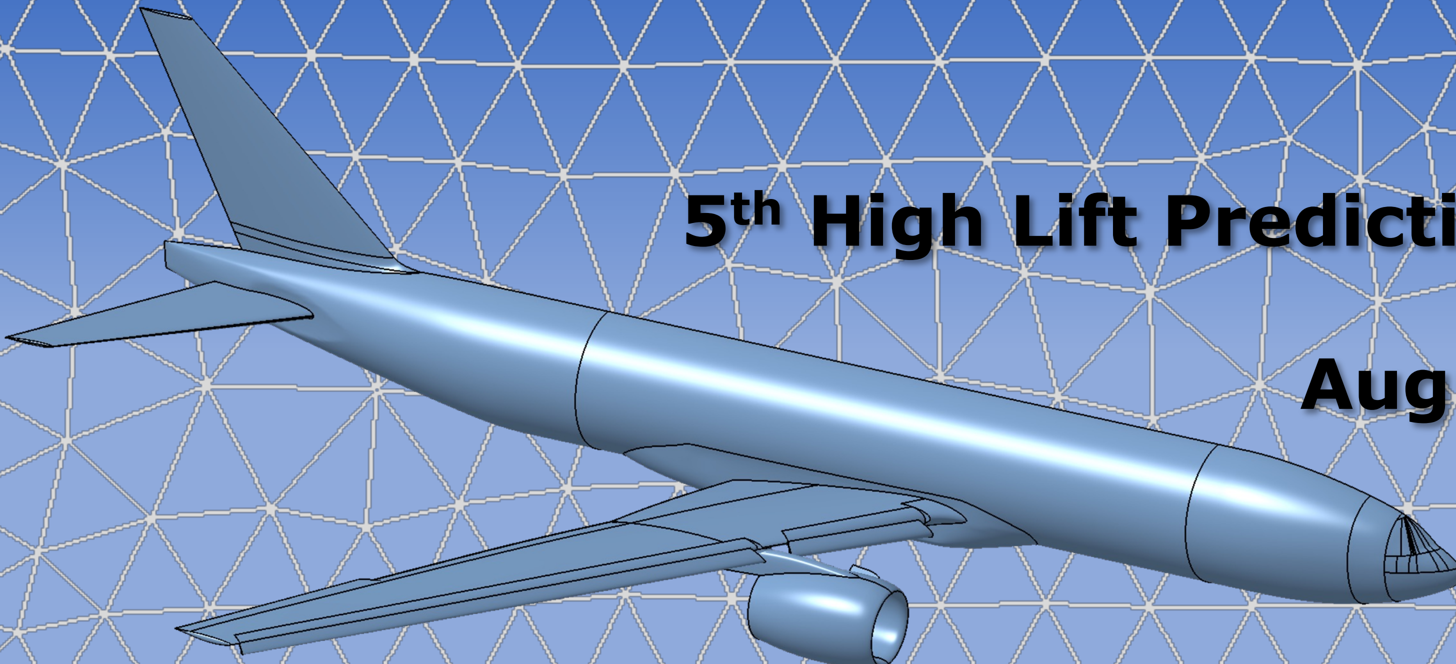

5th High Lift Prediction Workshop

August 2-3, 2024

WMLES Technology Focus Group Summary

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Special thanks to:

- *WMLES TFG Participants for data submissions*
- *Jordan Angel & Aditya Ghate for their continuous support in post-processing*
- *Christopher Rumsey for compiling participants' submission data*
- *ONERA for providing Wind Tunnel data for Cases 2.2, 2.3, and 2.4*
- *HLPW5 leadership team and TFG leads*

WMLES TFG Participants

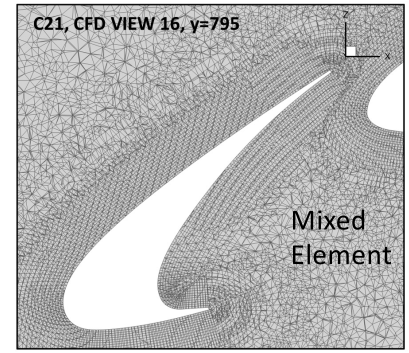
TFG Name	**WMLES**
Number of Active Participants	12 Teams
Number of Observers	40+

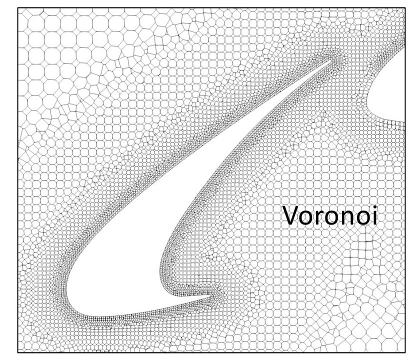
Participant ID	Organization	Code	Cases			Discretization	Grid Type	Time Integration	Grid Used
			1	2	3				Committee (C) Self (S)
W-001	KTH	Adaptive Euler	x	x	x	Finite Element (Incompressible)	Mixed Element	Implicit	C
W-003	Boeing	BCFD	x		x	2nd order Finite Volume	Mixed Element	Implicit	S
W-004	Boeing & Cadence	CharLES	x	x	x	2nd order Finite Volume	Voronoi	Explicit	S
W-005	NASA LaRC	FUN3D	x	x	x	2nd order Finite Volume & Finite Element	Mixed Element	Implicit	C
W-006	U of Kansas	hpMusic	x	x	x	High order Flux Reconstruction	Mixed Element	Implicit	C
W-007	NASA ARC	LAVA	x	x	x	2nd order Finite Volume	Voronoi	Explicit	S
W-009	Dassault Systems	PowerFLOW	x	x	x	Lattice Boltzmann (D3Q19 + Energy Equation)	Cartesian	Explicit	S
W-010	AWS & Volcano Platforms	Volcano ScaLES	x	x	x	4th & 2nd order Finite Difference	Cartesian	Explicit	S
W-011	Tohoku University	FFVHC-ACE			x	2nd order Finite Difference	Cartesian	Explicit	S
W-012	Scientific-Sims LLC	NSU3D	x	x		2nd order Finite Volume	Mixed Element	Implicit	C
W-013	Embraer	SU2		x		2nd order Finite Volume	Mixed Element	Implicit	C
W-014	ANSYS	FLUENT		x		2nd order Finite Volume	Mixed Element / Octree Cartesian	Implicit	S

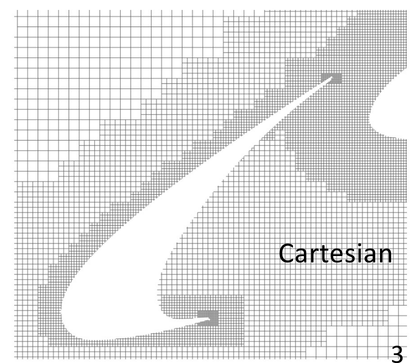
WMLES TFG Solver Characteristics

https://hiliftpw.larc.nasa.gov/Workshop5/TFG_wmles.html

- Flow solvers: Navier-Stokes (10), lattice-Boltzmann (1), Adapted Euler (1)
- Spatial discretization: Finite Volume (6) & Finite Difference (4), Finite Element(2), HO(1)
- Time integration or iteration method: Implicit (7) & Explicit (5)
- Name of committee grids (or "self-prepared"): Self (8), Committee(5)
- Cases submitted: TC1 (6), TC2(10), TC3(9)
- Initialization method: **Freestream cold-started** (12)
- Grid topology: Mixed Element (7), Voronoi (2), Cartesian (3)
- Typical DoF (mesh points or cells) (Case #): 120 Million-11.6 Billion
- Wall modeling: **Algebraic Equilibrium** (10), Extended Turb. Model (1)
- SGS closure: Constant Vreman (7), Dynamic Smagorinsky (2), VLES(1), CSM(1), WALE(1)
- Transition treatment: **None** (10), Numerical Trip(1), TKE Wall Turb Sensor (1), Turbulent(1)
- Typical time step normalized by CTU: 10^{-3} – 1.0^{-5}
- Target wall-normal grid spacing normalized by MAC: 1.0^{-3} – 1.0^{-4}
- Aspect ratio range (tangential spacing/wall-normal): **less than 5** (10), more than 5 (2)
- WM exchange location: 0.5-1.0Δx_{min} (7), 1.5Δx_{min} (1), 2.0Δx_{min} (1), 3.5Δx_{min} (1), 4Δx_{min} (1)





