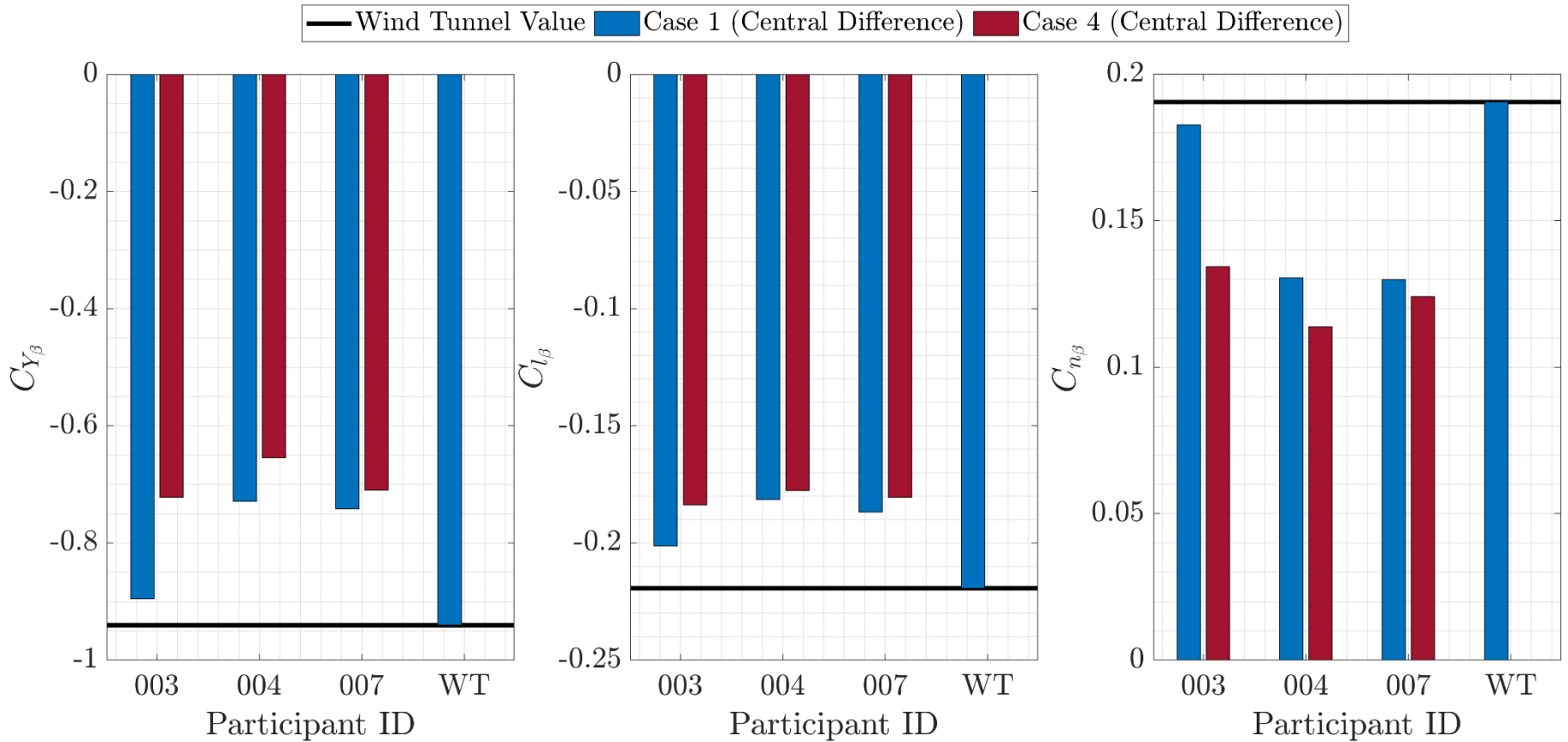
— Wind Tunnel Value ■ Central Difference ■ Polynomial Differentiation ■ Case 4 Submission



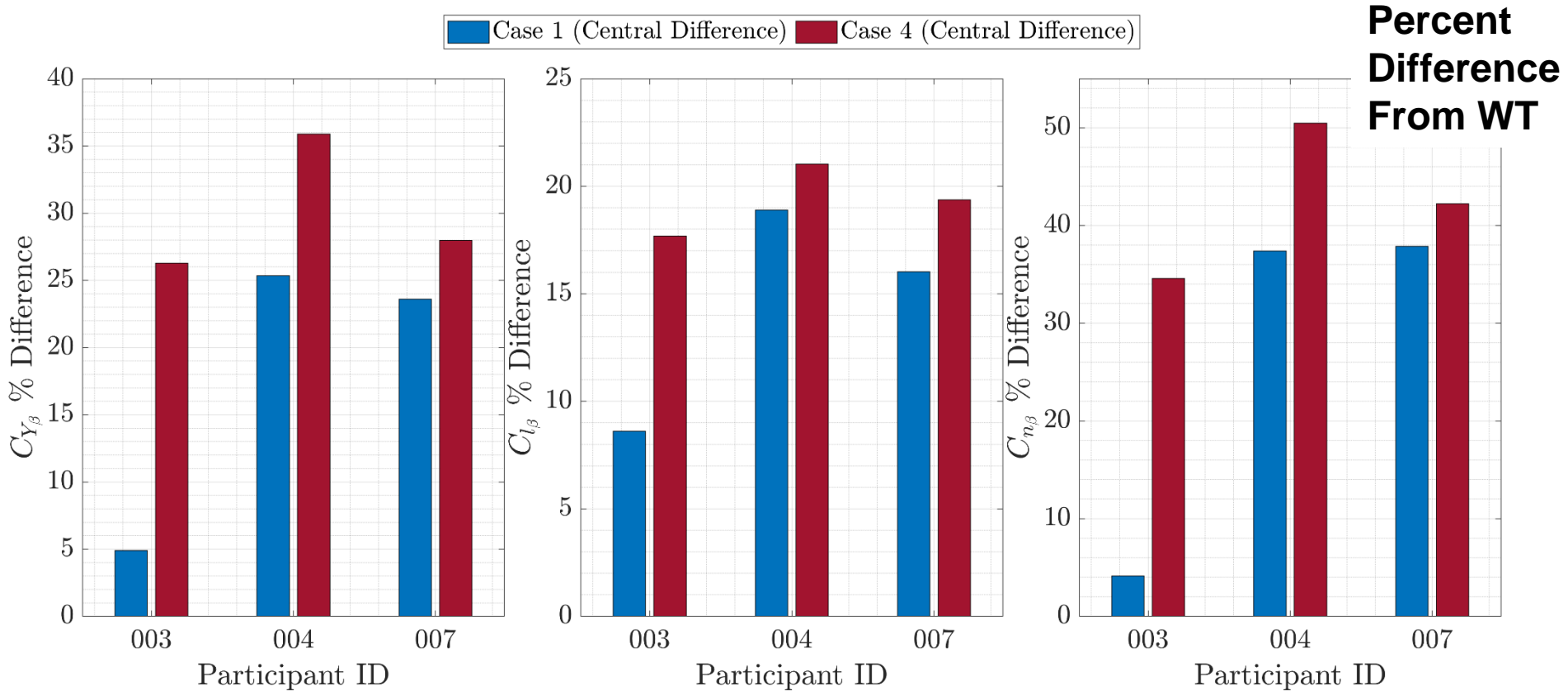
Case 4c: Static Stability Derivatives ($\alpha = 4^\circ$)



Case 1c/4c: Static Stability Derivatives ($\alpha = 4^\circ$)



Case 1c/4c: Static Stability Derivatives ($\alpha = 4^\circ$)

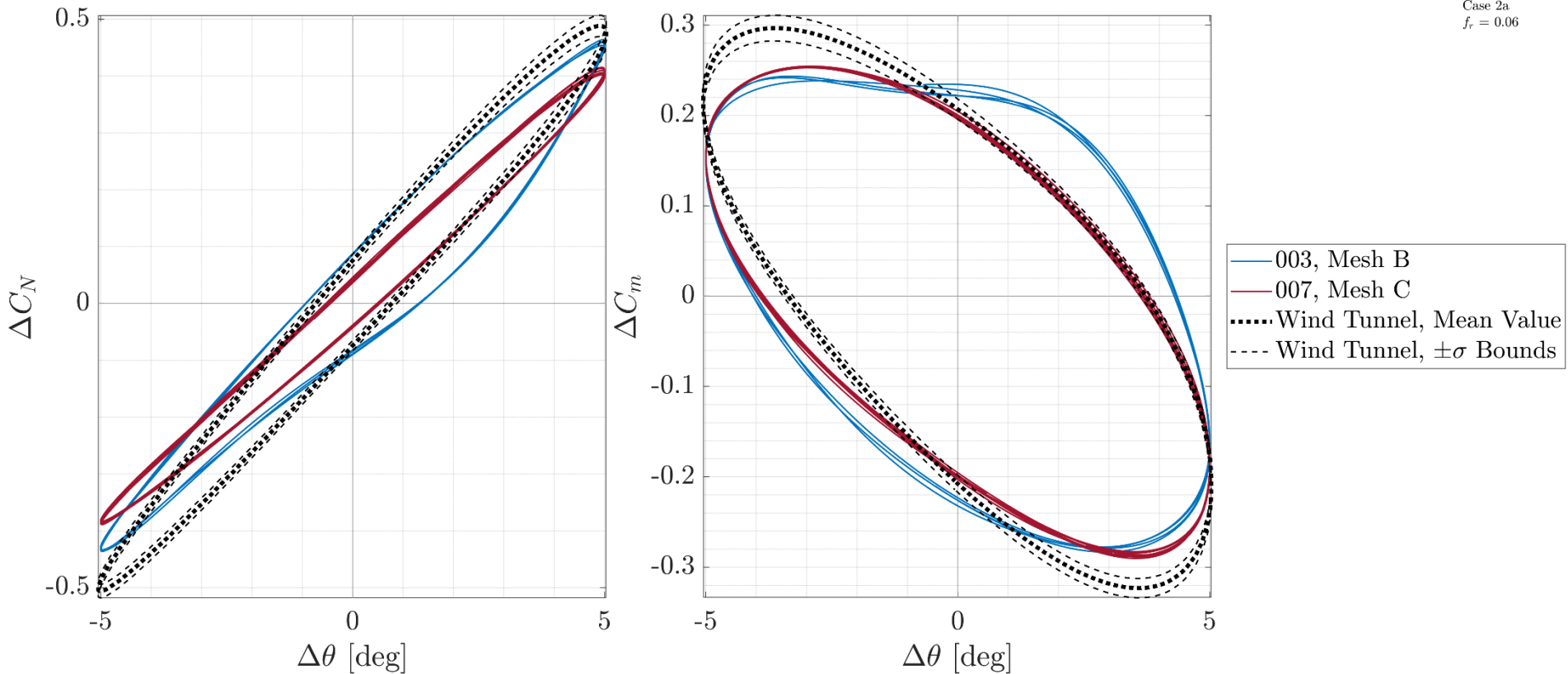


Optional Dynamic Test Cases With Sting

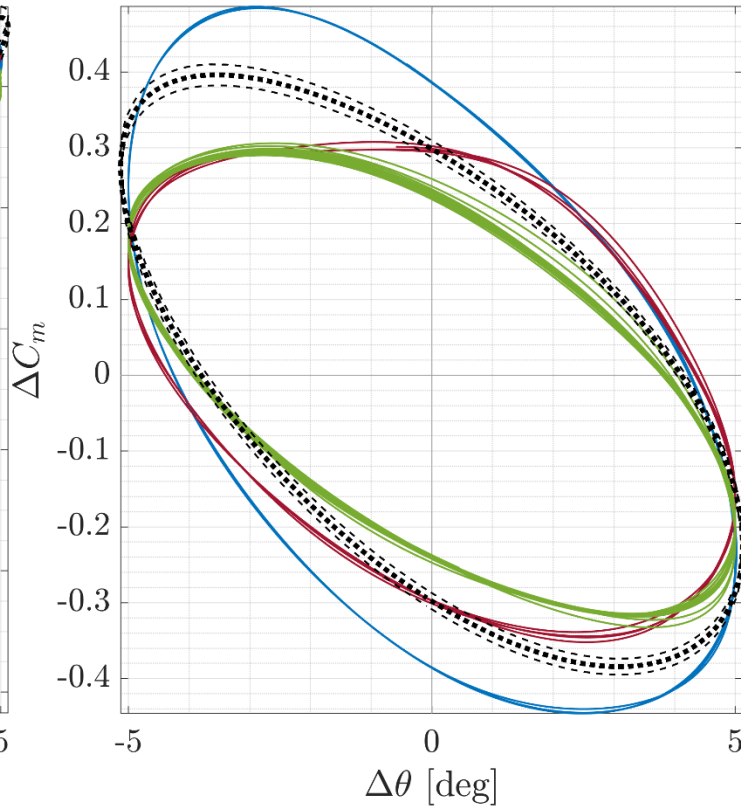
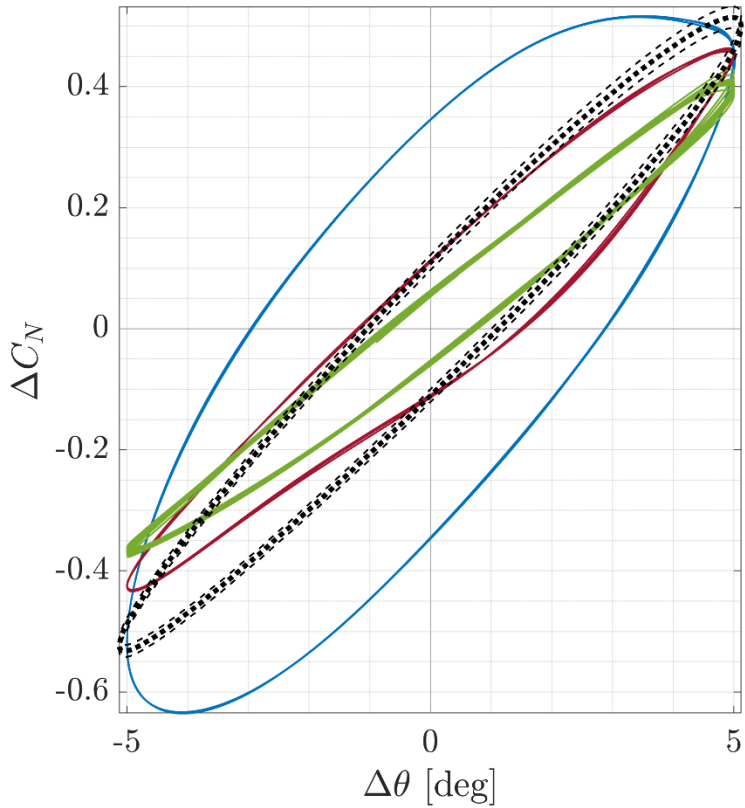
Case 2a Results – Optional

- Pitch forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\theta \leq +5^\circ$
- $f_r = \frac{\omega \bar{c}}{2V} = 0.04$ (optional: 0.06, 0.08, 0.10)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with sting and tail

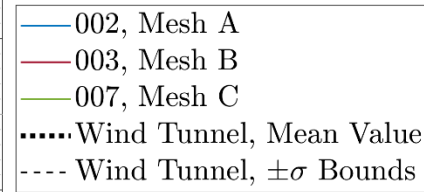
Case 2a: Hysteresis Loops ($f_r = 0.06$)



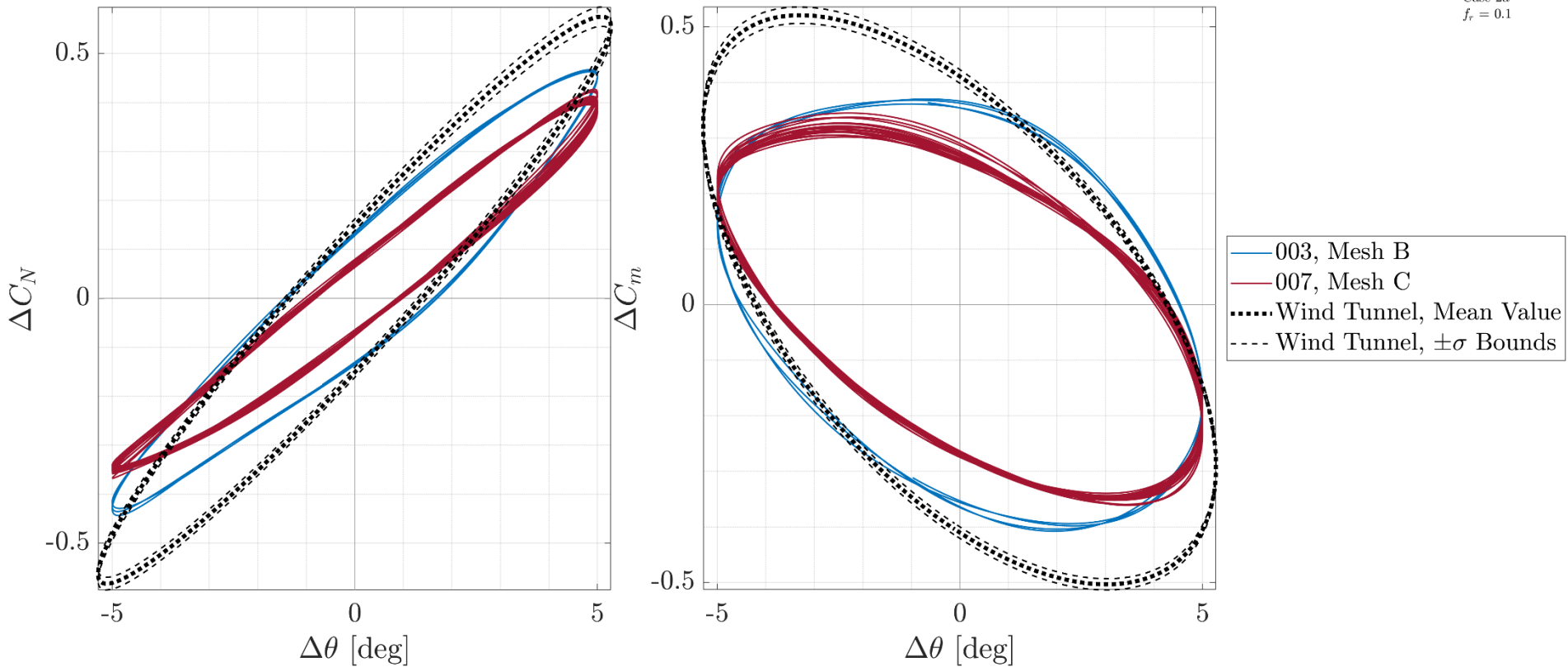
Case 2a: Hysteresis Loops ($f_r = 0.08$)



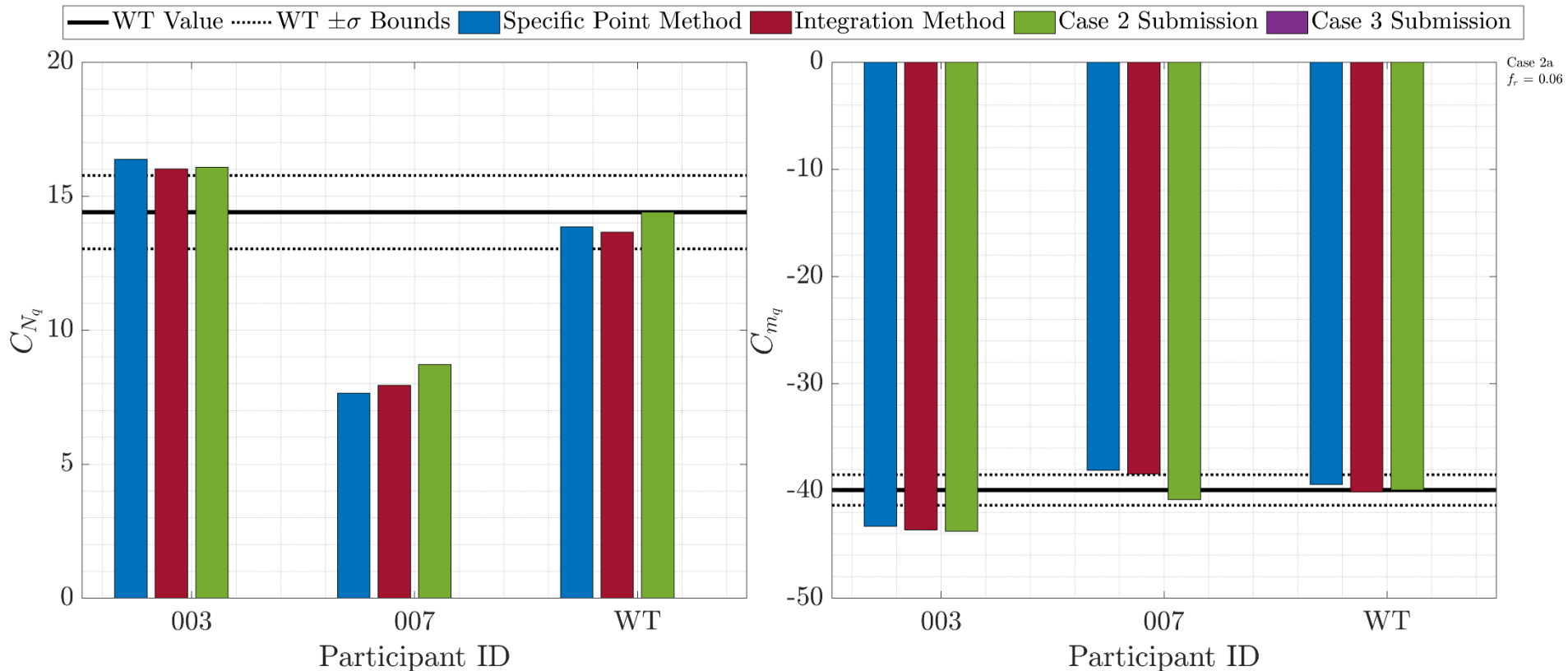
Case 2a
 $f_r = 0.08$



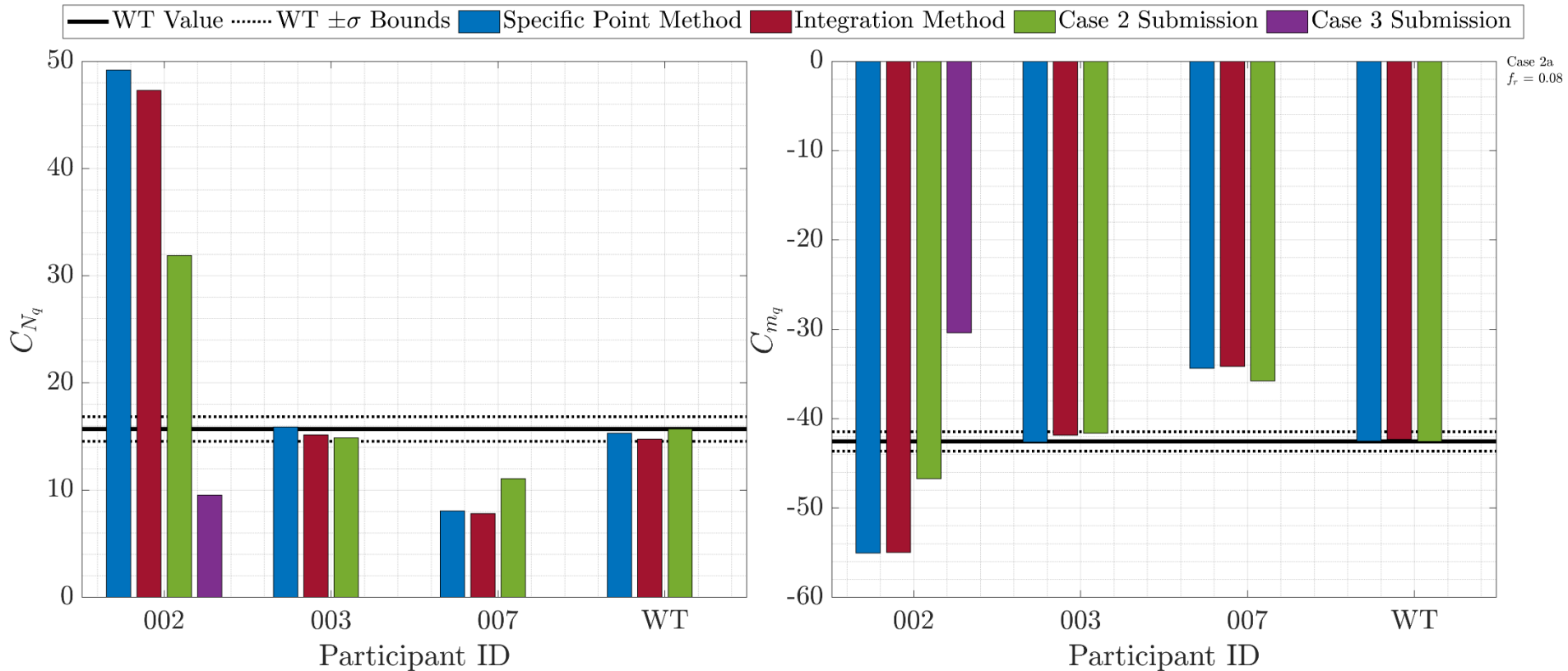
Case 2a: Hysteresis Loops ($f_r = 0.10$)



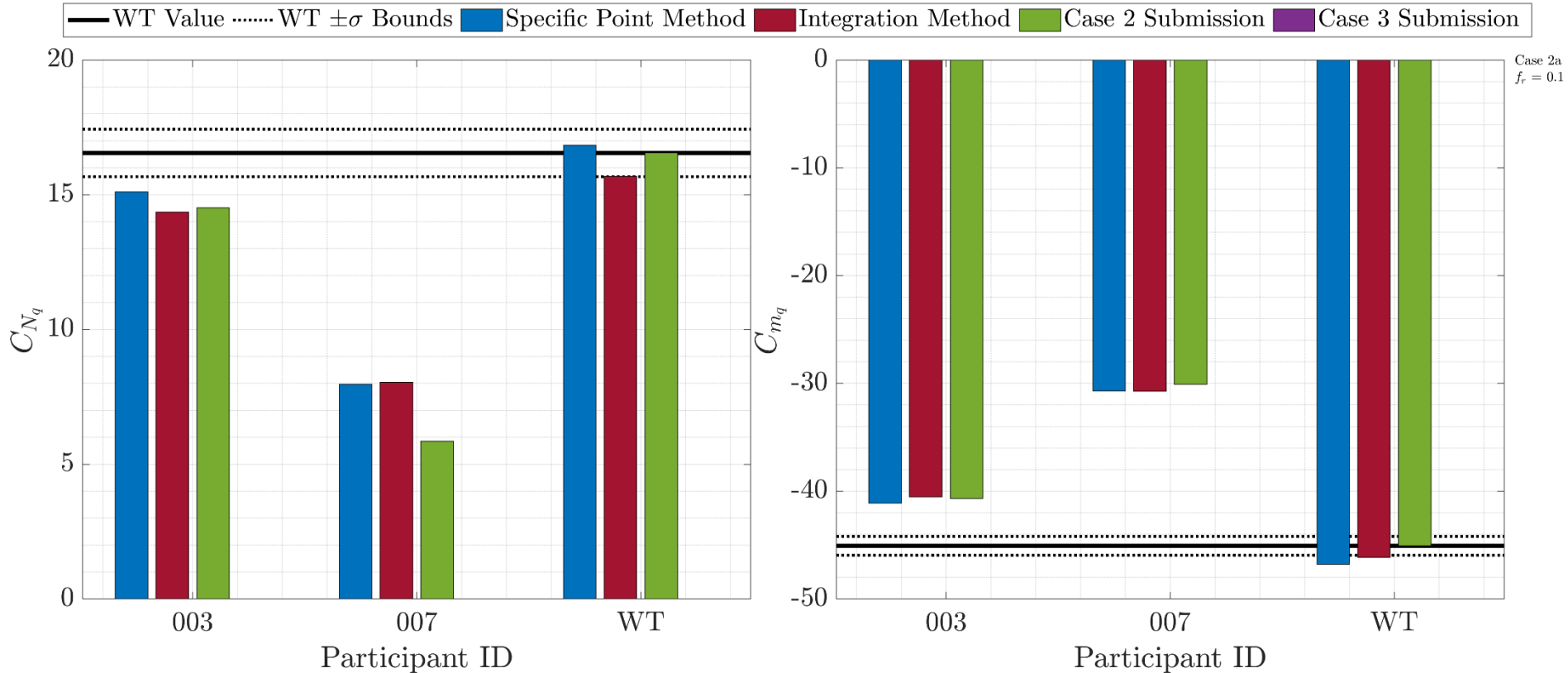
Case 2a: Dynamic Stability Derivatives ($f_r = 0.06$)



Case 2a: Dynamic Stability Derivatives ($f_r = 0.08$)

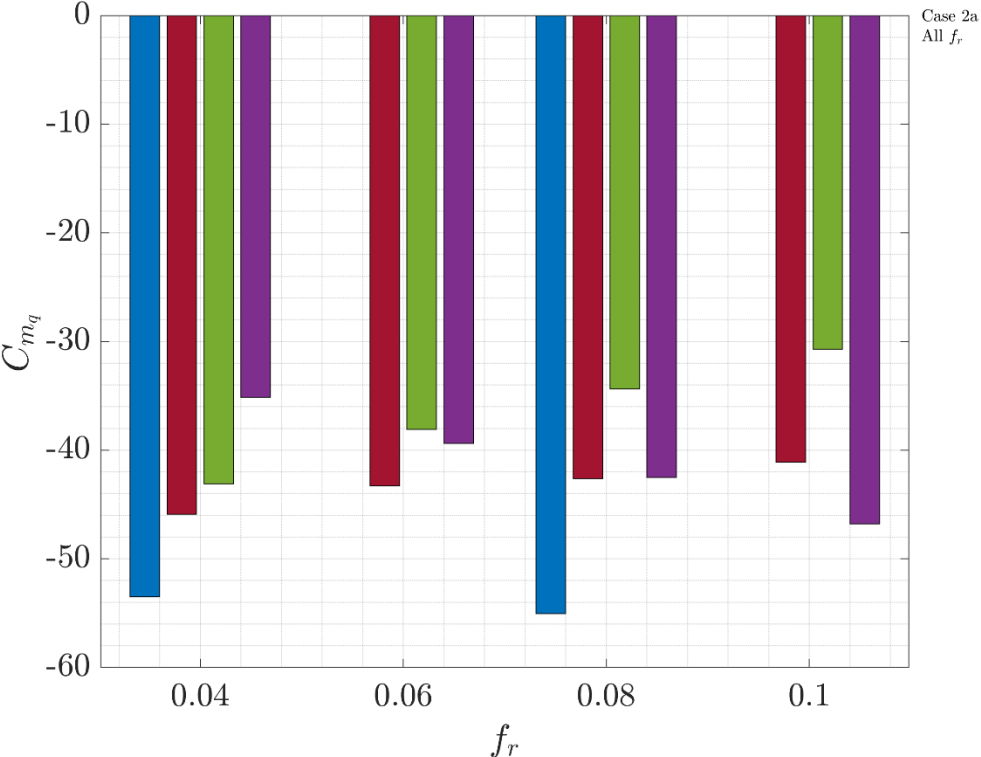
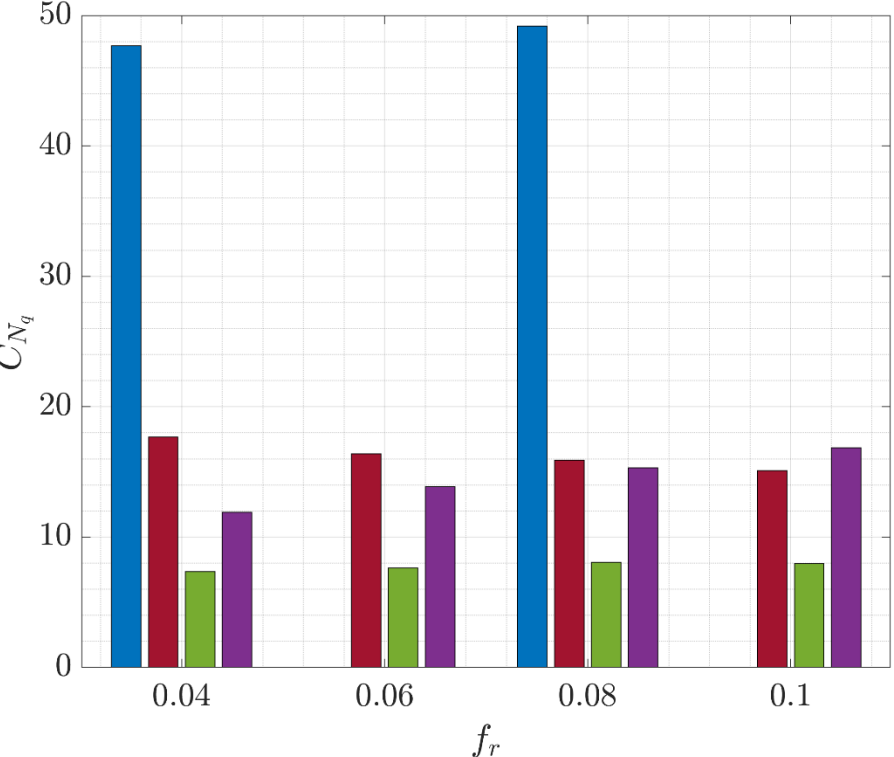


Case 2a: Dynamic Stability Derivatives ($f_r = 0.10$)



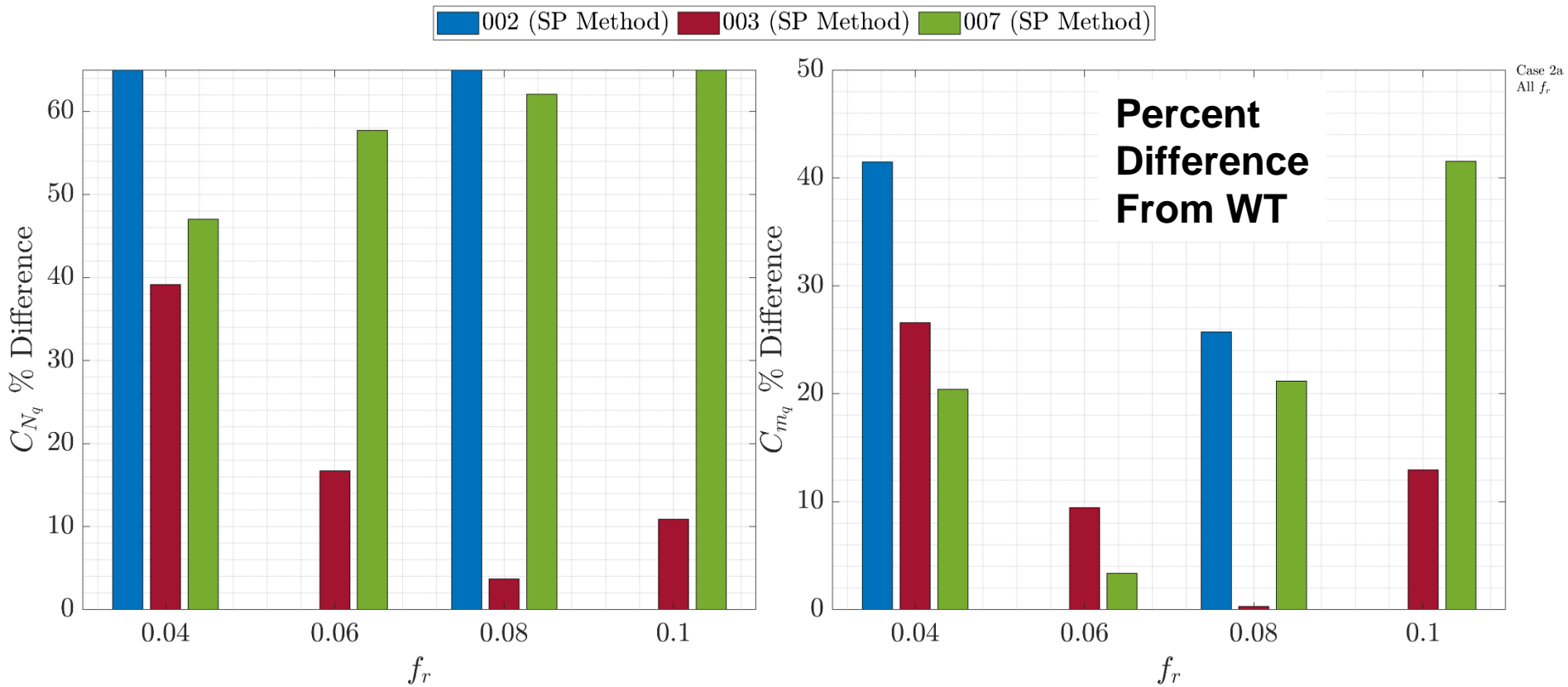
Case 2a: Dynamic Stability Derivatives (All f_r)

002 (SP Method) 003 (SP Method) 007 (SP Method) WT (SP Method)