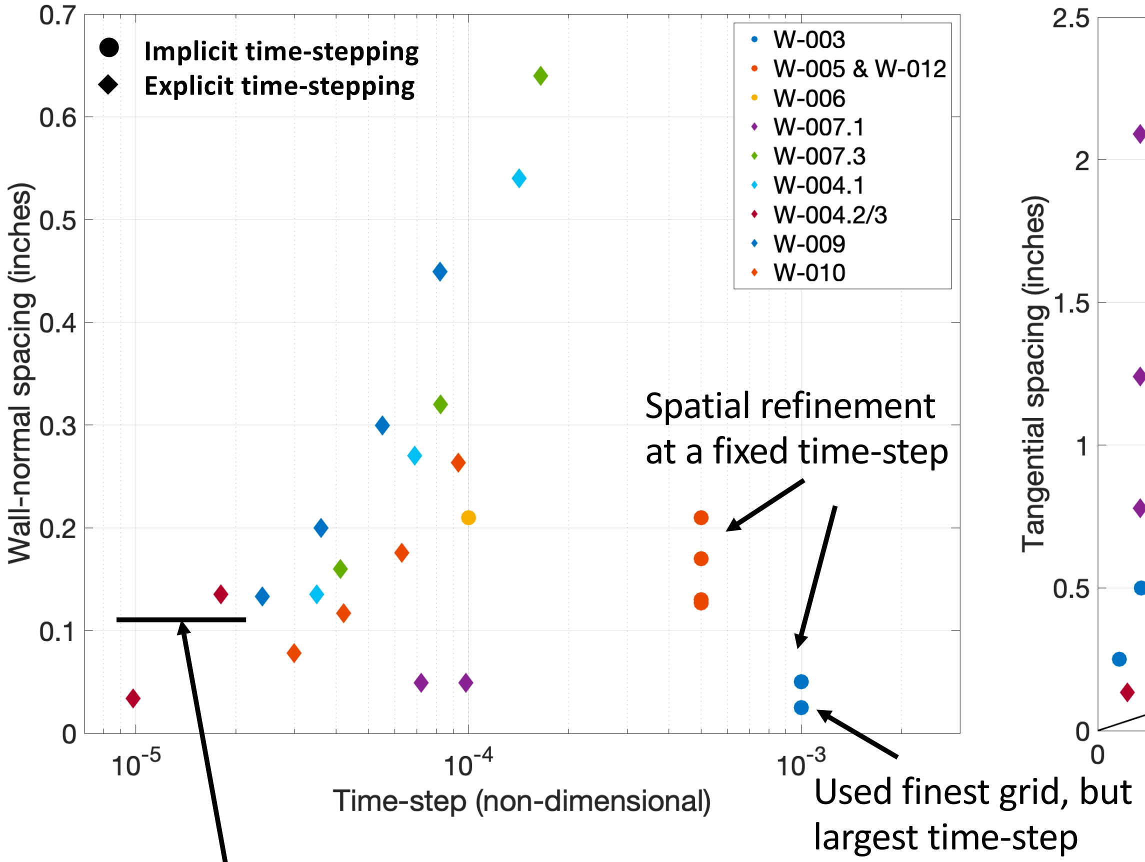


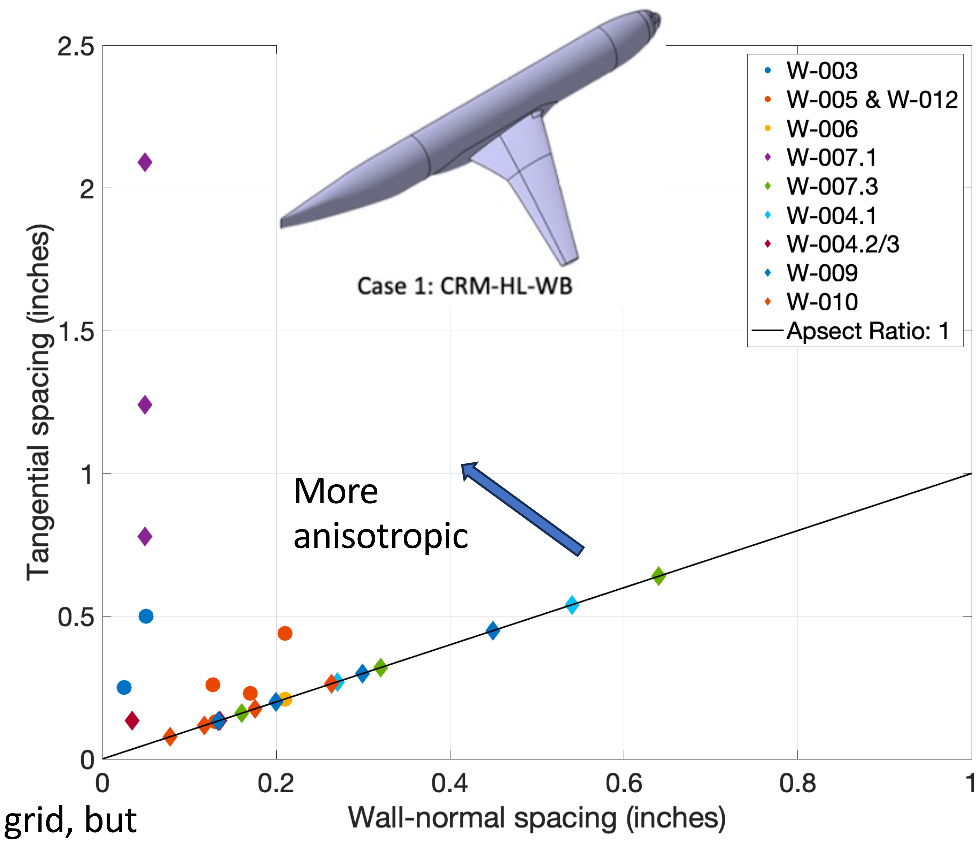
WMLES TFG Objectives for Case 1 & Case 2.1

- Identify challenges posed to WMLES for clean (untripped) wings at moderate Reynolds numbers.
  - Observation: Lack of explicit tripping leads to a scatter in numerical transition on the wing surface.

- Is there a potential to obtain grid convergence?
  - Observation: Maybe but because of the transition issue, it is unclear whether the converged solution is the "correct" solution

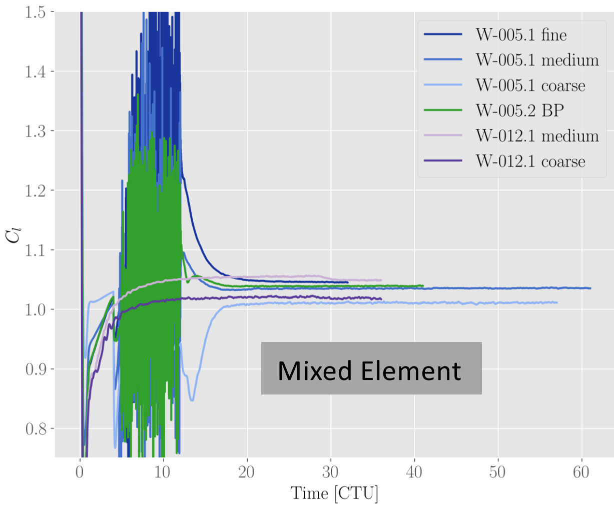
Case1: Time-step (implicit / explicit) & Grid spacing (isotropic / anisotropic)

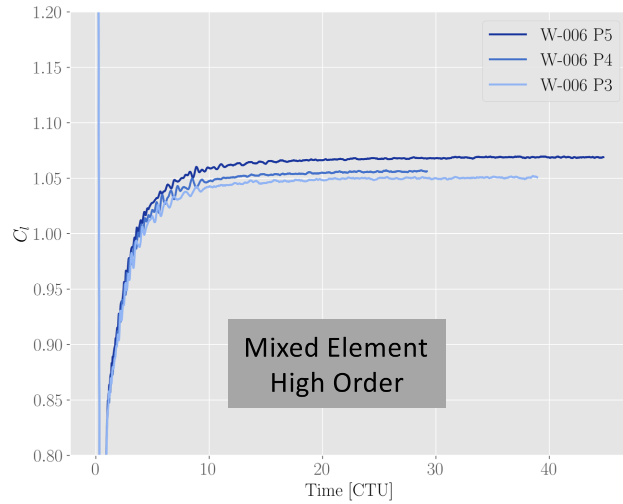


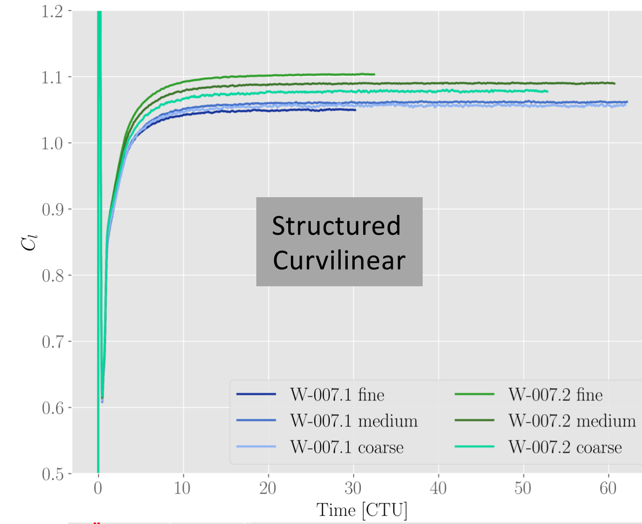


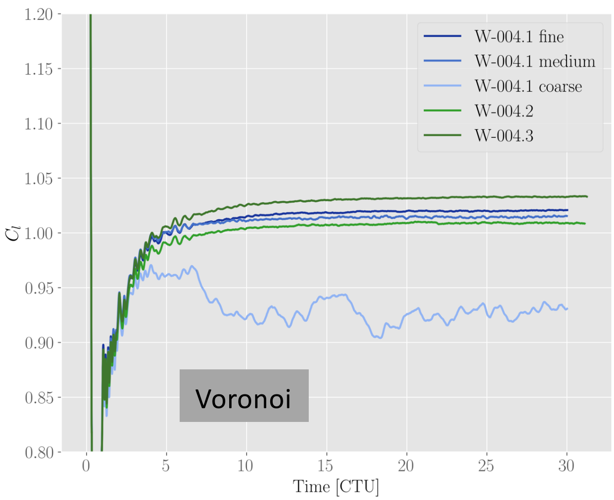
3mm/0.11inch = y+ of approx. 100 at approx. 25% MAC