Case 2a
All f_r

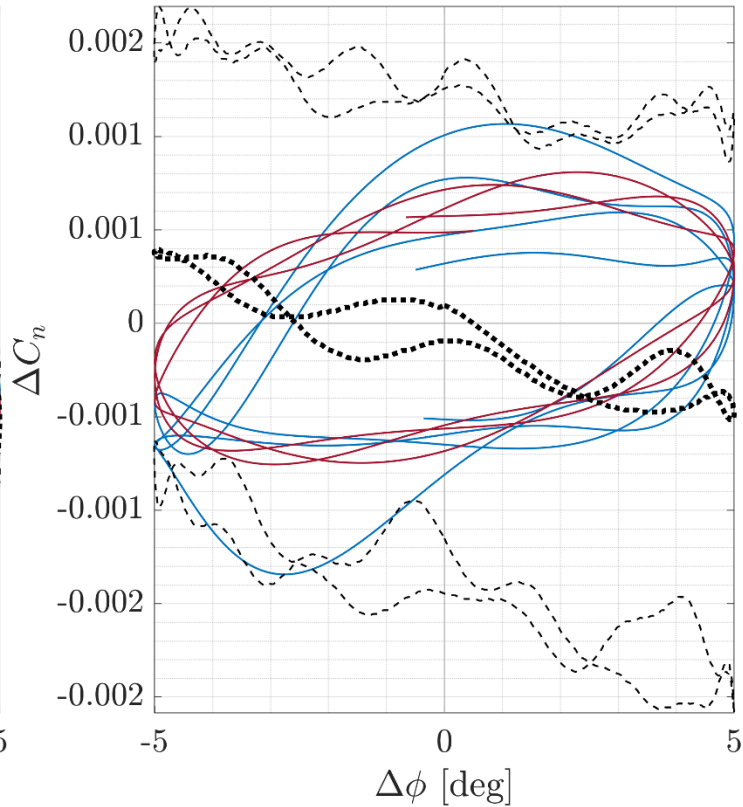
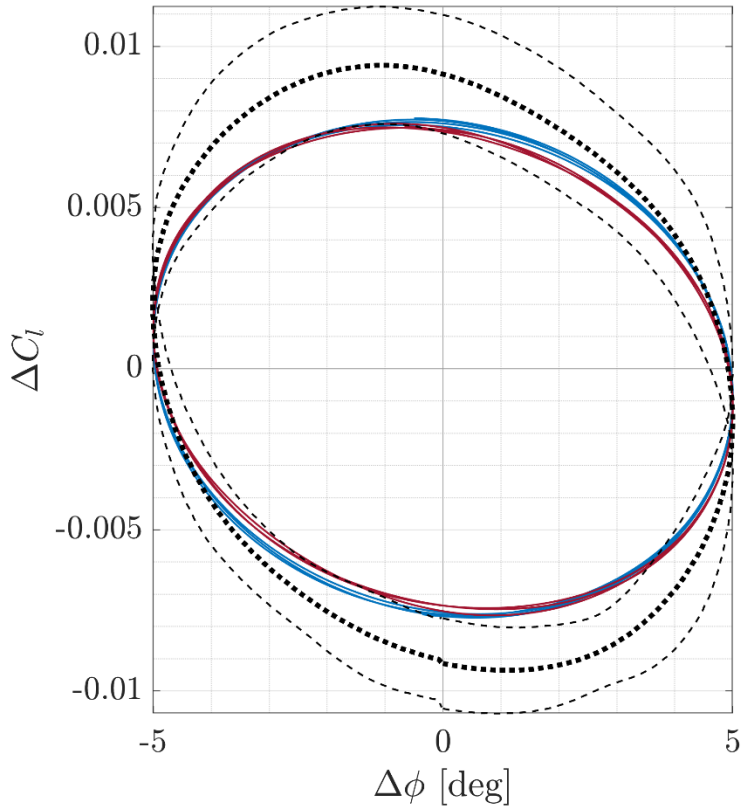
Case 2a: Dynamic Stability Derivatives (All f_r)



Case 2b Results – Optional

- Roll forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\phi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with sting and tail

Case 2b: Hysteresis Loops ($f_r = 0.2$)

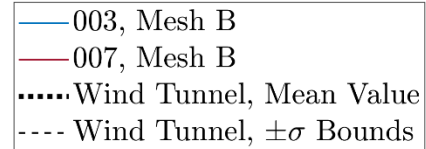
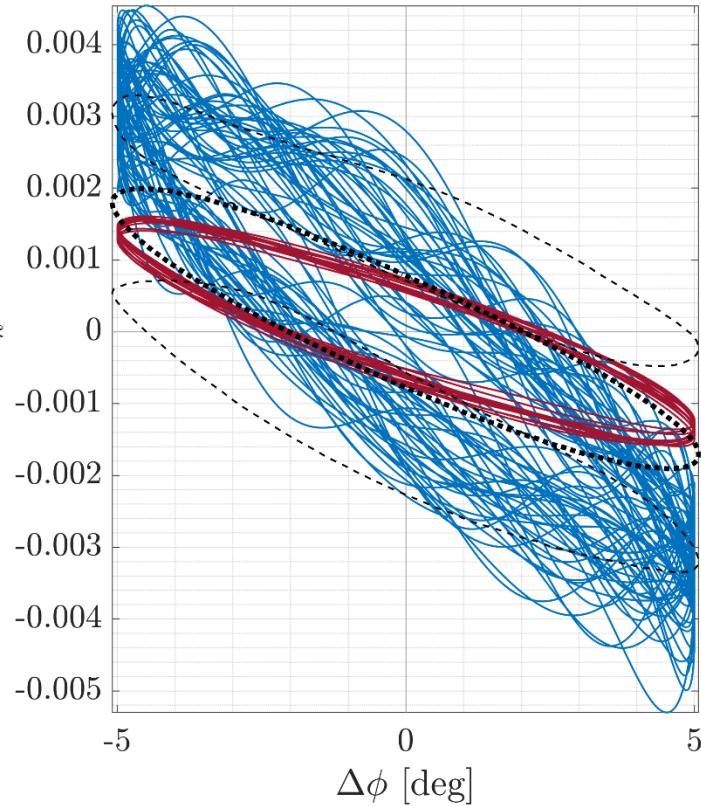
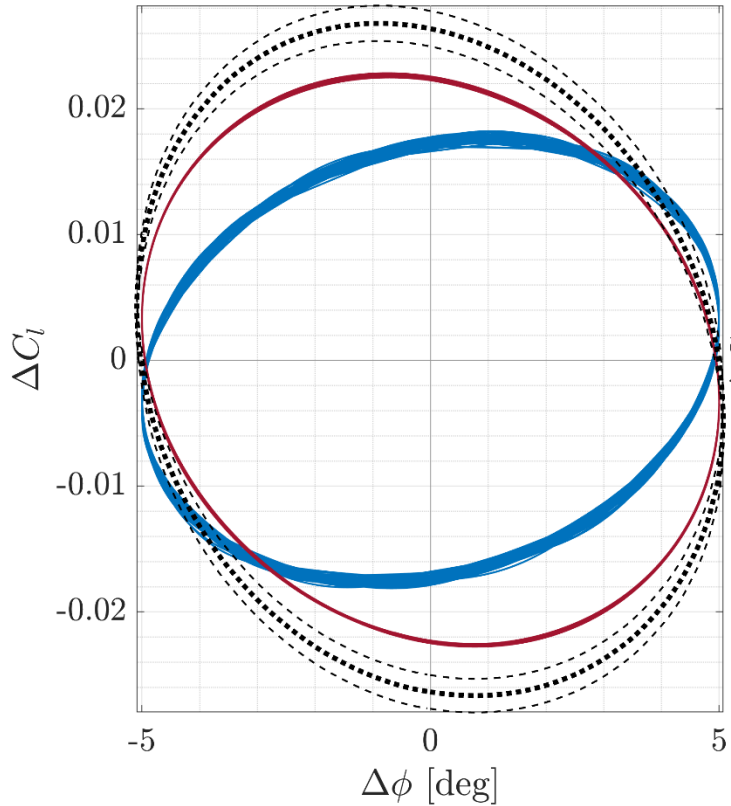


Case 2b
 $f_r = 0.2$

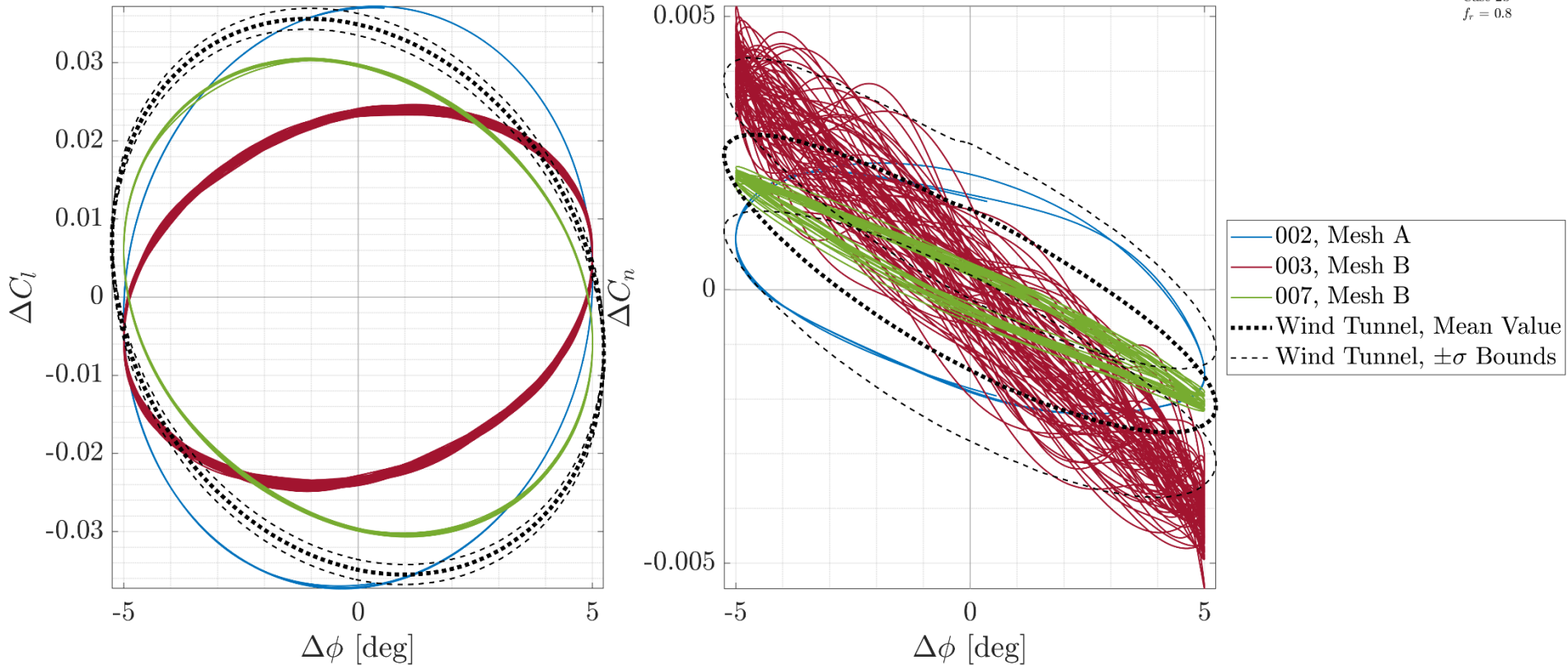
- 003, Mesh B
- 007, Mesh B
- Wind Tunnel, Mean Value
- - - Wind Tunnel, $\pm\sigma$ Bounds

Case 2b: Hysteresis Loops ($f_r = 0.6$)

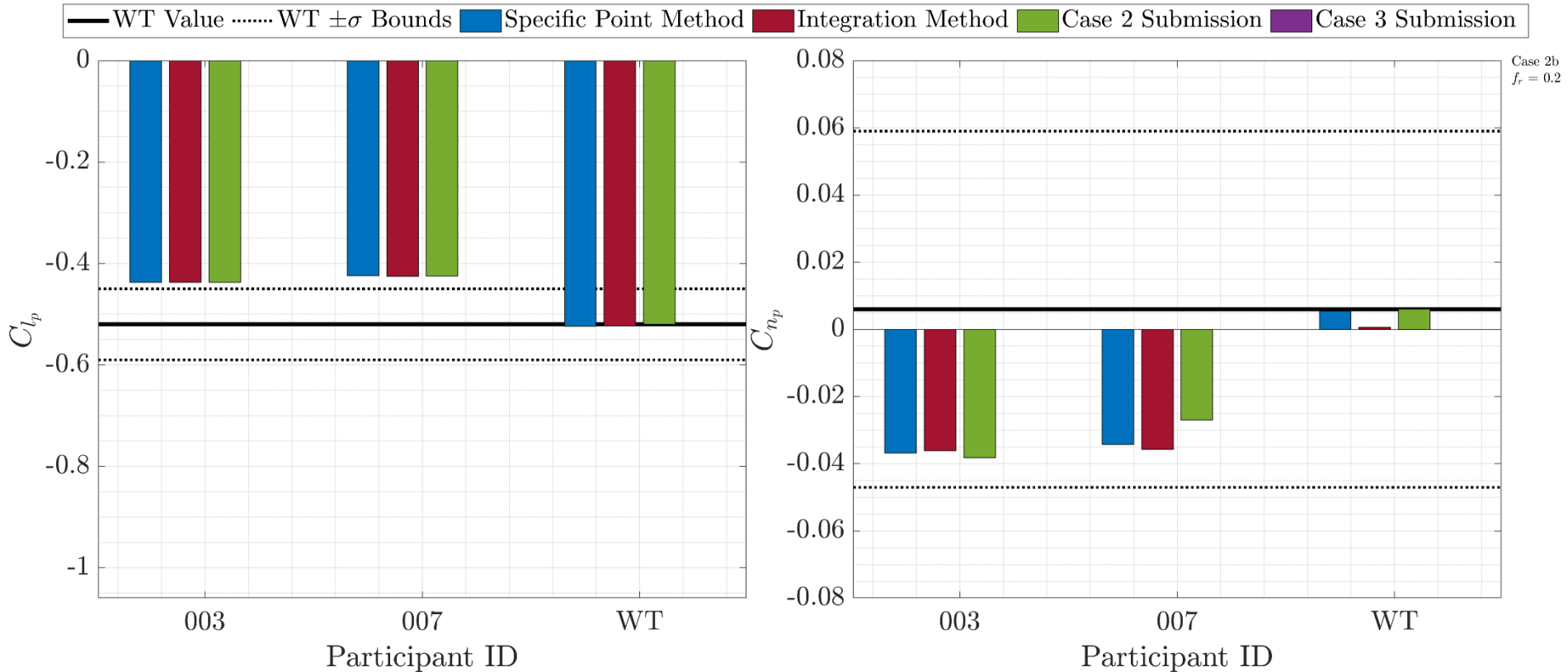
Case 2b
 $f_r = 0.6$



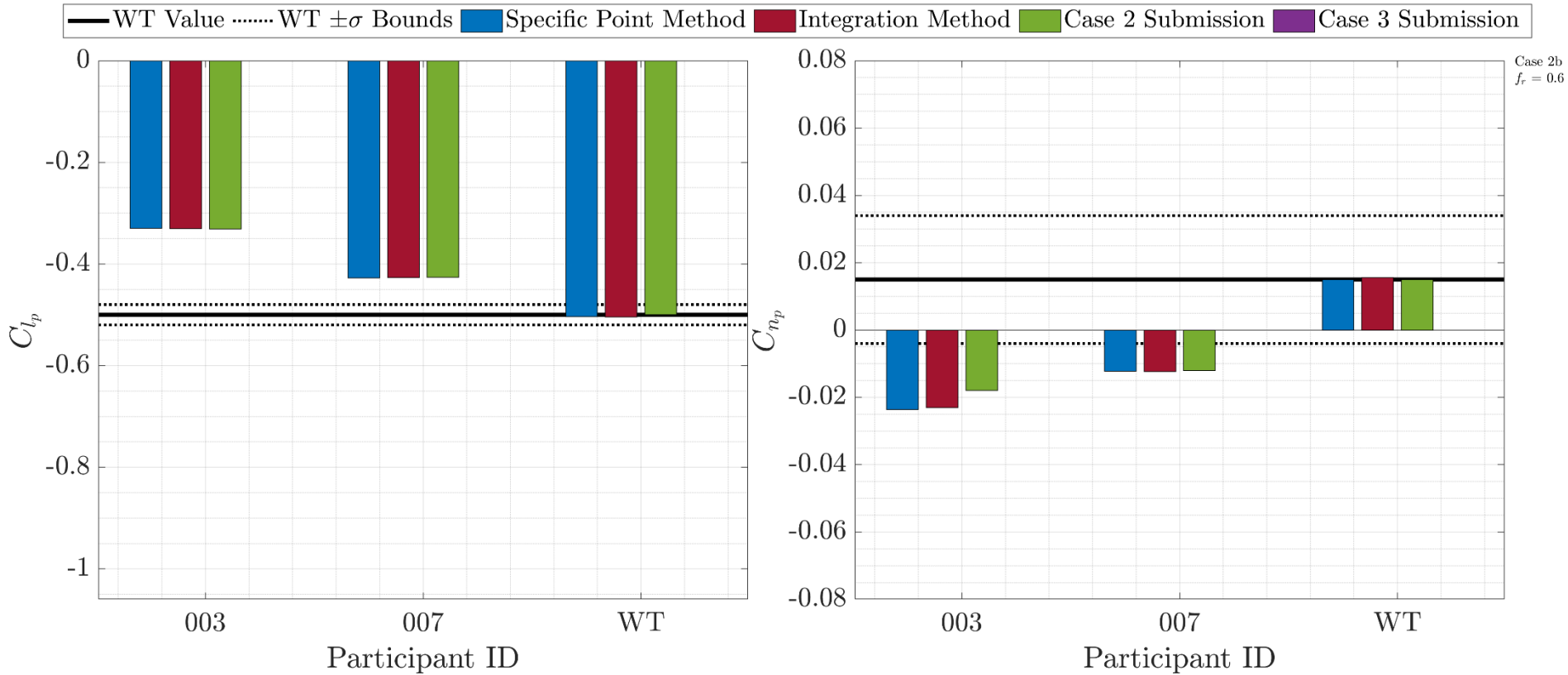
Case 2b: Hysteresis Loops ($f_r = 0.8$)



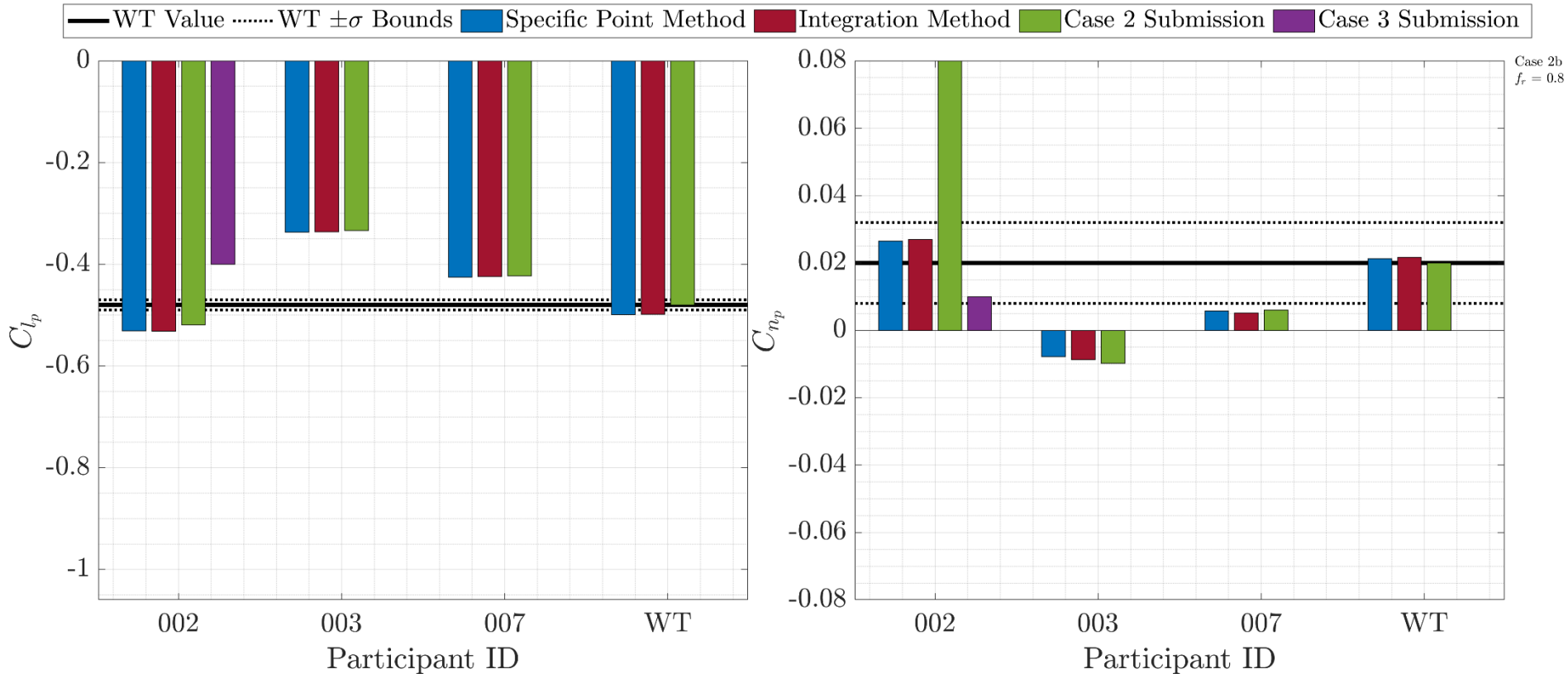
Case 2b: Dynamic Stability Derivatives ($f_r = 0.2$)



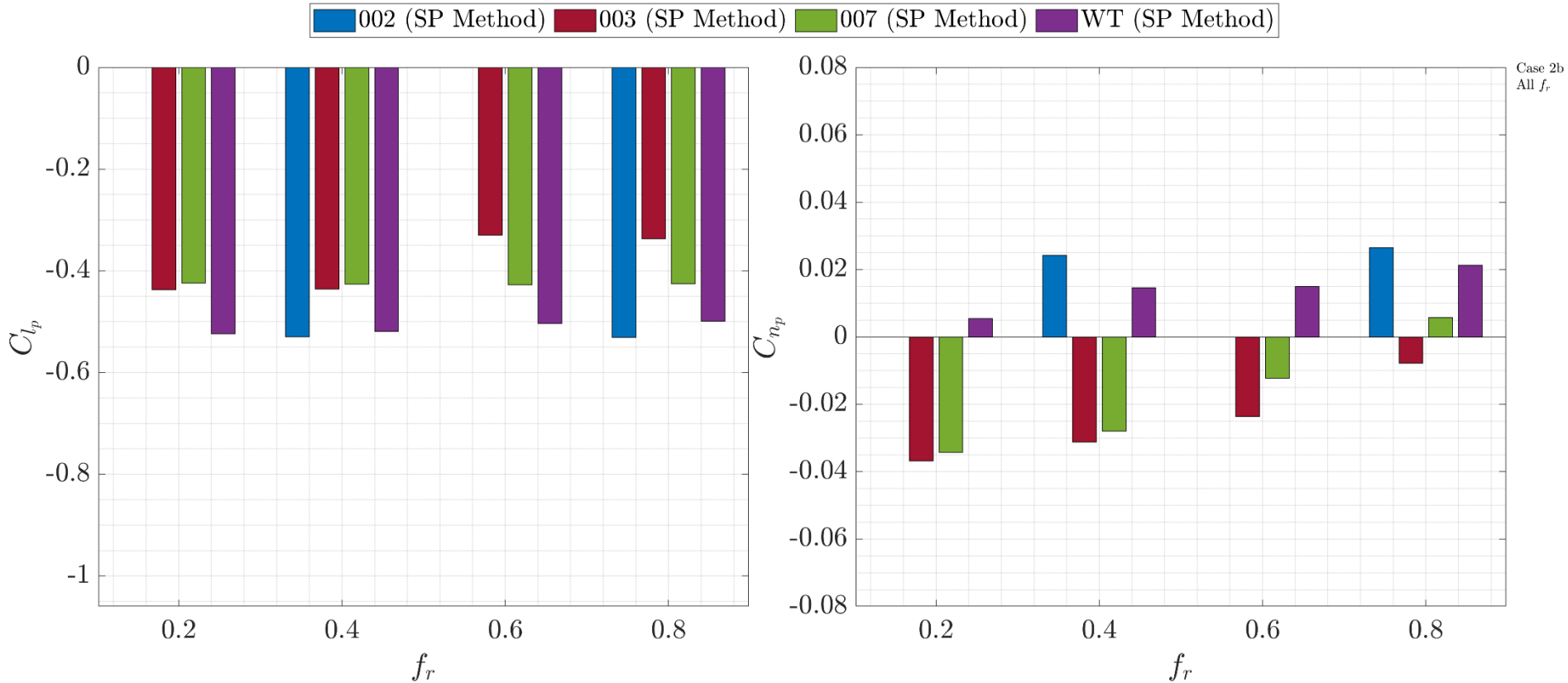
Case 2b: Dynamic Stability Derivatives ($f_r = 0.6$)



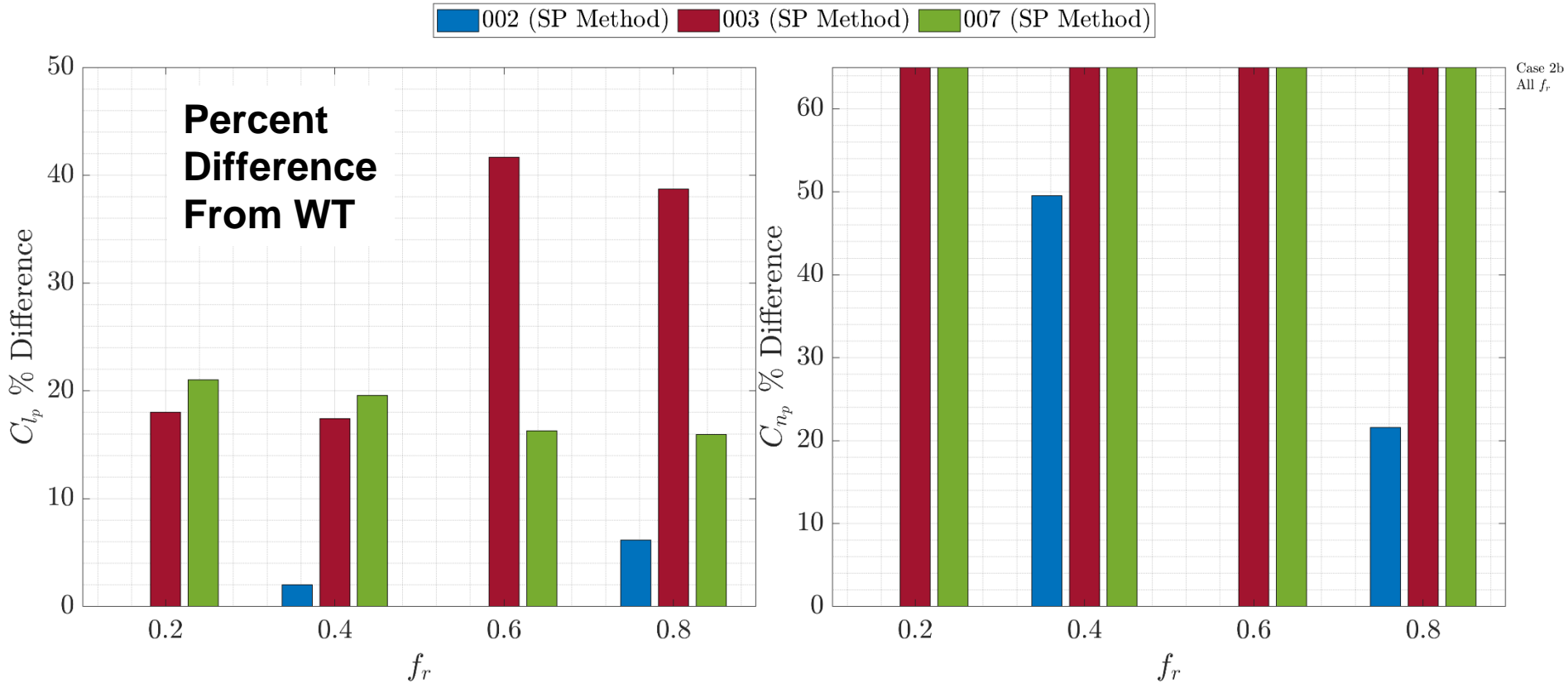
Case 2b: Dynamic Stability Derivatives ($f_r = 0.8$)



Case 2b: Dynamic Stability Derivatives (All f_r)



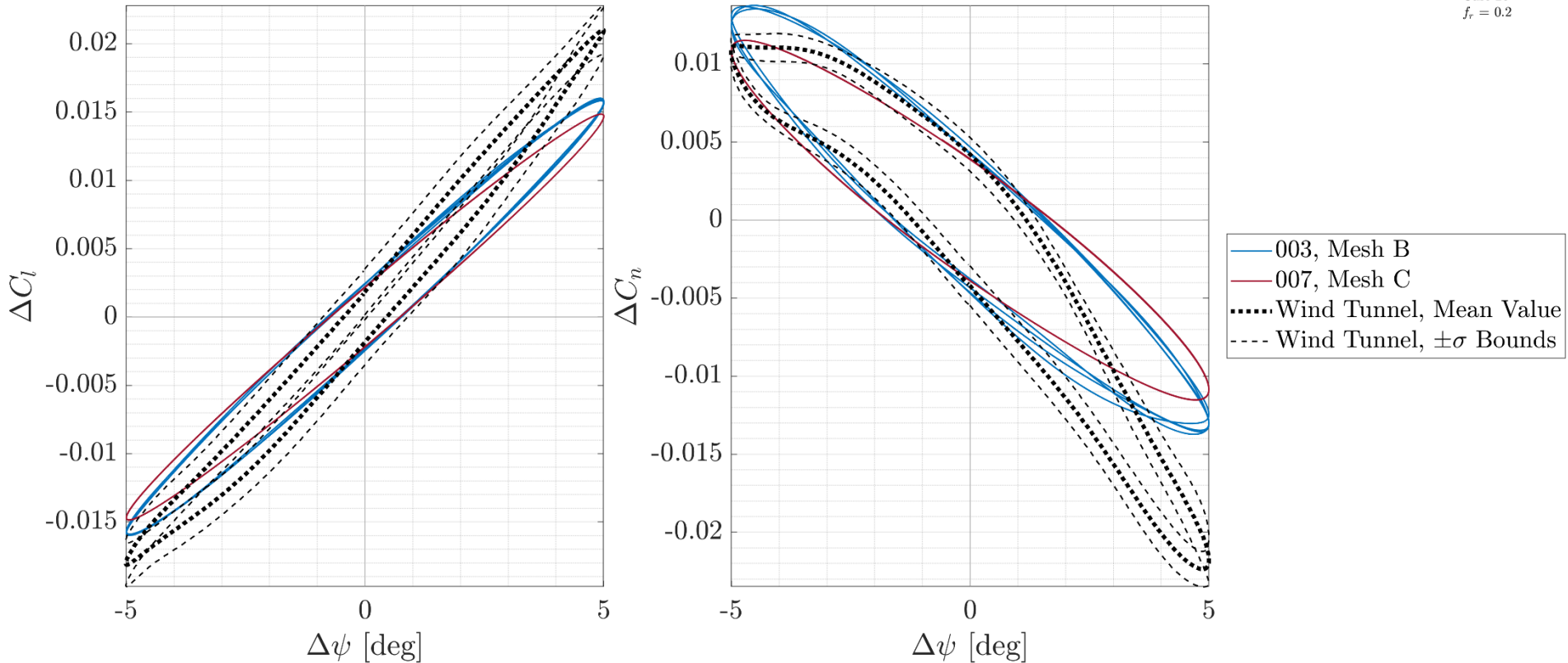
Case 2b: Dynamic Stability Derivatives (All f_r)



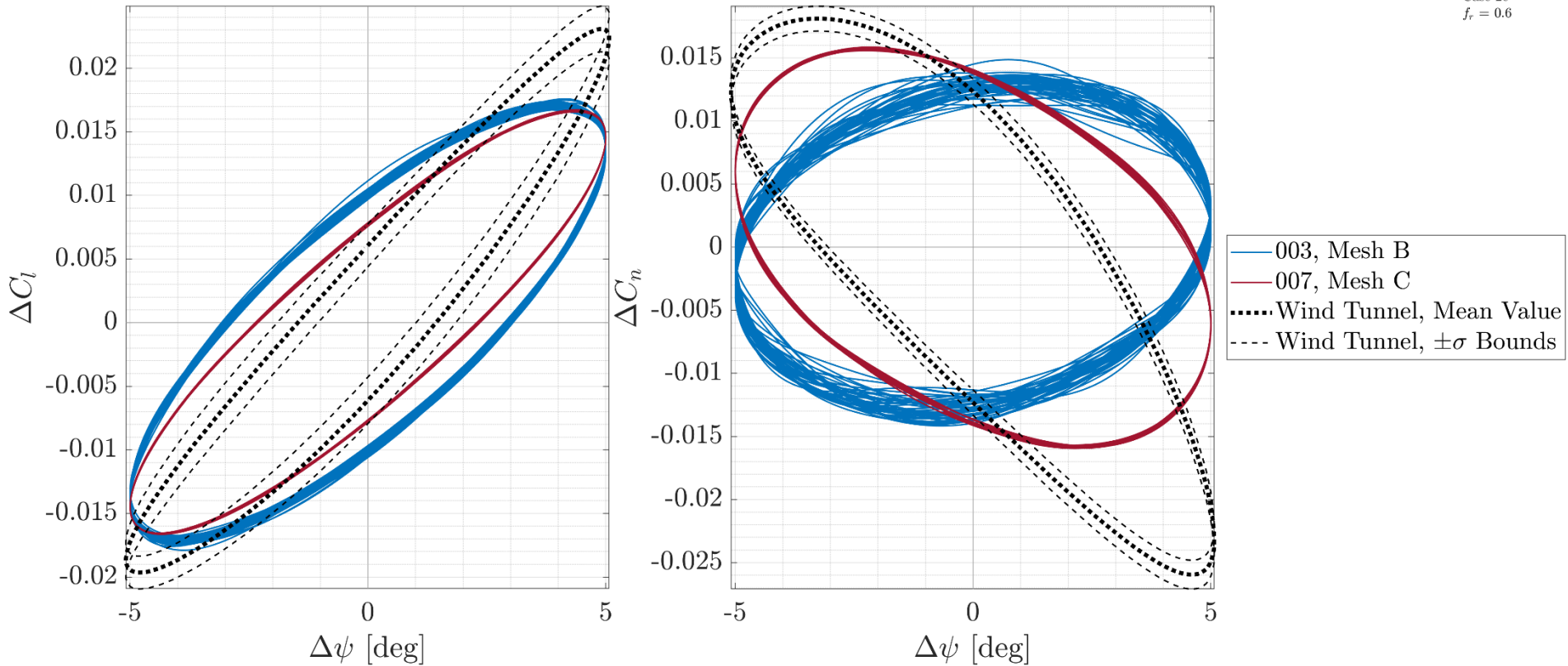
Case 2c Results – Optional

- Yaw forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\psi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with sting and tail

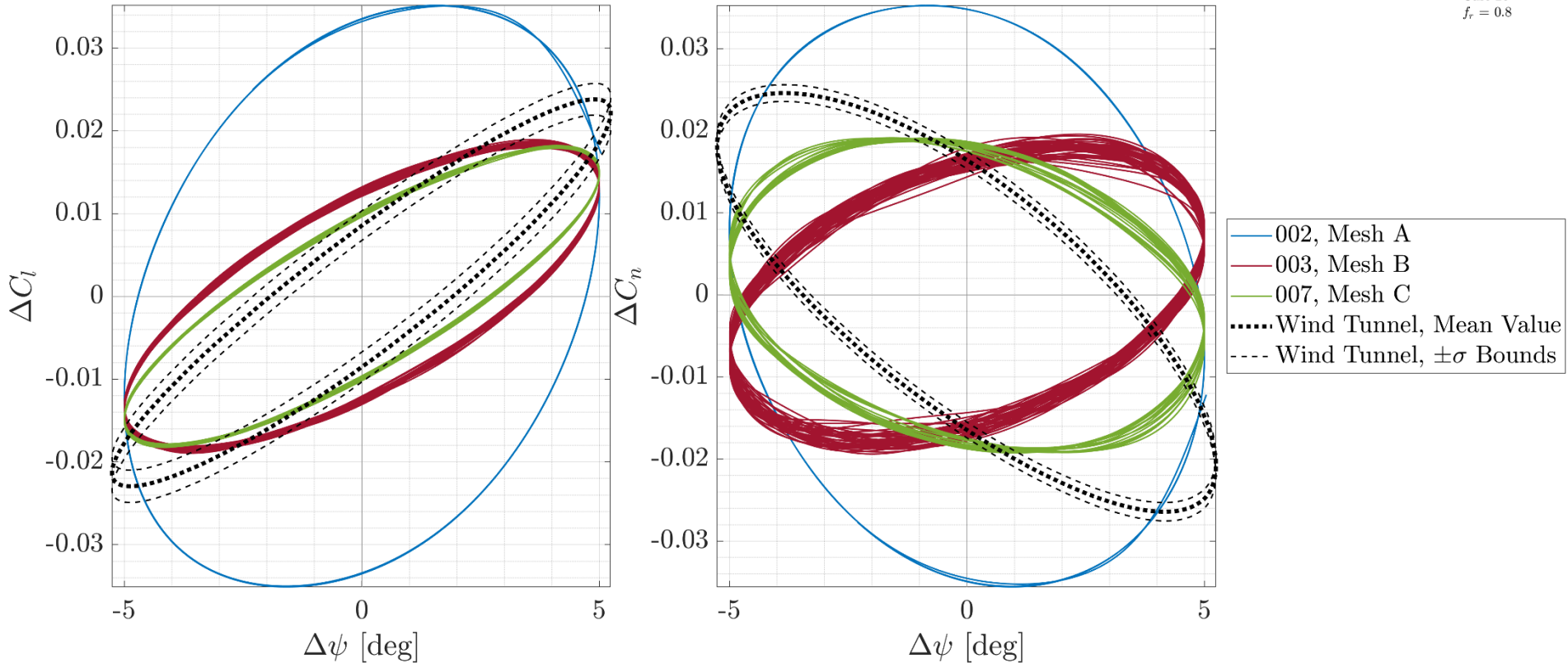
Case 2c: Hysteresis Loops ($f_r = 0.2$)



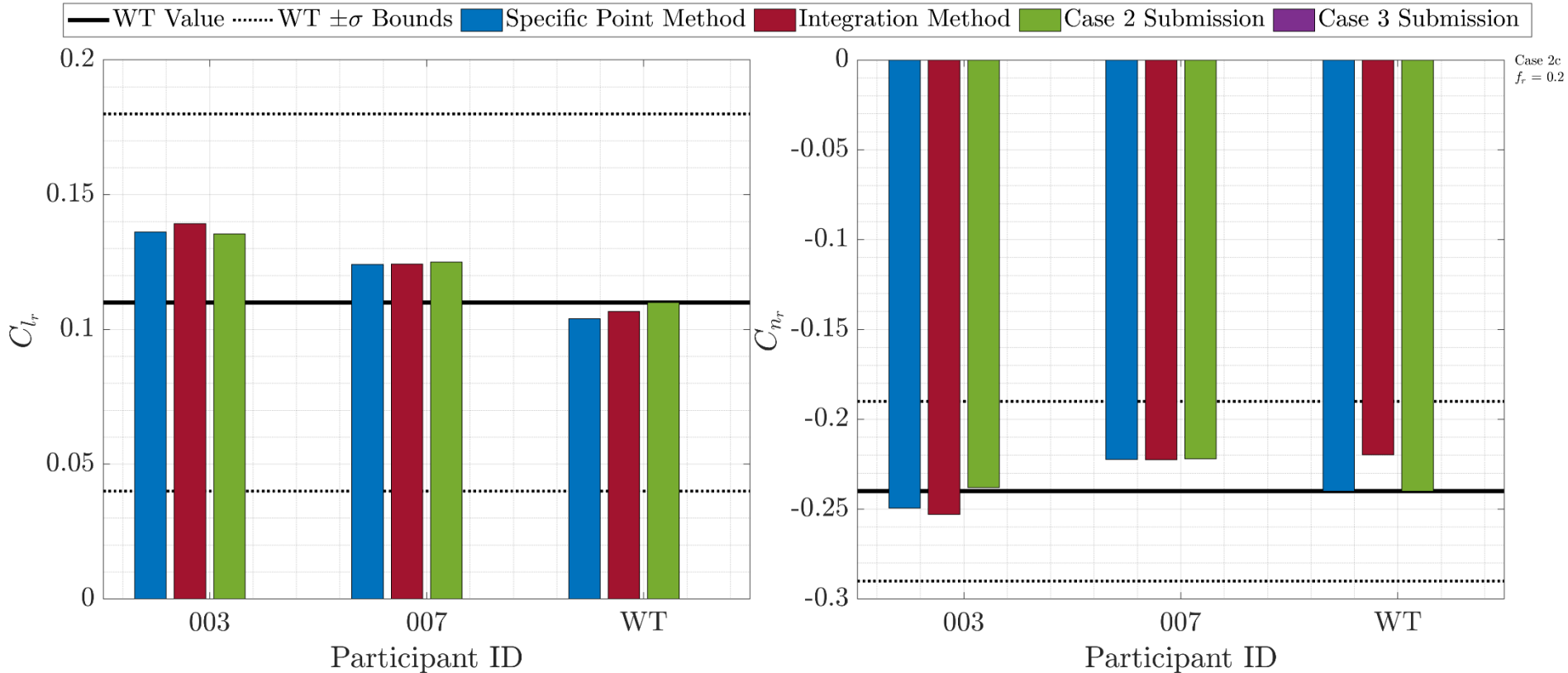
Case 2c: Hysteresis Loops ($f_r = 0.6$)