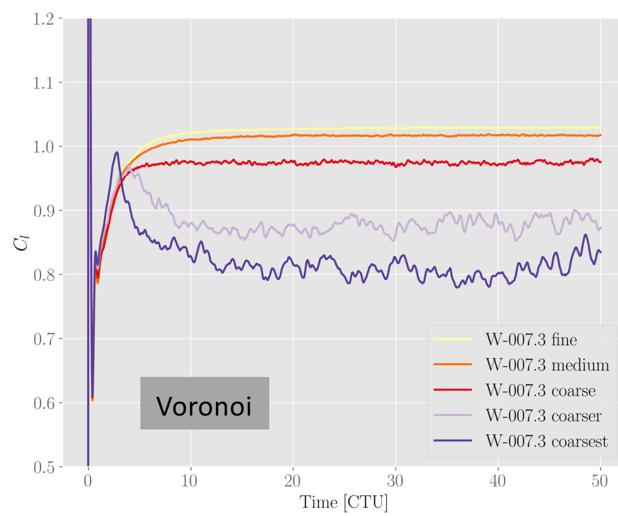
Case 1: Load Time History (C_L)

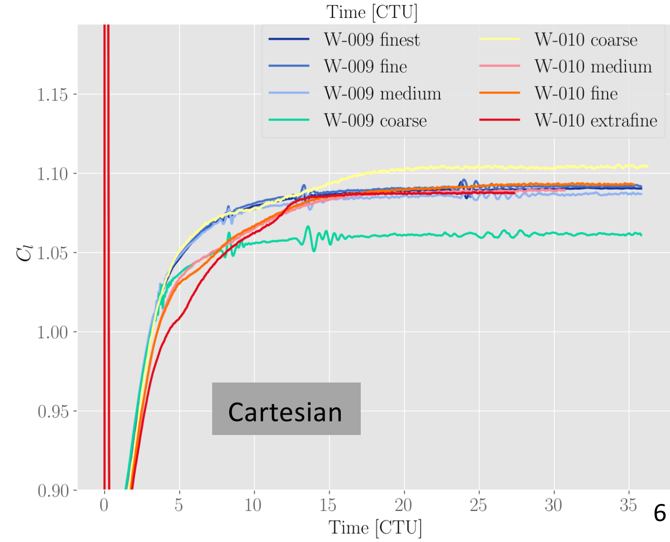




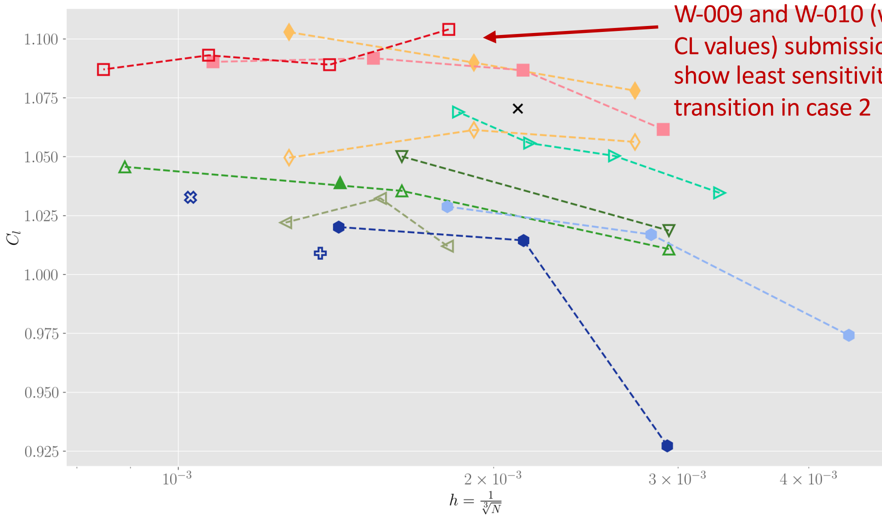


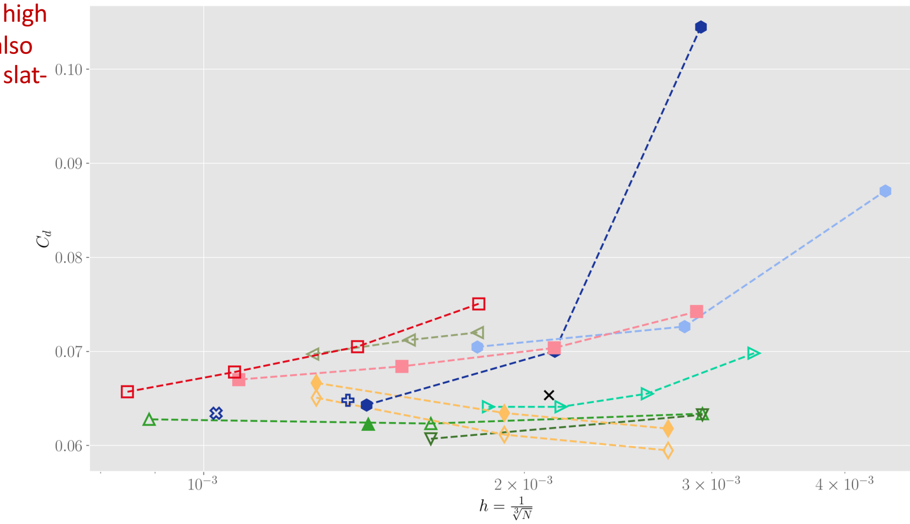


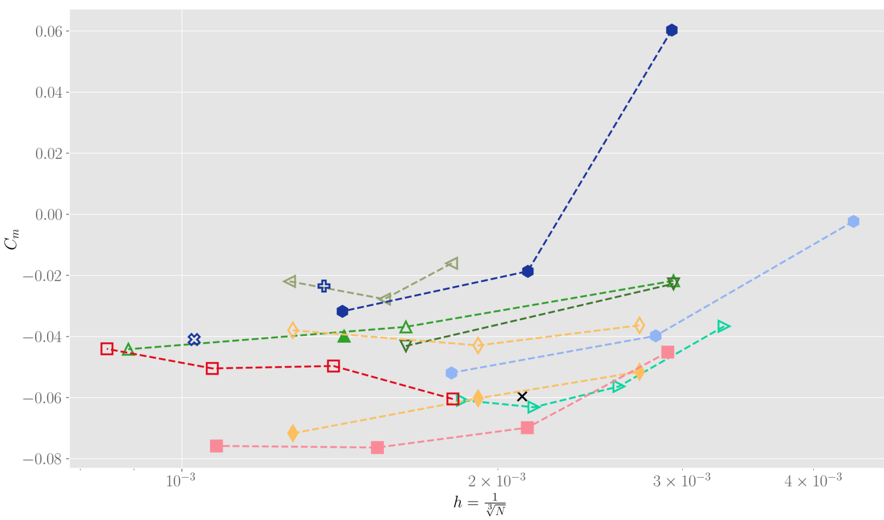




Grid Resolution Studies (Force & Moment)