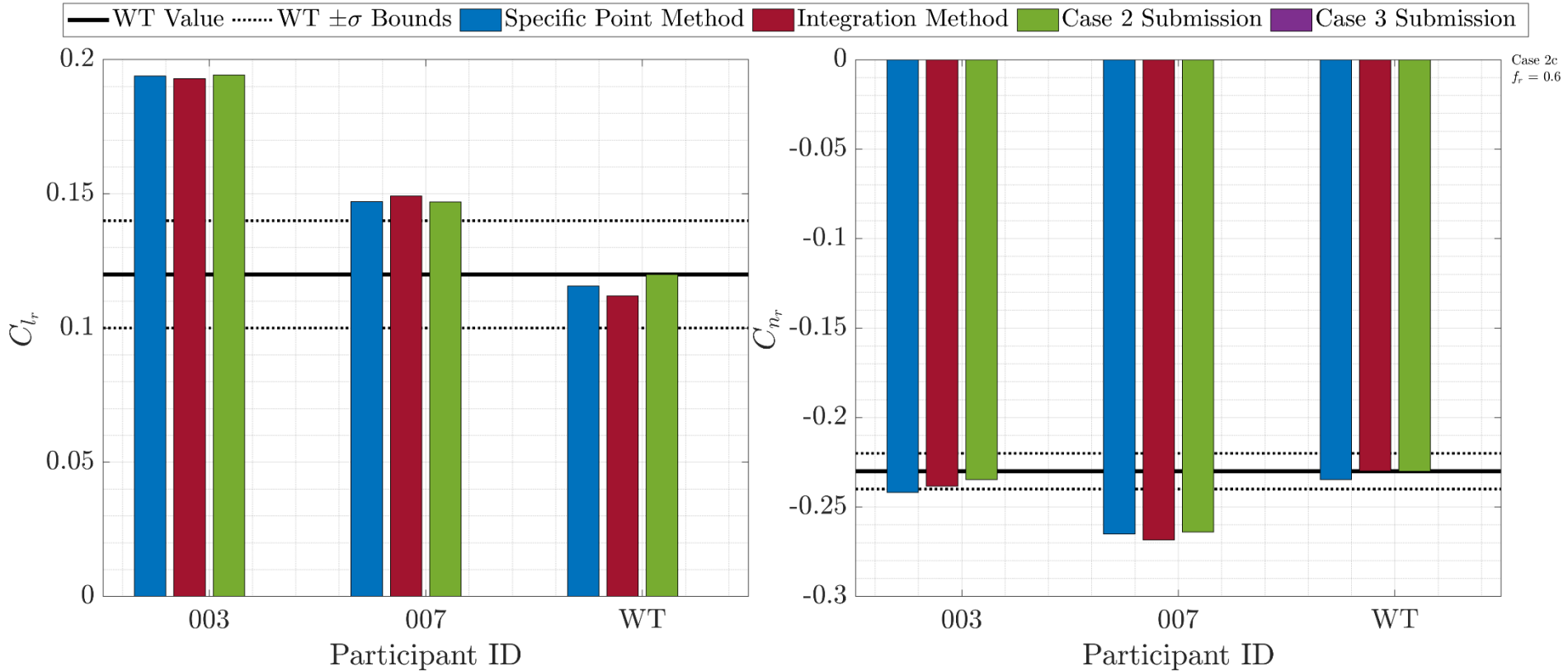
Case 2c: Hysteresis Loops ($f_r = 0.8$)



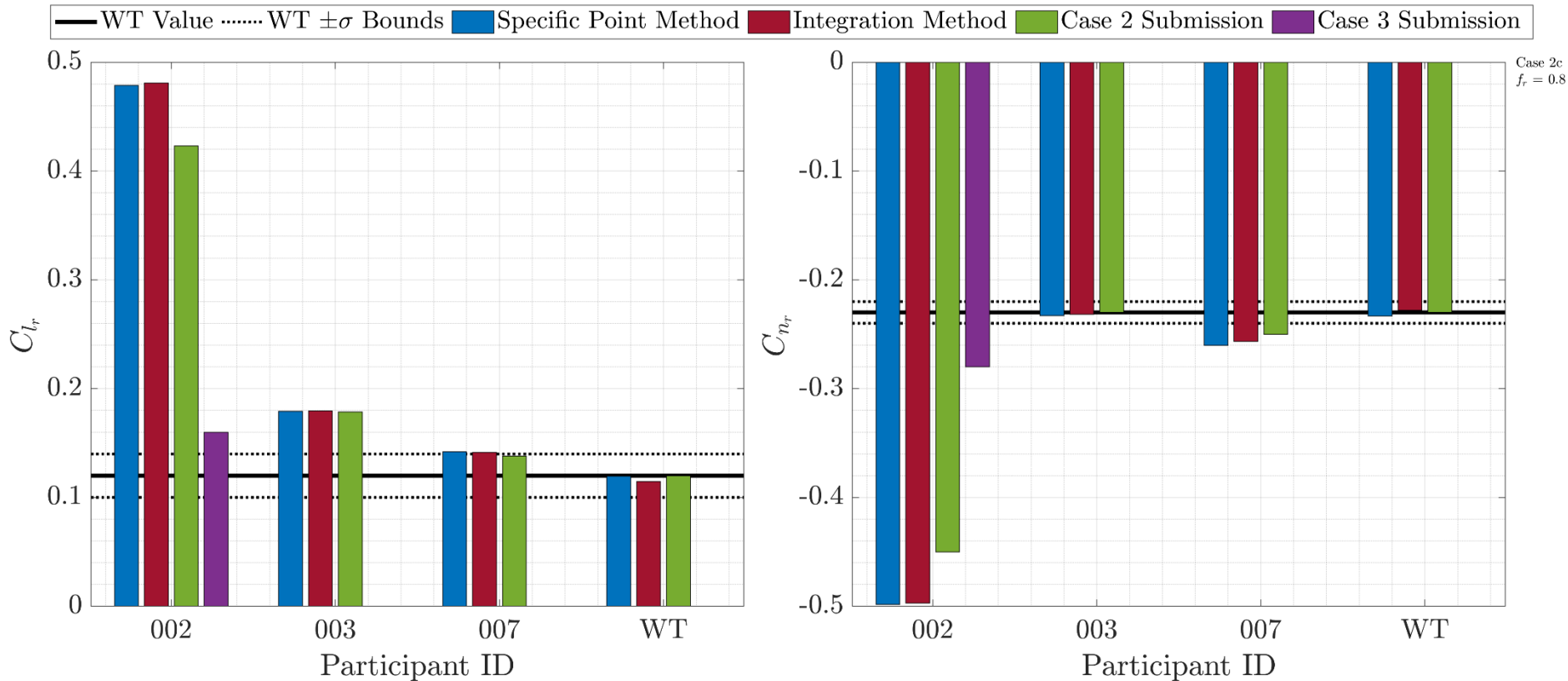
Case 2c: Dynamic Stability Derivatives ($f_r = 0.2$)



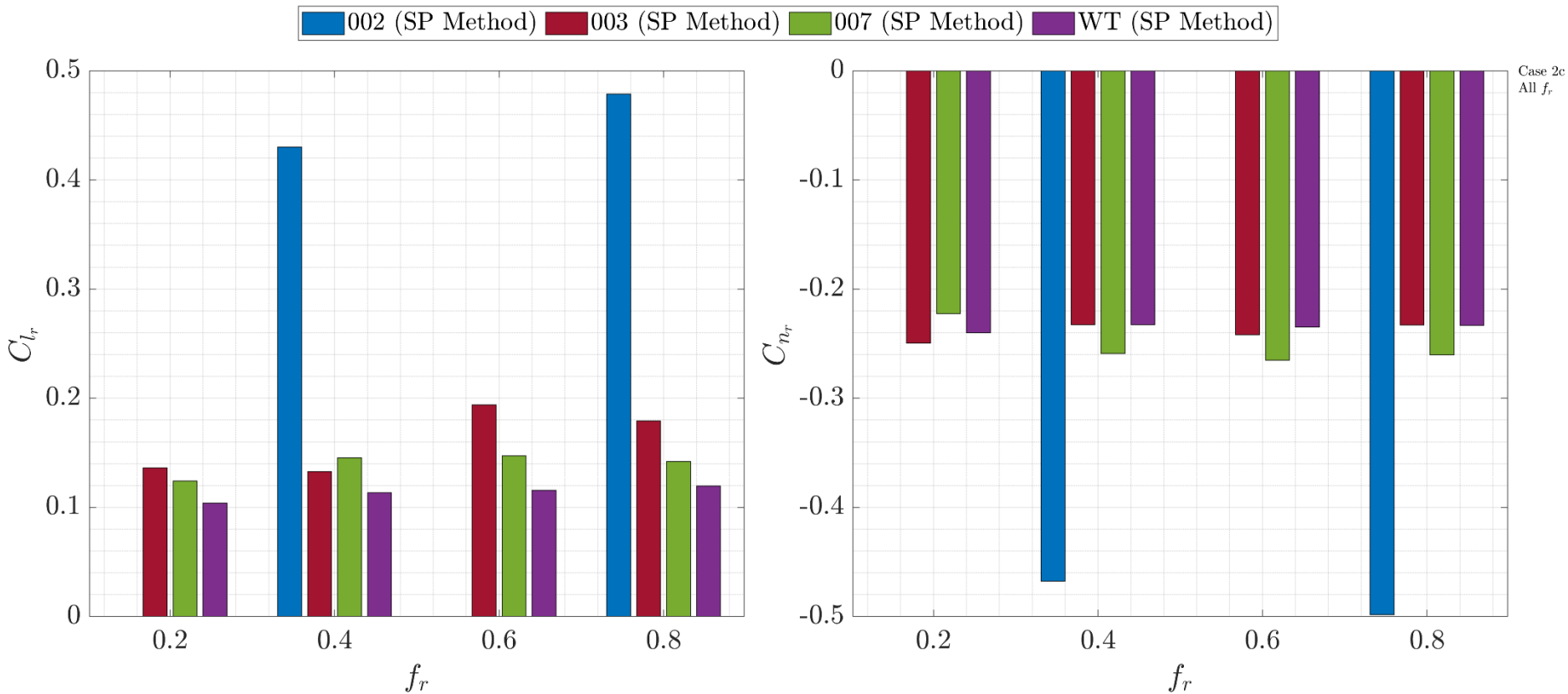
Case 2c: Dynamic Stability Derivatives ($f_r = 0.6$)



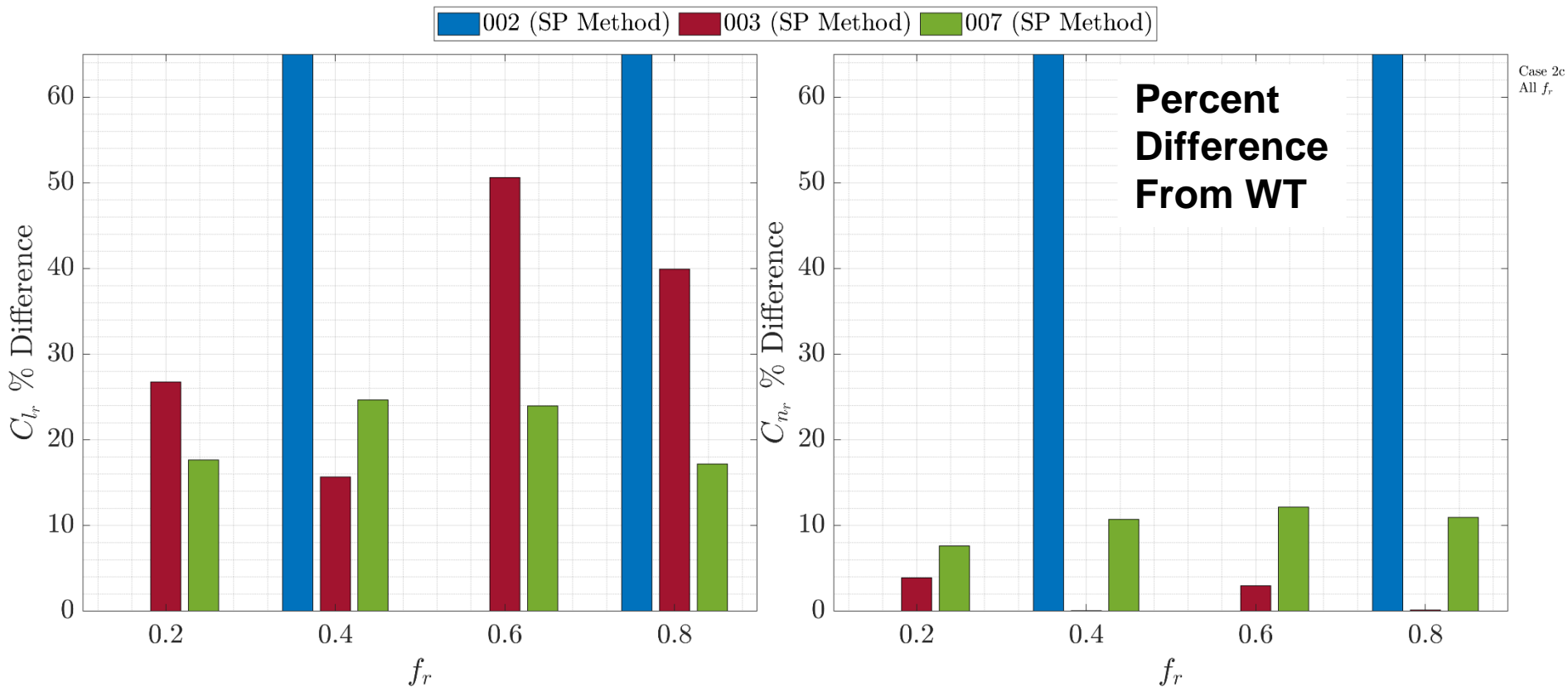
Case 2c: Dynamic Stability Derivatives ($f_r = 0.8$)



Case 2c: Dynamic Stability Derivatives (All f_r)



Case 2c: Dynamic Stability Derivatives (All f_r)



Optional Dynamic Test Cases Without Sting

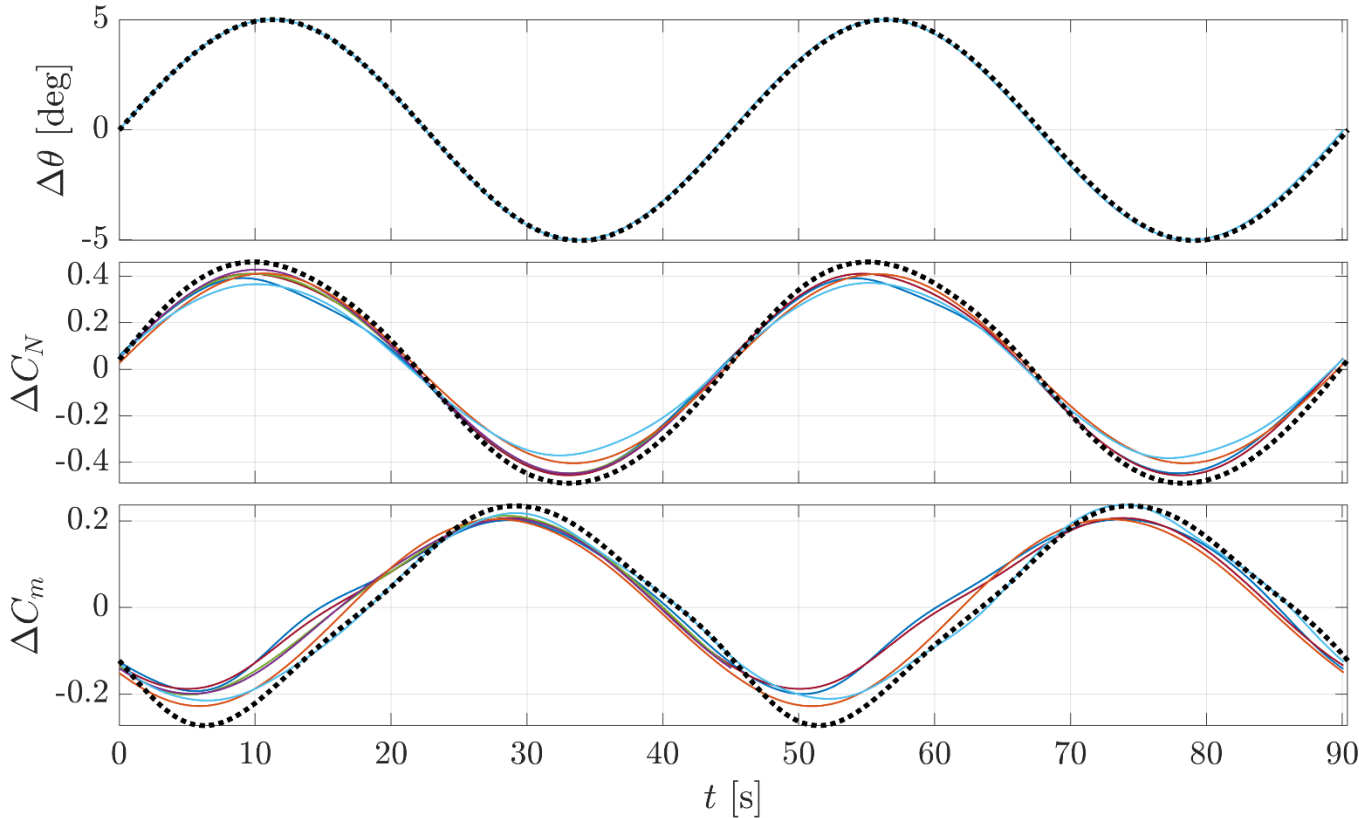
Case 5a Results

- Pitch forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\theta \leq +5^\circ$
- $f_r = \frac{\omega \bar{c}}{2V} = 0.04$ (optional: 0.06, 0.08, 0.10)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with tail and no sting

**Note: wind tunnel results
still have sting effects**

Case 2a/5a: Time Histories ($f_r = 0.04$)

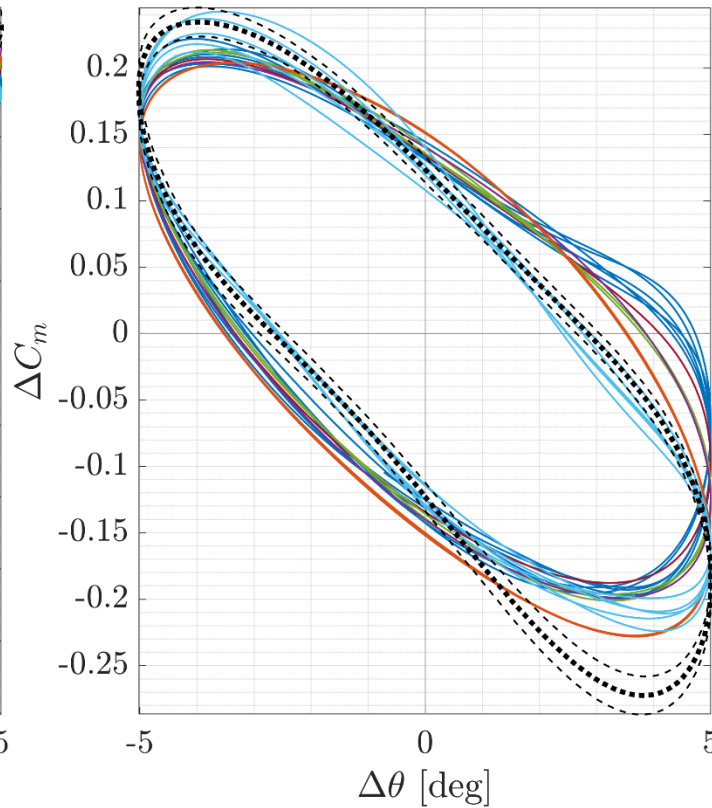
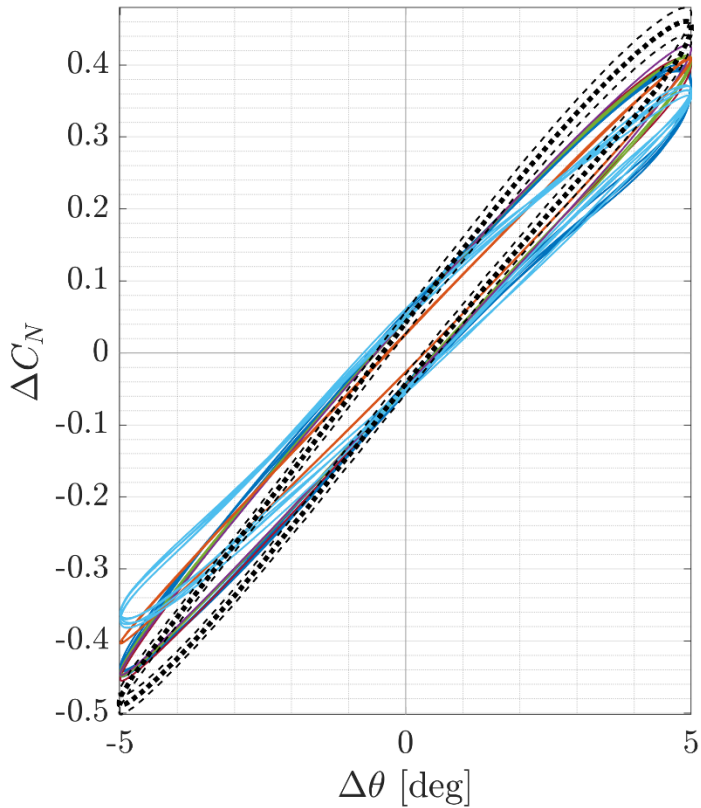
Case 2a/5a
 $f_r = 0.04$



- 004, Case 2a, Mesh D
- 004, Case 5a, Mesh D
- 006, Case 2a, Mesh C, 2x Steps
- 006, Case 5a, Mesh C
- 007, Case 2a, Mesh C
- 007, Case 5a, Mesh C
- Wind Tunnel, Mean Value ($t/0.024$)

Case 2 = With Sting
Case 5 = No Sting

Case 2a/5a: Hysteresis Loops ($f_r = 0.04$)

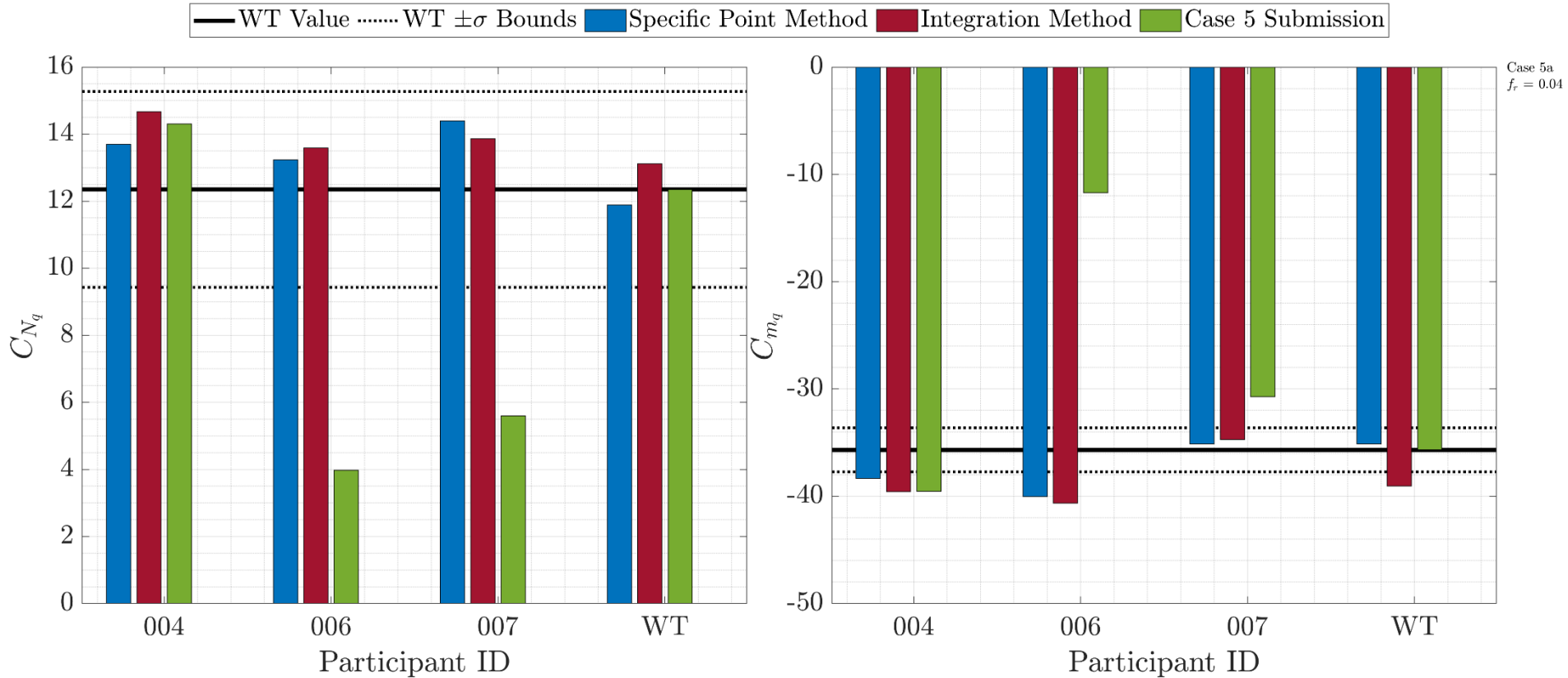


Case 2a/5a
 $f_r = 0.04$

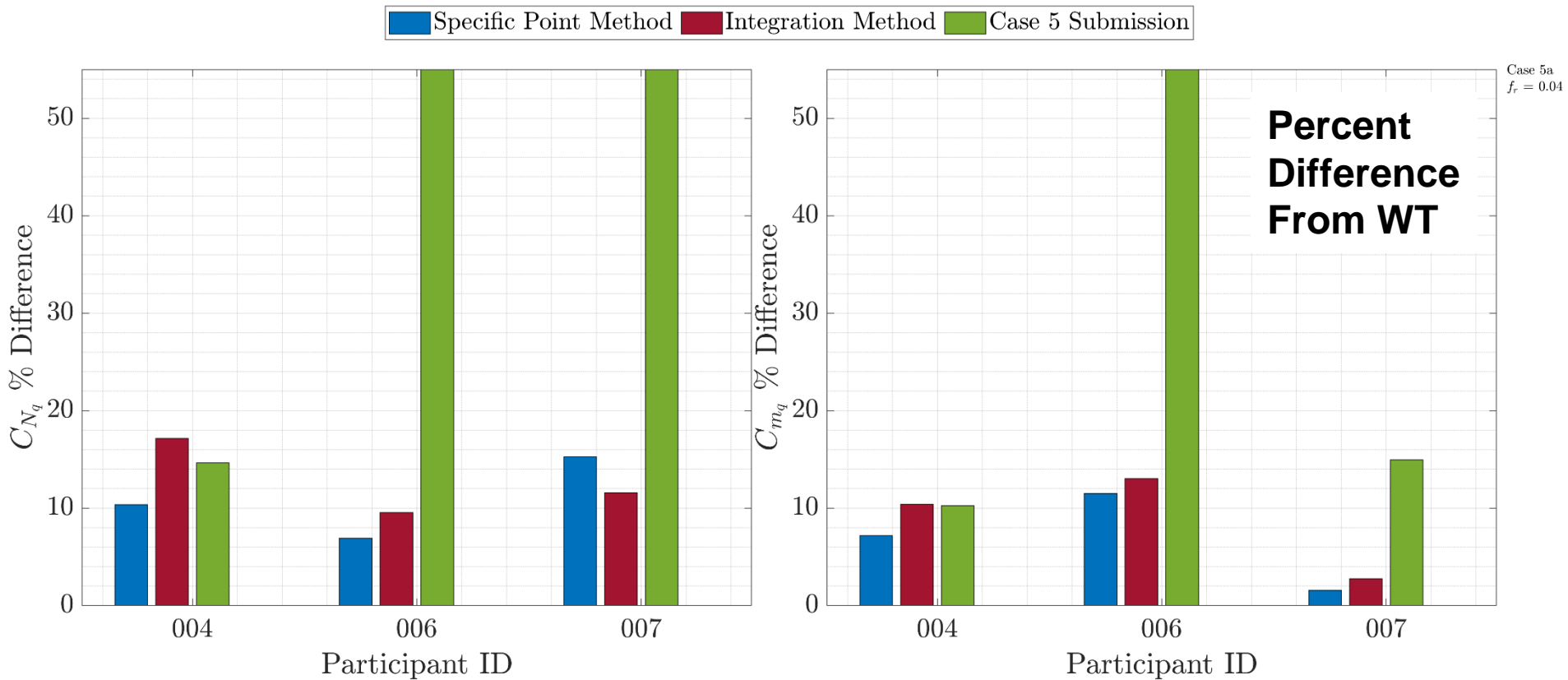
- 004, Case 2a, Mesh D
- 004, Case 5a, Mesh D
- 006, Case 2a, Mesh C, 2x Steps
- 006, Case 5a, Mesh C
- 007, Case 2a, Mesh C
- 007, Case 5a, Mesh C
- ⋯ Wind Tunnel, Mean Value
- - - Wind Tunnel, $\pm\sigma$ Bounds

Case 2 = With Sting
Case 5 = No Sting

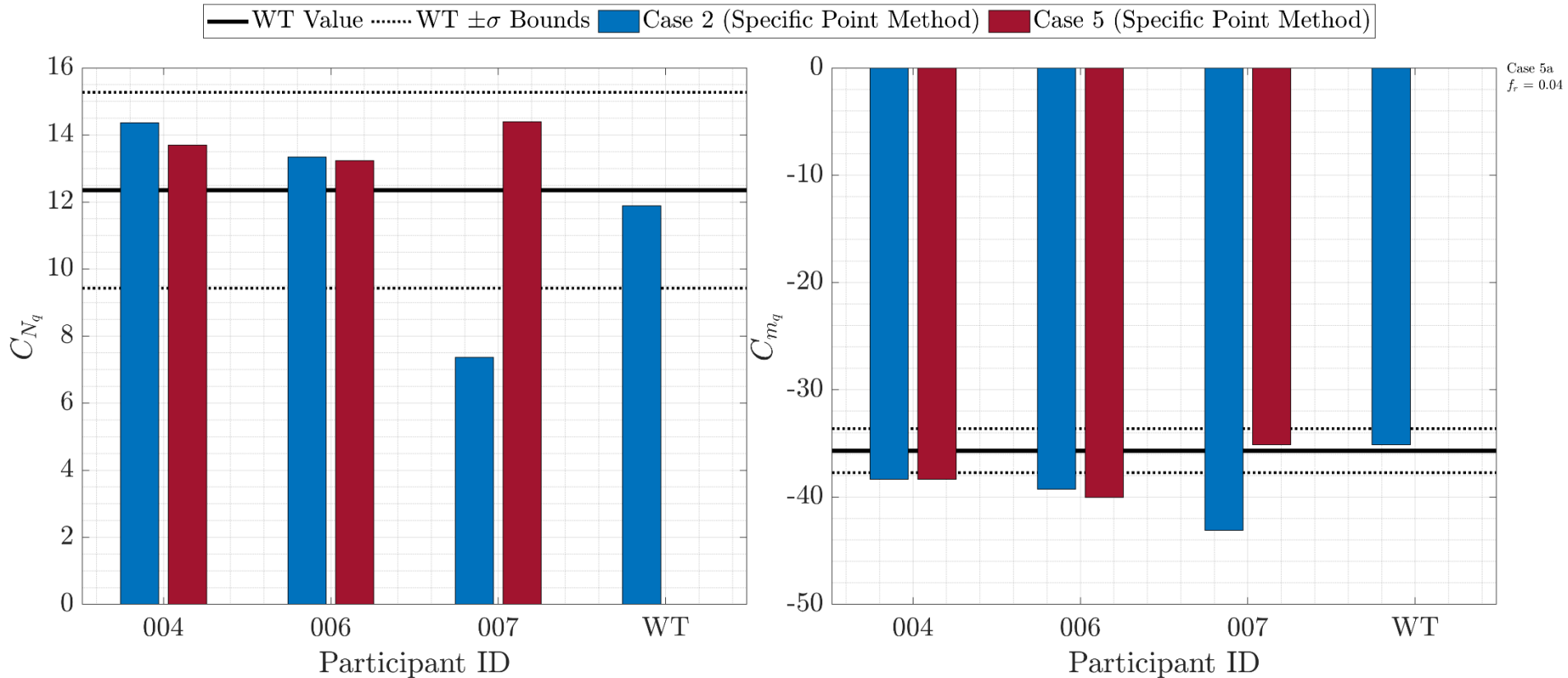
Case 5a: Dynamic Stability Derivatives ($f_r = 0.04$)



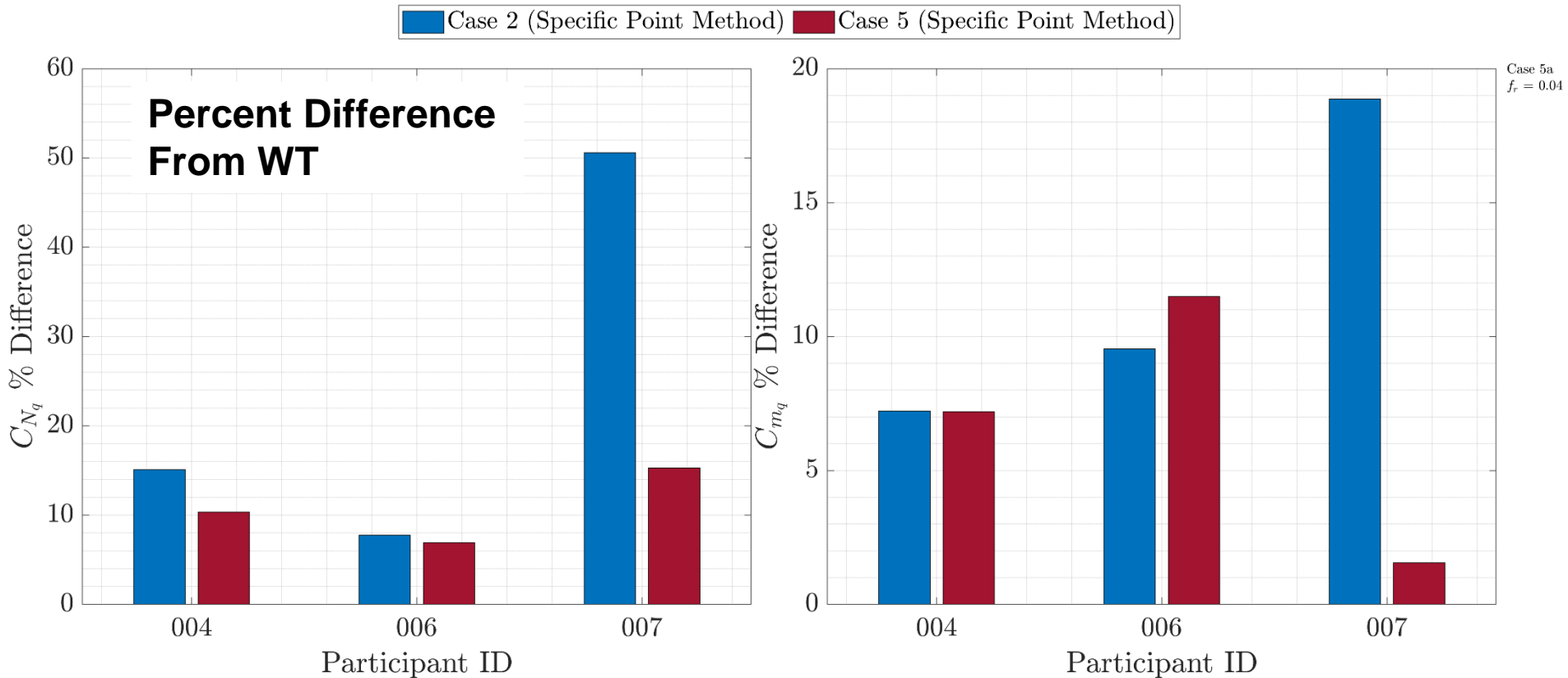
Case 5a: Dynamic Stability Derivatives ($f_r = 0.04$)



Case 2a/5a: Dyn. Stability Derivatives ($f_r = 0.04$)



Case 2a/5a: Dyn. Stability Derivatives ($f_r = 0.04$)