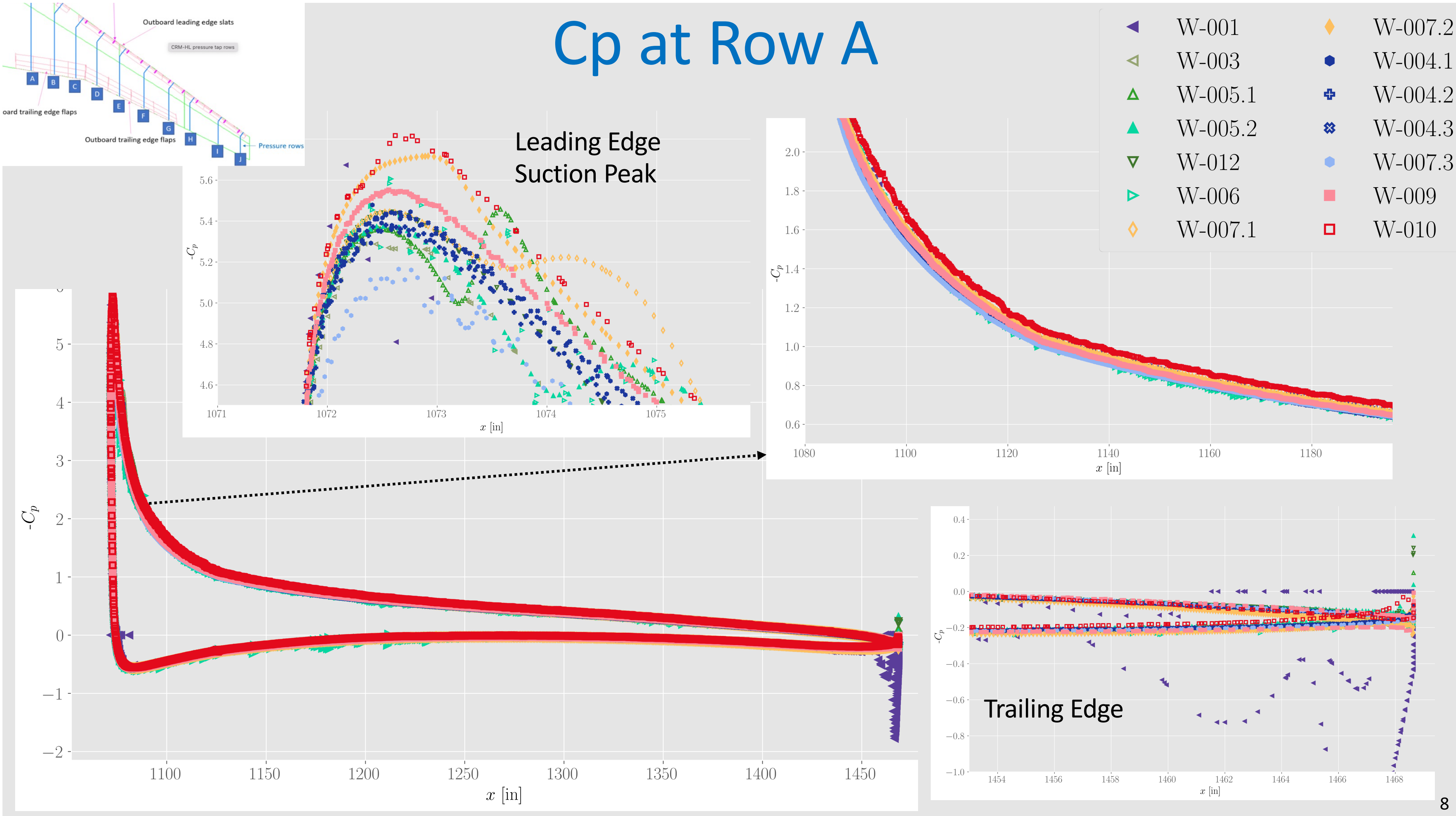




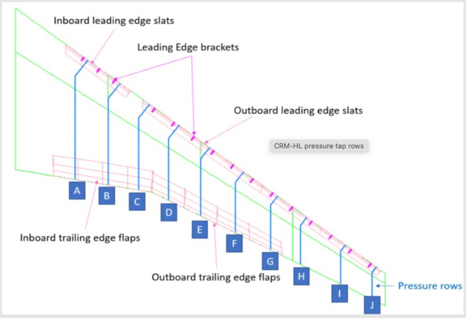


7.1 and 7.2 for Case 1 are from structural curvilinear grid.
They are different submissions from 7.1 and 7.2 in Cases 2 & 3.

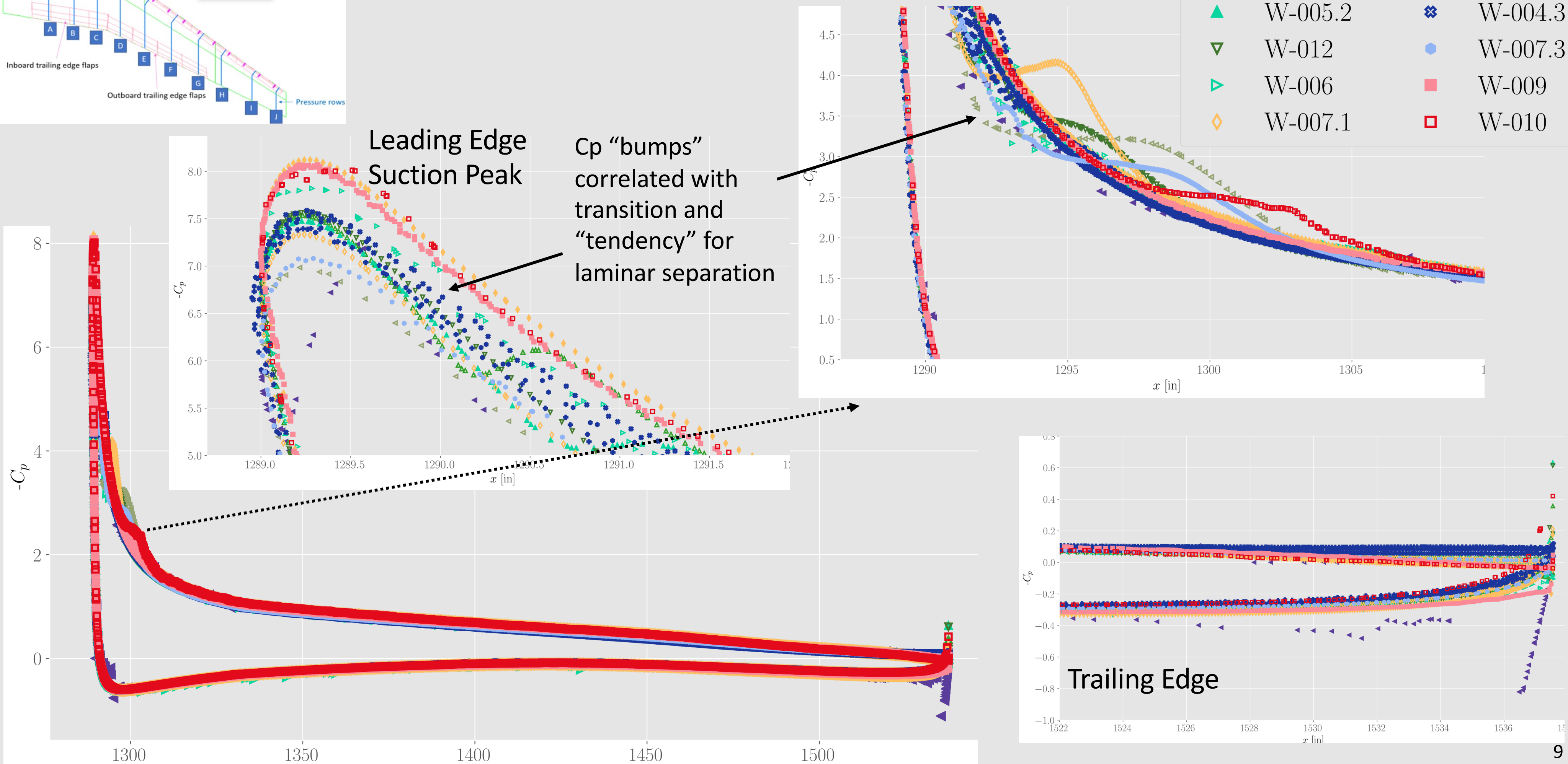
Cp at Row A


Outboard leading edge slats
CRM-HL pressure tap rows
oard trailing edge flaps
Outboard trailing edge flaps
Pressure rows
Leading Edge
Suction Peak
Trailing Edge
W-001
W-003
W-005.1
W-005.2
W-012
W-006
W-007.1
W-007.2
W-004.1
W-004.2
W-004.3
W-007.3
W-009
W-010
-C_p
x [in]

Cp at Row D

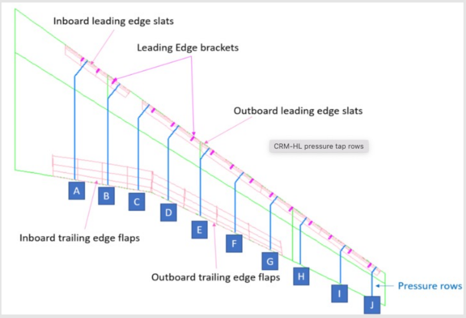


Inboard leading edge slats
Leading Edge brackets
Outboard leading edge slats
CRM-HL pressure tap rows
Inboard trailing edge flaps
Outboard trailing edge flaps
Pressure rows
A
B
C
D
E
F
G
H
I
J



W-001
W-003
W-005.1
W-005.2
W-012
W-006
W-007.1
W-007.2
W-004.1
W-004.2
W-004.3
W-007.3
W-009
W-010
Leading Edge Suction Peak
Cp "bumps" correlated with transition and "tendency" for laminar separation
-C_p
x [in]
Trailing Edge

Cp at Row J



Inboard leading edge slats
Leading Edge brackets
Outboard leading edge slats
CRM-HL pressure tap rows
Inboard trailing edge flaps
Outboard trailing edge flaps
Pressure rows
A
B
C
D
E
F
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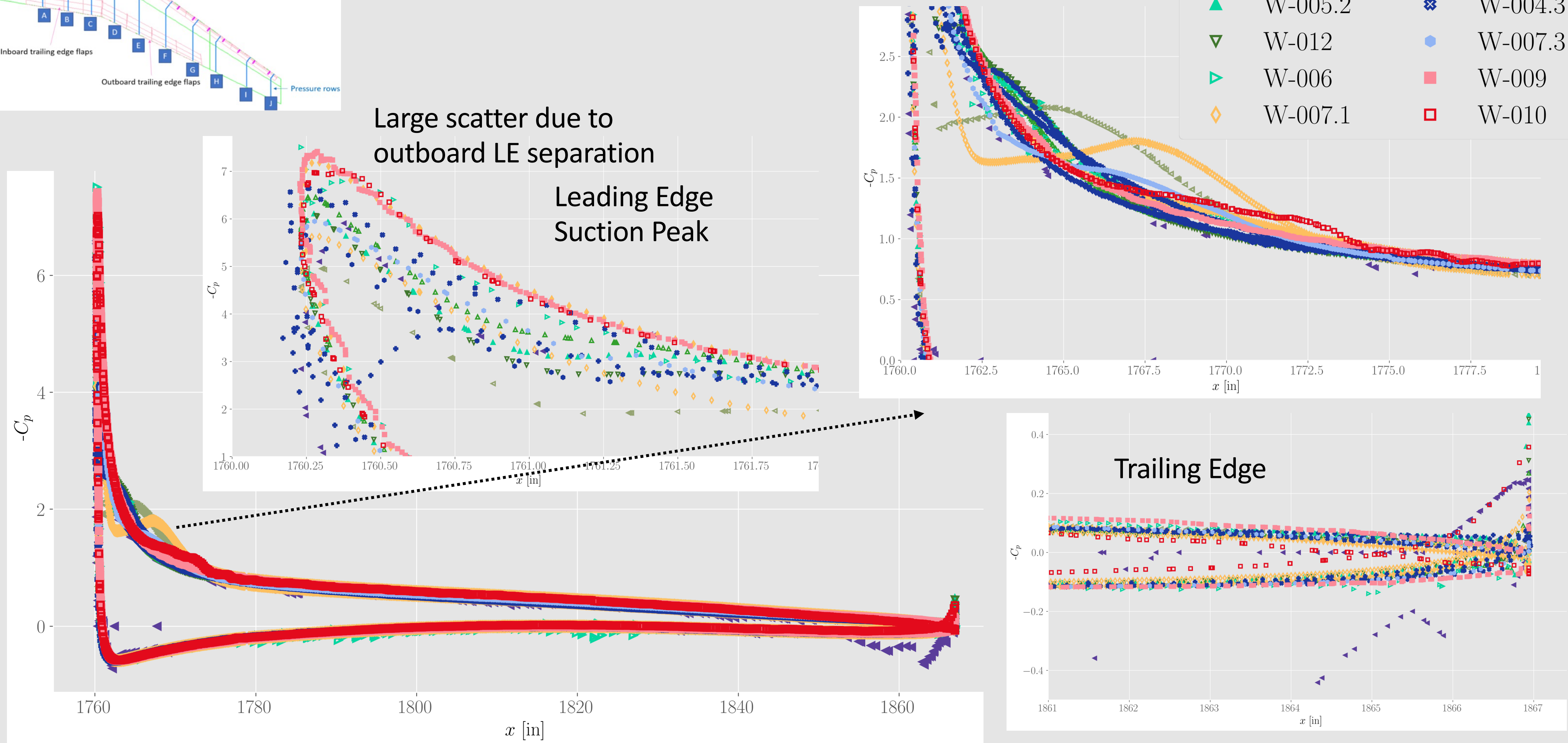


Large scatter due to outboard LE separation
Leading Edge Suction Peak
Trailing Edge
W-001
W-003
W-005.1
W-005.2
W-012
W-006
W-007.1
W-007.2
W-004.1
W-004.2
W-004.3
W-007.3
W-009
W-010
$-C_p$
x [in]

WMLES Challenges for Clean Wing Configurations

Grid – spacings are influenced by two properties:

1. **Inviscid influence**: Surface curvature
   - Wall-normal spacings are particularly important in high-curvature LE; sensitivity most-strongly seen in drag coefficient
2. **Viscous influence**: Boundary layer thickness
   A. Log-law only applies in the bottom 15-25% of the BL -> dictates minimum number of points inside the BL (points-per-delta)
   B. Behavior of WMLES under natural transition is still an open question -> this makes clean-wing WMLES particularly challenging and “unlike” fully-turbulent RANS

Open Question: How should WMLES behave when BL is “subgrid” ---> relevant for LE

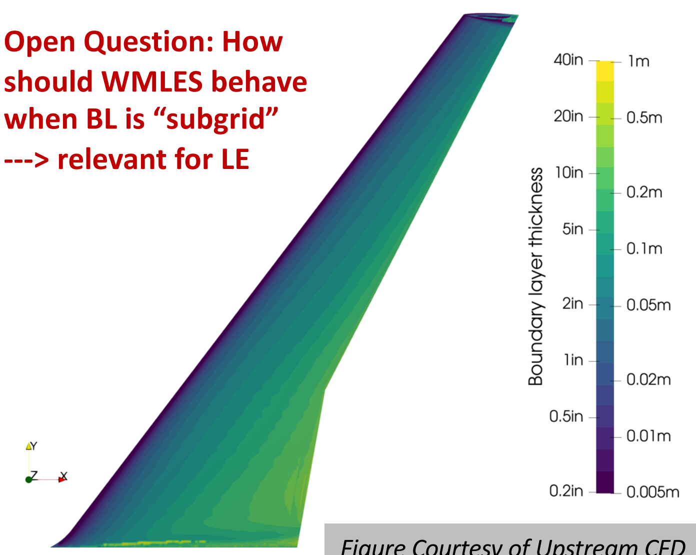
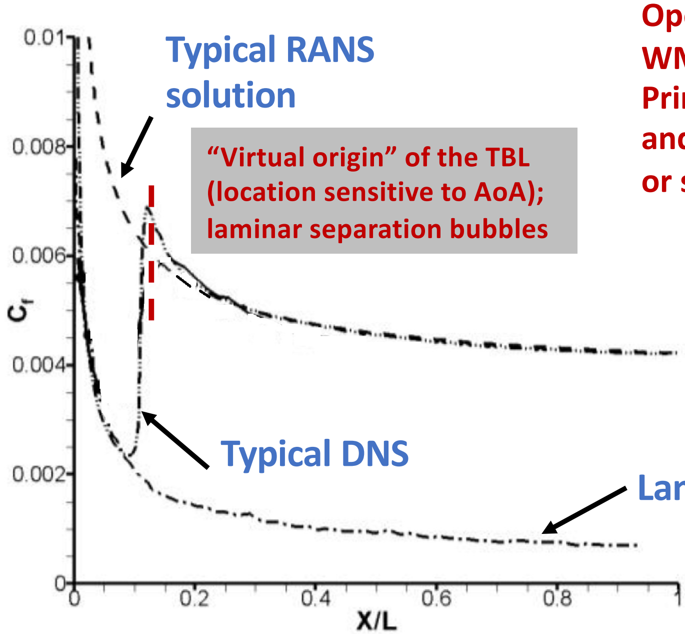


Figure Courtesy of Upstream CFD



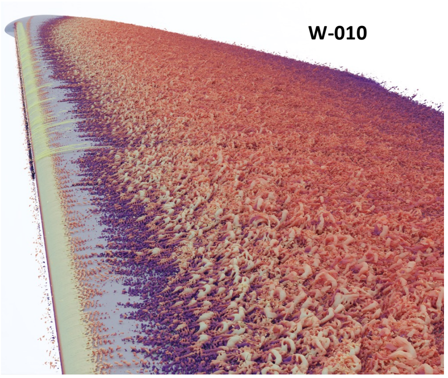
Open Question: How should WMLES model transition? Primarily applicable for Case 1 and Case 2.1 (absence of tripping or slat wakes)

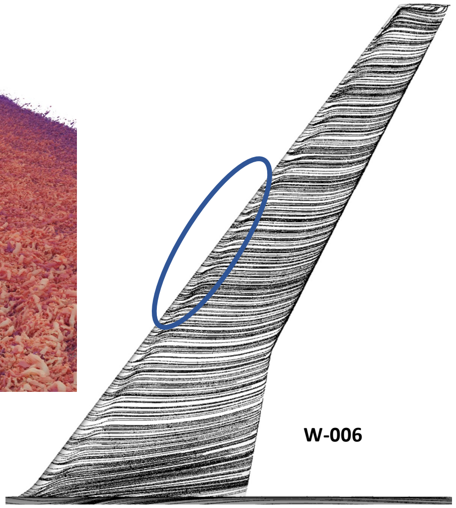
“Clean” wing/airfoil WMLES at low-Re is not common – handful of examples in literature: Balakumar (2020), Ghate et al. (2022) & Goc et al. (2023); vast majority of simulations use “tripping”