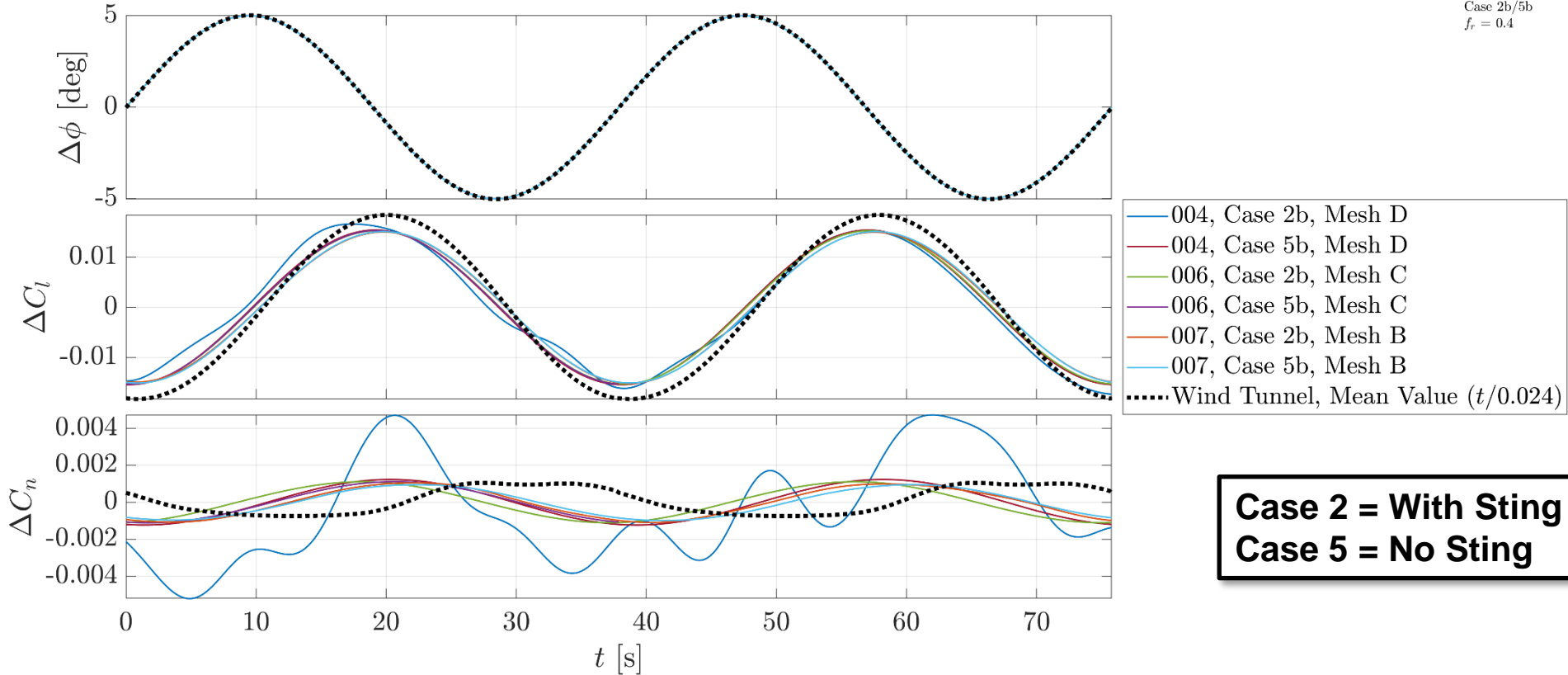
Case 5b Results

- Roll forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\phi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with tail and no sting

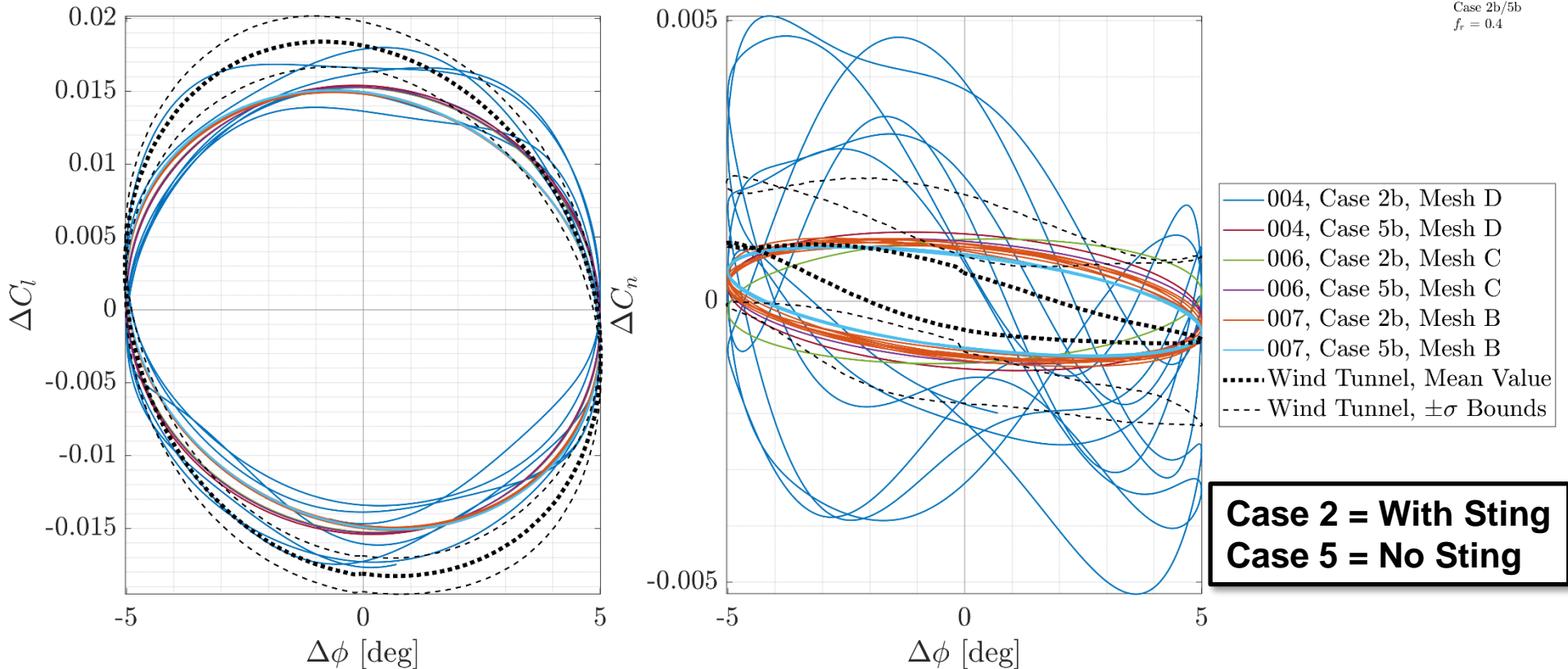
**Note: wind tunnel results
still have sting effects**

Case 2b/5b: Time Histories ($f_r = 0.4$)

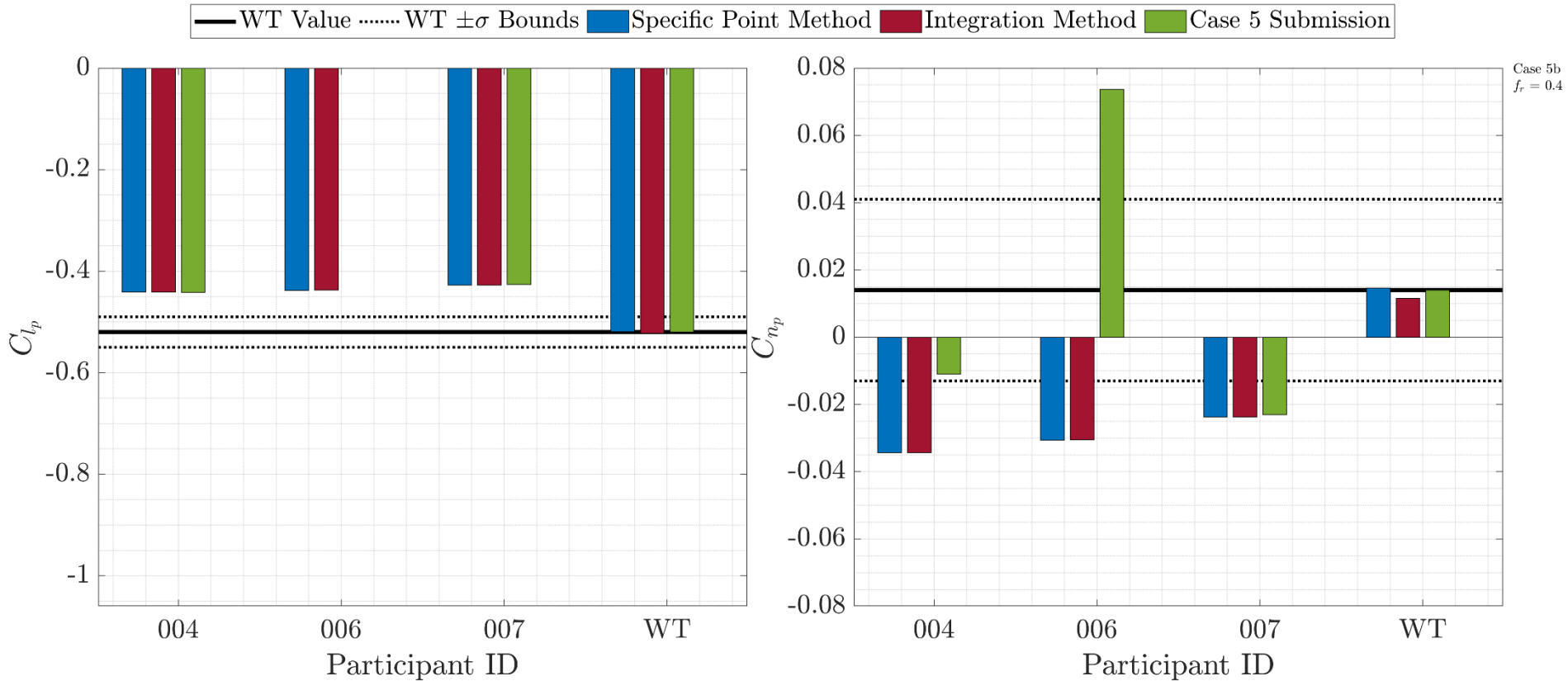
Case 2b/5b
 $f_r = 0.4$



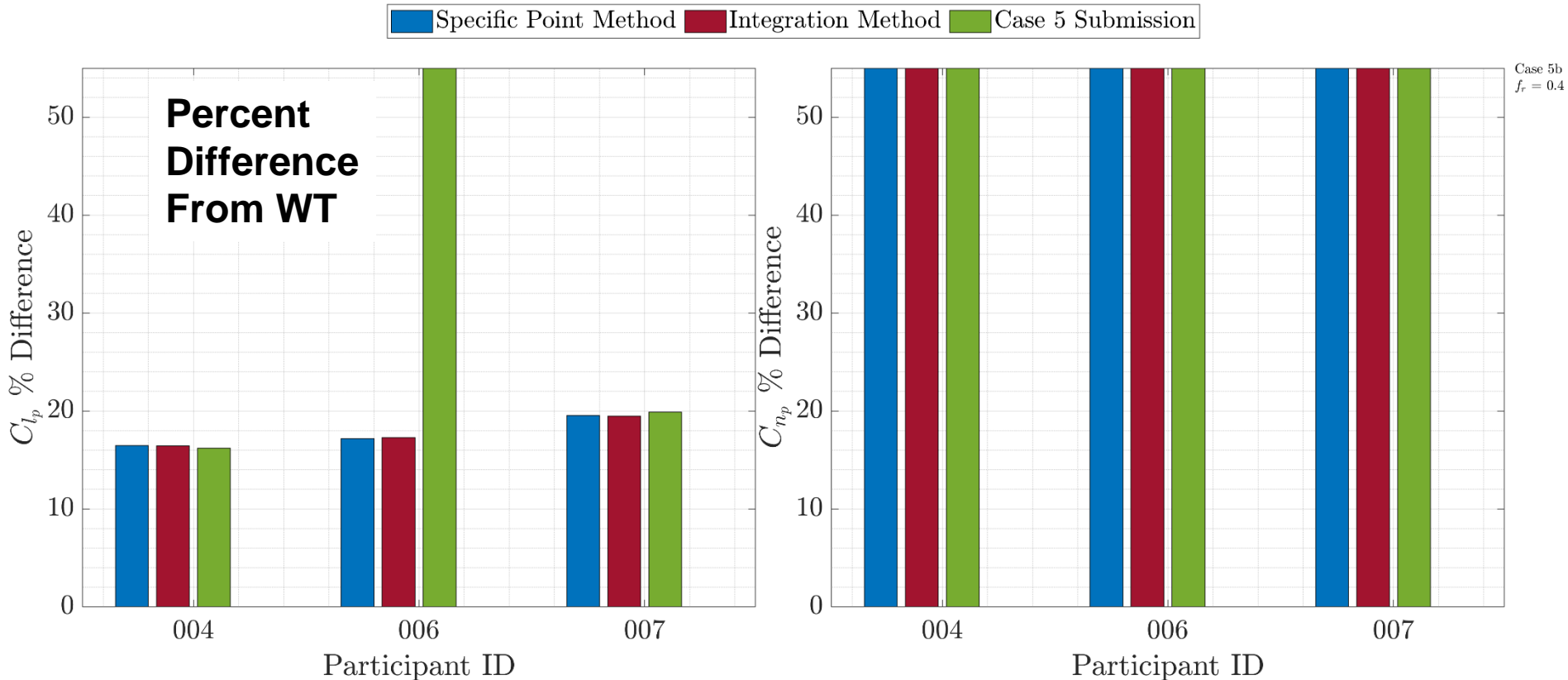
Case 2b/5b: Hysteresis Loops ($f_r = 0.4$)



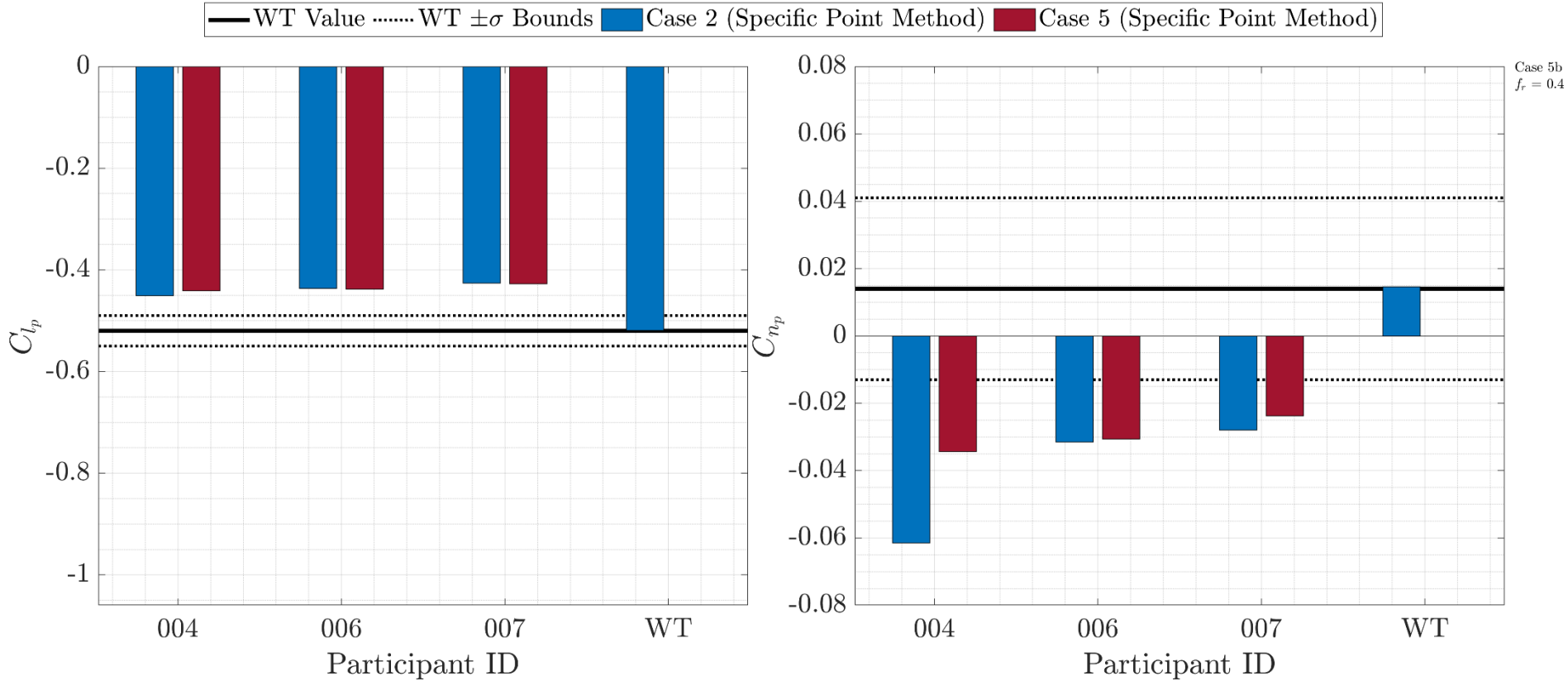
Case 5b: Dynamic Stability Derivatives ($f_r = 0.4$)



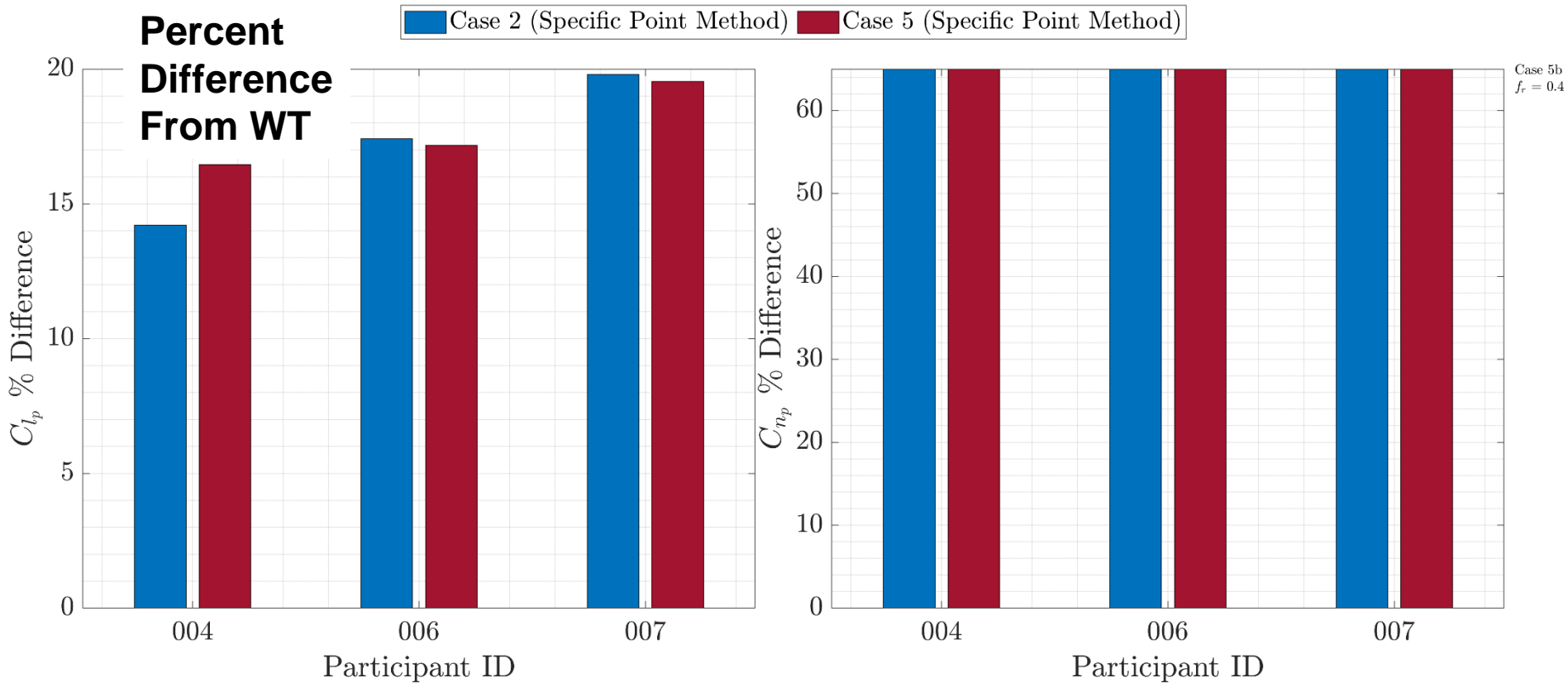
Case 5b: Dynamic Stability Derivatives ($f_r = 0.4$)