Main Flow Features: Case 1

Feature 1: Transition at LE

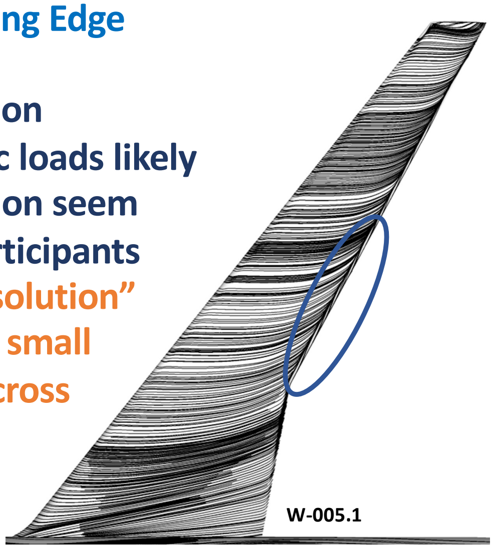
- Some effect on aerodynamic loads could be verified
- Massive variation amongst submissions
- "converged solution" CANNOT be established in the absence of tripping





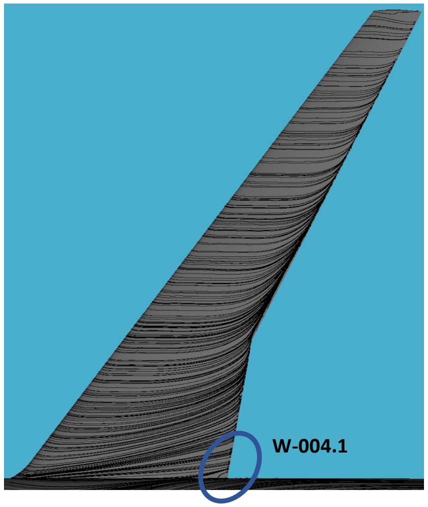
Feature 2: Trailing Edge Separation

- Some effect on aerodynamic loads likely
- Some variation seem amongst participants
- "finest grid solution" shows some small variability across participants



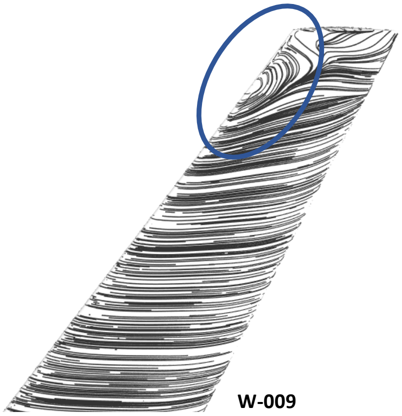
Feature 3: Corner-Flow Separation

- Large variation amongst participants
- Influence on integrated aerodynamic loads is unlikely (very small bubble)
- "finest grid solution" shows small variability in the corner flow separation across participants



Feature 4: Outboard Leading Edge Separation

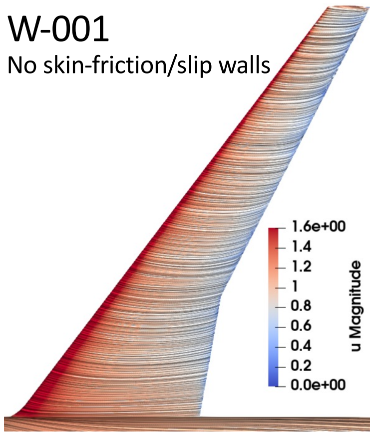
- Consistent observations amongst participants with refinement
- Some-influence on aerodynamic loads
- "converged solution" is consistent across participants



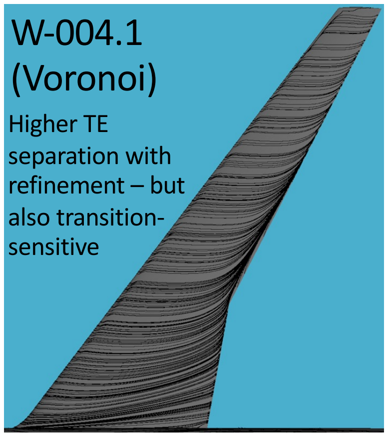
Case 1: Streamlines

finest submitted grids

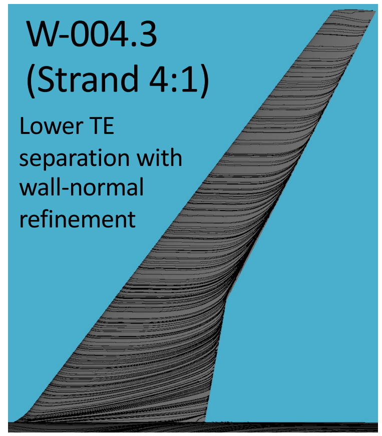
W-001
No skin-friction/slip walls



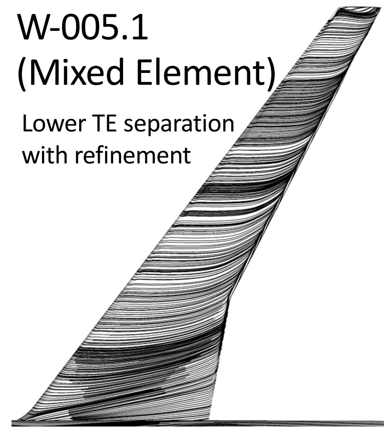
W-004.1
(Voronoi)
Higher TE separation with refinement – but also transition-sensitive



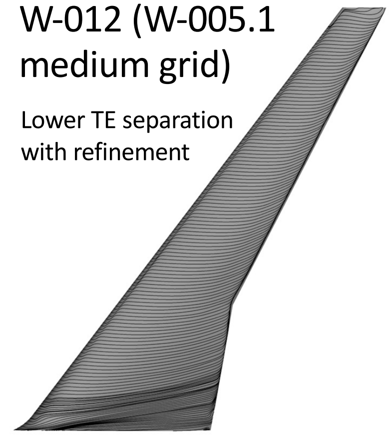
W-004.3
(Strand 4:1)
Lower TE separation with wall-normal refinement



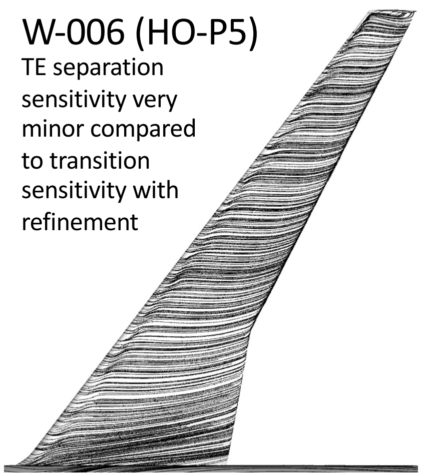
W-005.1
(Mixed Element)
Lower TE separation with refinement



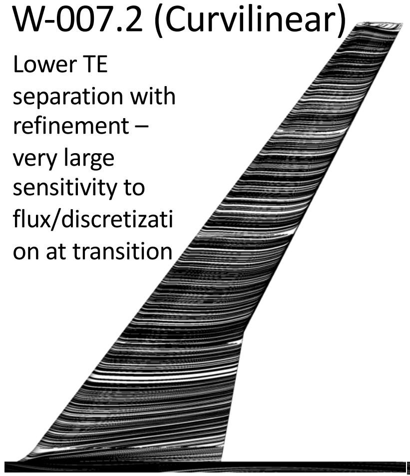
W-012 (W-005.1 medium grid)
Lower TE separation with refinement



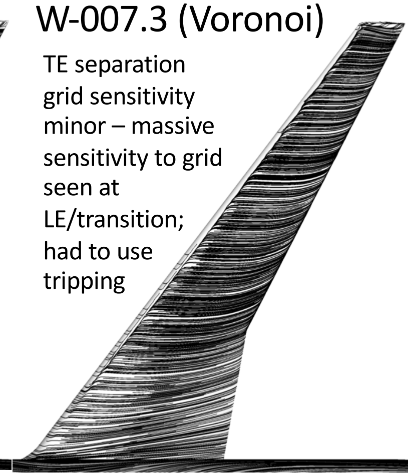
W-006 (HO-P5)
TE separation sensitivity very minor compared to transition sensitivity with refinement



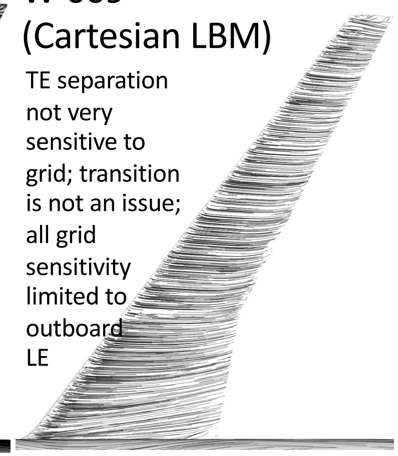
W-007.2 (Curvilinear)
Lower TE separation with refinement – very large sensitivity to flux/discretization at transition



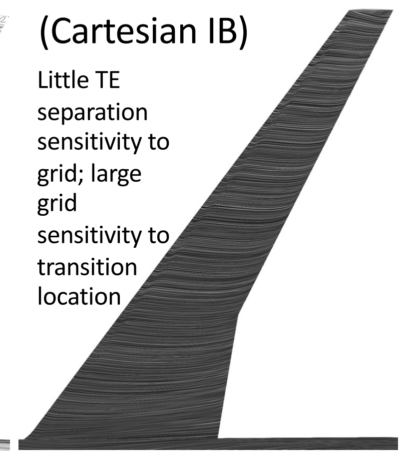
W-007.3 (Voronoi)
TE separation grid sensitivity minor – massive sensitivity to grid seen at LE/transition; had to use tripping



W-009
(Cartesian LBM)
TE separation not very sensitive to grid; transition is not an issue; all grid sensitivity limited to outboard LE



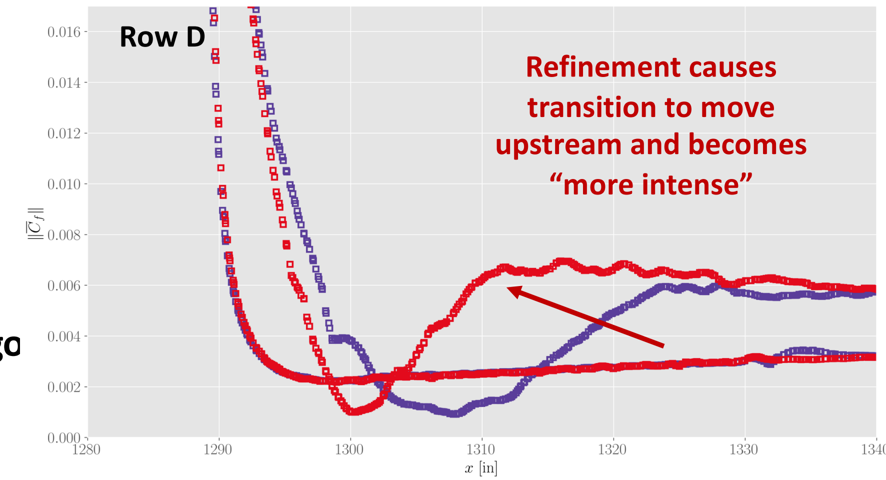
W-010
(Cartesian IB)
Little TE separation sensitivity to grid; large grid sensitivity to transition location

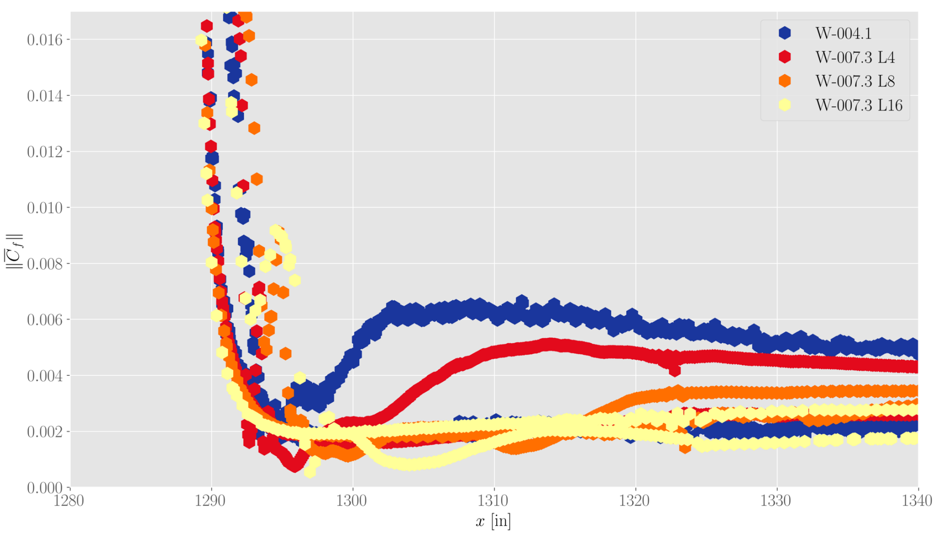


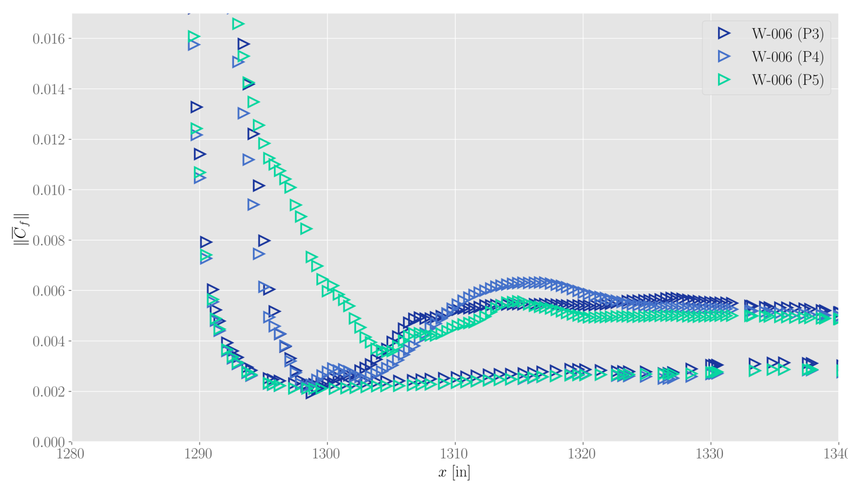
Clean Wings – can numerical transition be correct?

Recall the notion of a virtual origin (Case 1) –

- Exact onset of transition is influenced by mesh, numerical dissipation and SGS closure
- Some submissions showed **artificially thickened boundary layer** on coarser grid (lower CL on coarser grids)
- Some submissions showed **slip-wall like behavior** on coarser grids (higher CL on coarser grids):
- **Has ramifications on slat behavior on Case 2: Does the slat go turbulent too quickly? Turbulent slat BL -> lower slat lift**







Case 1 Observations

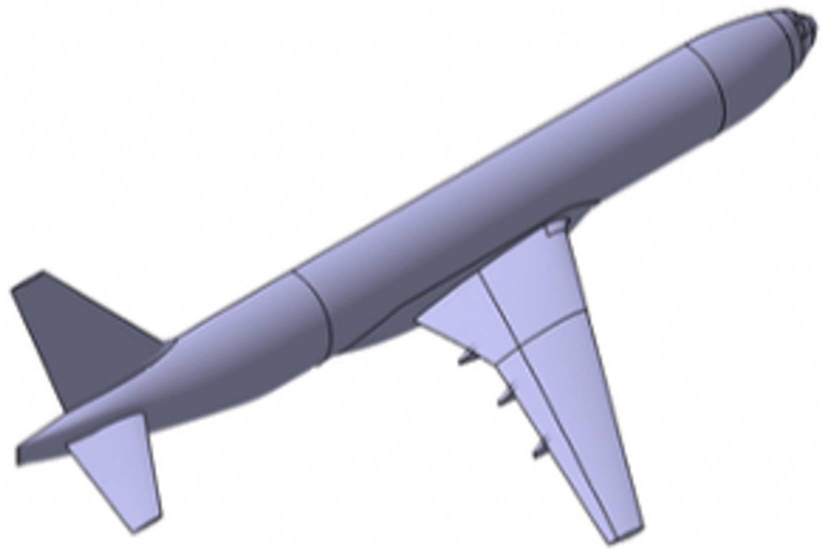
- "Clean" wing involving free-transition at Re = 5.6 Million, is non-trivial for WMLES since it introduces additional uncertainties:
  - Even the finest grid submission is far too coarse to correctly predict natural transition
  - Unclear if methods based on no-slip wall treatment at LE (Bodart & Larsson, 2012) are accurate on isotropic grids with large wall-normal spacings; W-007 attempted this approach for Case 2.4 and obtained promising results for their specific grid
- More canonical problems (flat-plate and/or airfoils) are better to study transition behavior and sensitivities for WMLES

- Better definition for Case-1 (or Case 2.1) should have involved use of explicitly defined tripping – this would eliminate a major source of inconsistency amongst participants, **and be consistent with the upcoming experiment**
  - With tripping location specified explicitly, grid-convergence studies would make more sense to investigate features such as TE separation and corner-flow separation
  - No-slip/slip based BCs could be used upstream of tripping to prevent premature transition due to turbulent wall-stress

WMLES TFG Objectives for Case 2

- Assess quantitative accuracy of CLmax prediction in high-lift configurations using WMLES:
  - Observation: Many submissions have shown errors in CLmax that are within 1-2% of experimental data (via blind comparisons).
- Can WMLES predict the qualitative differences for configuration build-up?
  - Observation: Yes-many submission achieve a similar accuracy across all three configurations
- Identify challenges posed to WMLES when high-lift devices are used:
  - Observation: Slat (at CLmax) and flaps (at lower angles) continue to be the cause of scatter seen in participants. Incidentally, both lifting elements are at low Re_c.
- Does WMLES suffer from similar error cancellation observed in other methods?
  - Observation: Yes, but to a much lower extent compared to methods such as RANS. Some WMLES participants showing excellent CLmax agreement have been identified to do so because of error cancellation.