Case 2b/5b: Dyn. Stability Derivatives ($f_r = 0.4$)



Case 2b/5b: Dyn. Stability Derivatives ($f_r = 0.4$)



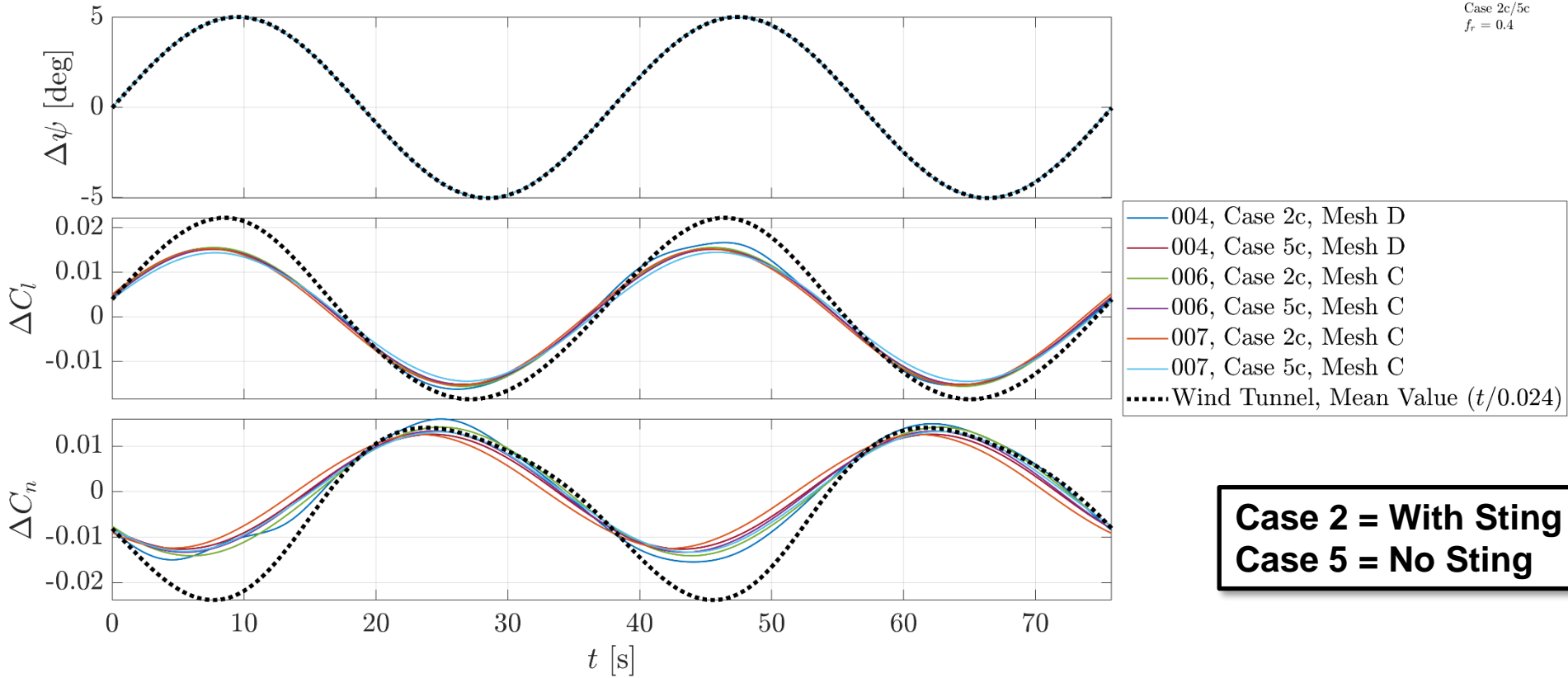
Case 5c Results

- Yaw forced oscillation at $\alpha_o = 3^\circ$
- $-5^\circ \leq \Delta\psi \leq +5^\circ$
- $f_r = \frac{\omega b}{2V} = 0.4$ (optional: 0.2, 0.6, 0.8)
- $M = 0.036$; $Re = 140,000$; $T = 518^\circ R$
- CRM with tail and no sting

**Note: wind tunnel results
still have sting effects**

Case 2c/5c: Time Histories ($f_r = 0.4$)

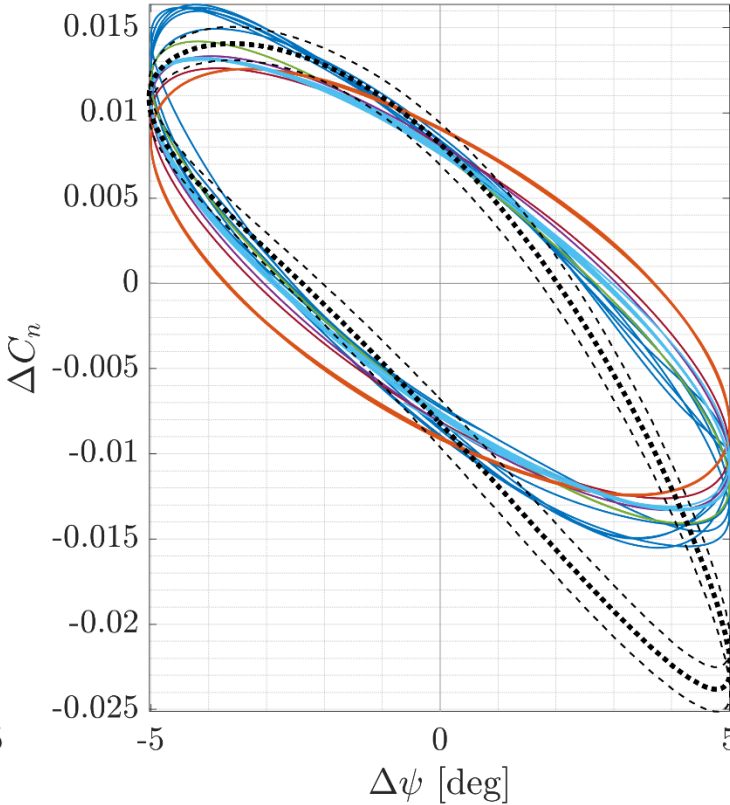
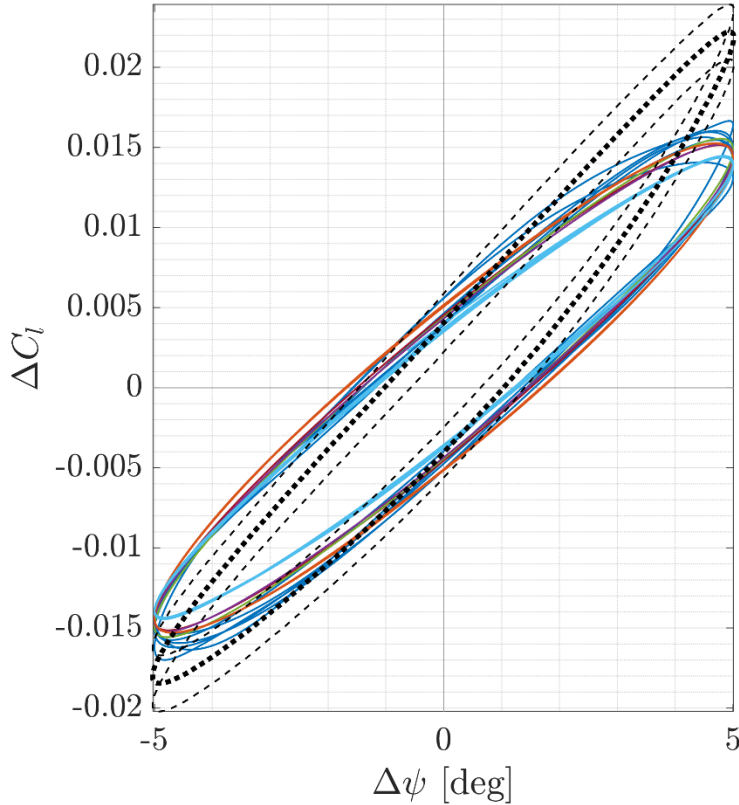
Case 2c/5c
 $f_r = 0.4$



Case 2 = With Sting
Case 5 = No Sting

Case 2c/5c: Hysteresis Loops ($f_r = 0.4$)

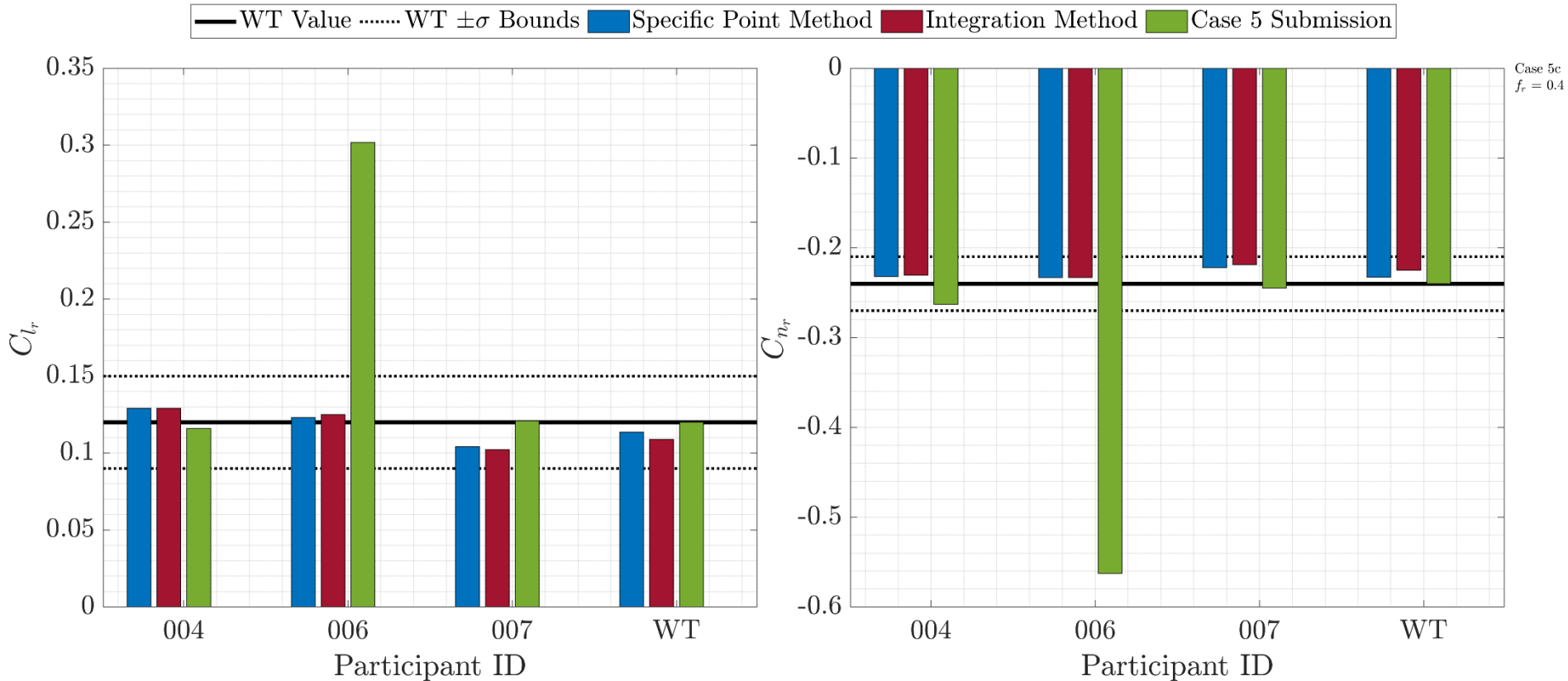
Case 2c/5c
 $f_r = 0.4$



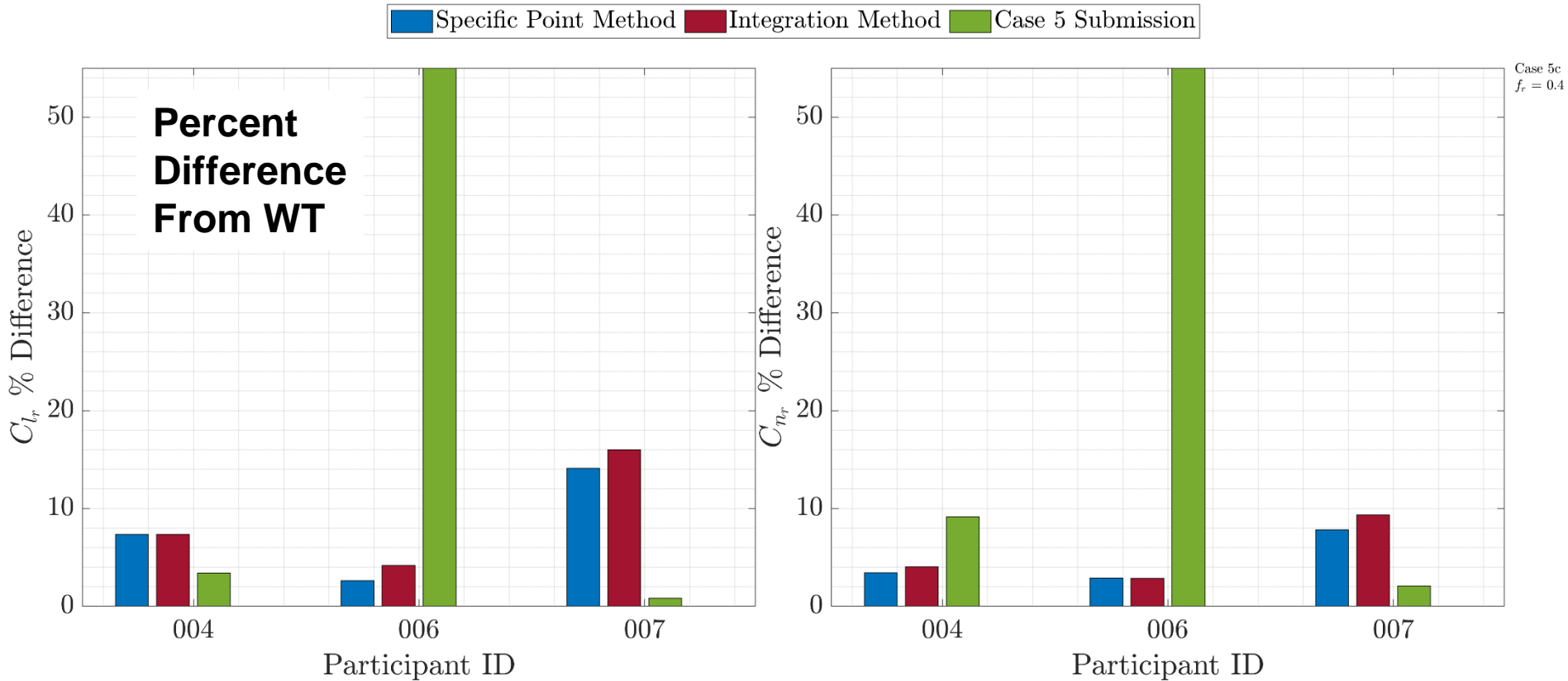
- 004, Case 2c, Mesh D
- 004, Case 5c, Mesh D
- 006, Case 2c, Mesh C
- 006, Case 5c, Mesh C
- 007, Case 2c, Mesh C
- 007, Case 5c, Mesh C
- Wind Tunnel, Mean Value
- - - Wind Tunnel, $\pm\sigma$ Bounds

Case 2 = With Sting
Case 5 = No Sting

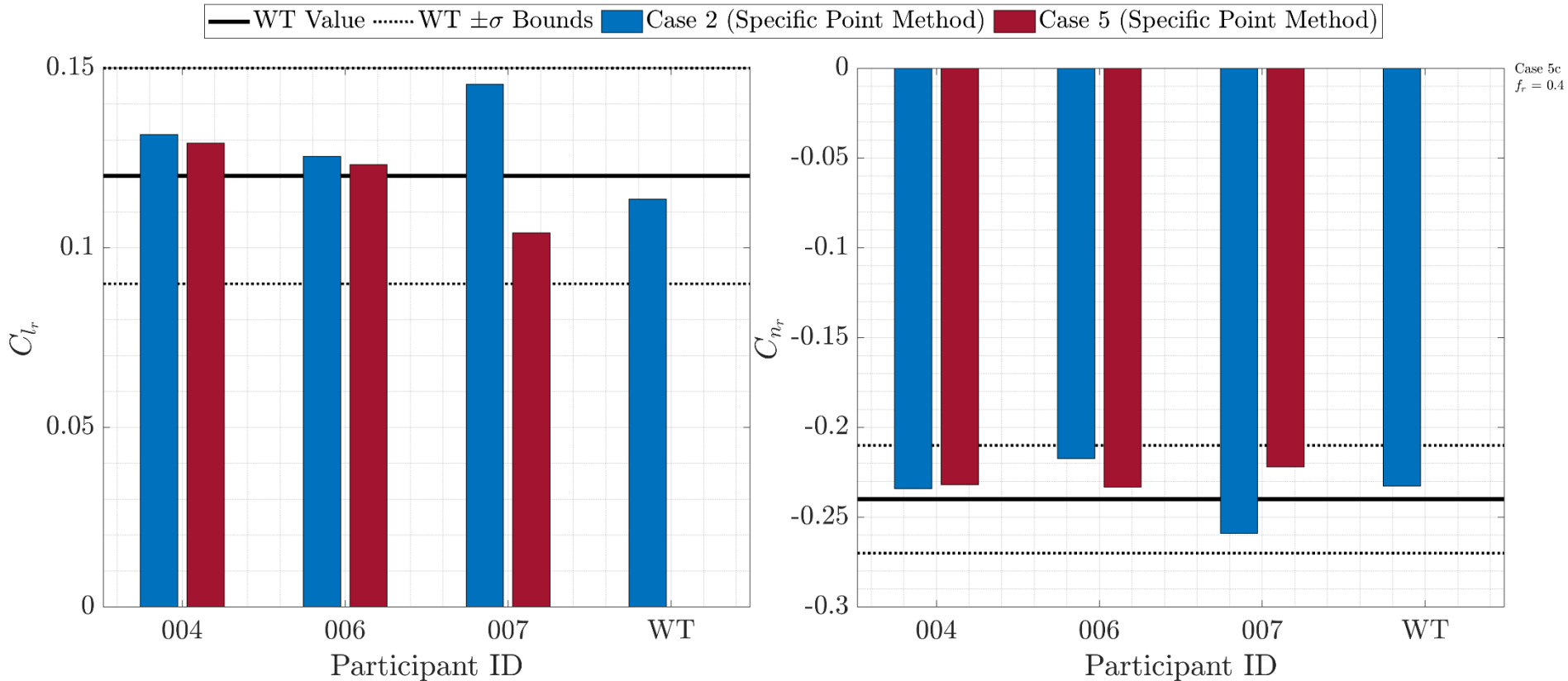
Case 5c: Dynamic Stability Derivatives ($f_r = 0.4$)



Case 5c: Dynamic Stability Derivatives ($f_r = 0.4$)



Case 2c/5c: Dyn. Stability Derivatives ($f_r = 0.4$)



Case 2c/5c: Dyn. Stability Derivatives ($f_r = 0.4$)