Case 2.1



Case 2.1: CRM-HL-WBHV

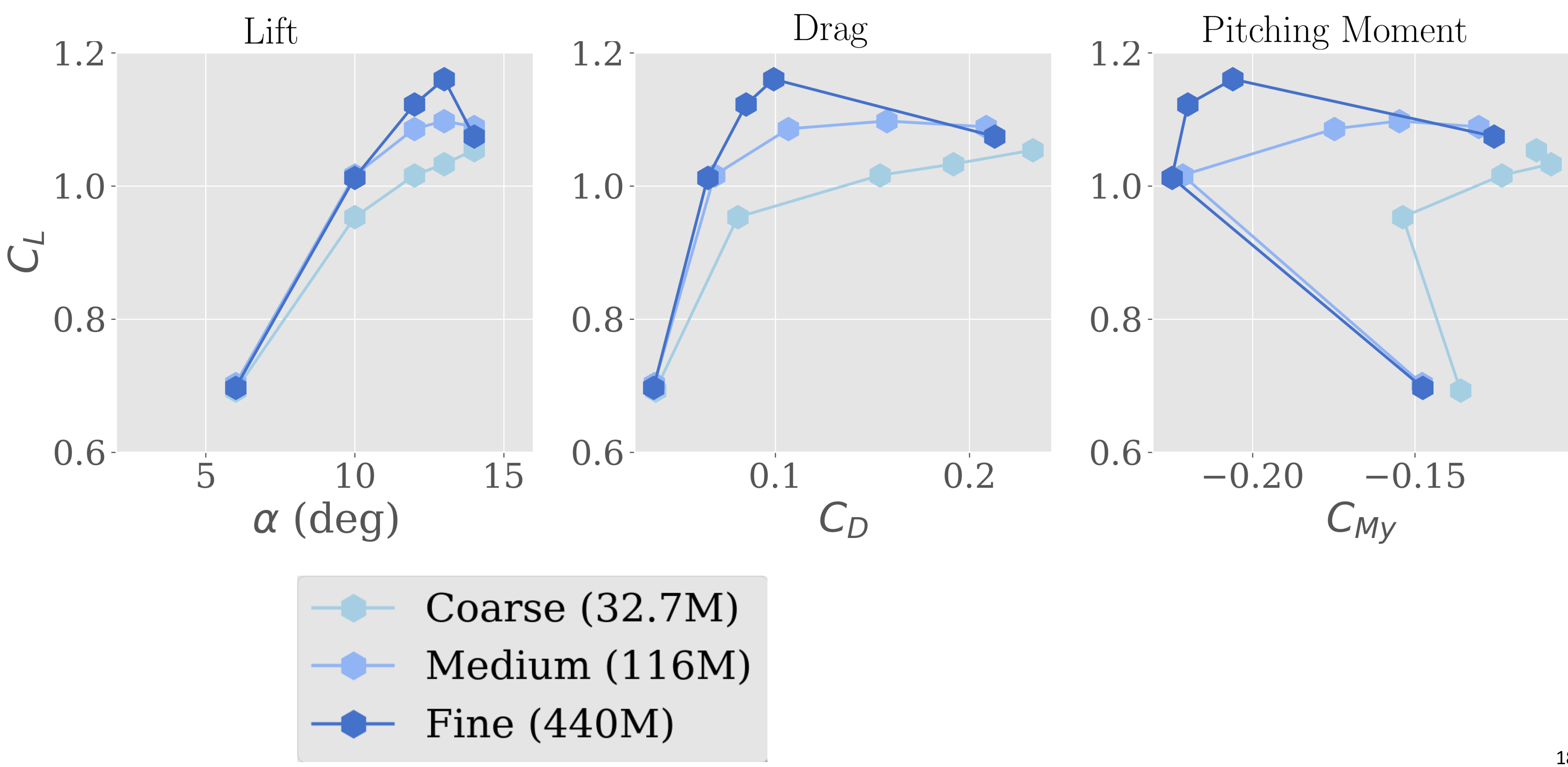
Angle of Attack (AoA)
Case 2.1: 6º , 10º , 12º , 13º , 14º
Case 2.2: 6º , 10º , 17.7º , 20º , 21.5º , 23º , 23.8º
Case 2.3: 6º , 10º , 14º , 16º , 17.7º , 20.7º , 23.5º
Case 2.4: 7.6º , 10º , 14º , 16º , 17.7º , 19.7º , 23.6º

Participant ID	Solver	Coarse Grid	Medium Grid	Fine Grid	Blind Submission?
W-005.1	FUN3D (FV)	170M	575M	1.35B*	Yes
W-004.1	CharLES (DSM)	32.7M	115.8M	439.7M*	Yes
W-007	LAVA		114M	252M*	Yes
W-009	PowerFLOW		255M*	678M	Yes

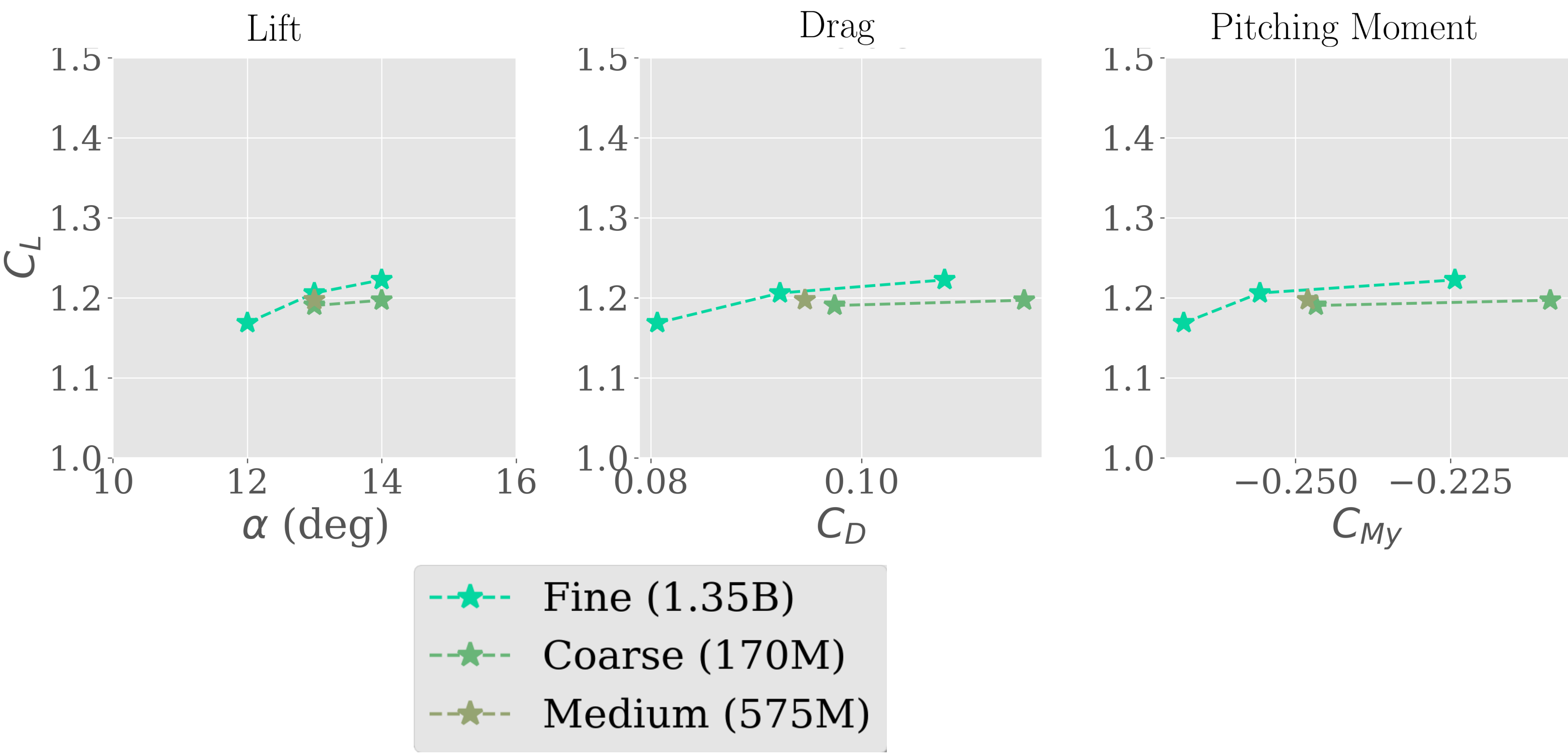
Wind Tunnel (WT) data is not available. Experiment dates TBD

**Nominal grid used by participants. Presented grid size unless otherwise mentioned.*

Case 2.1: W-004.1 Grid Resolution Study

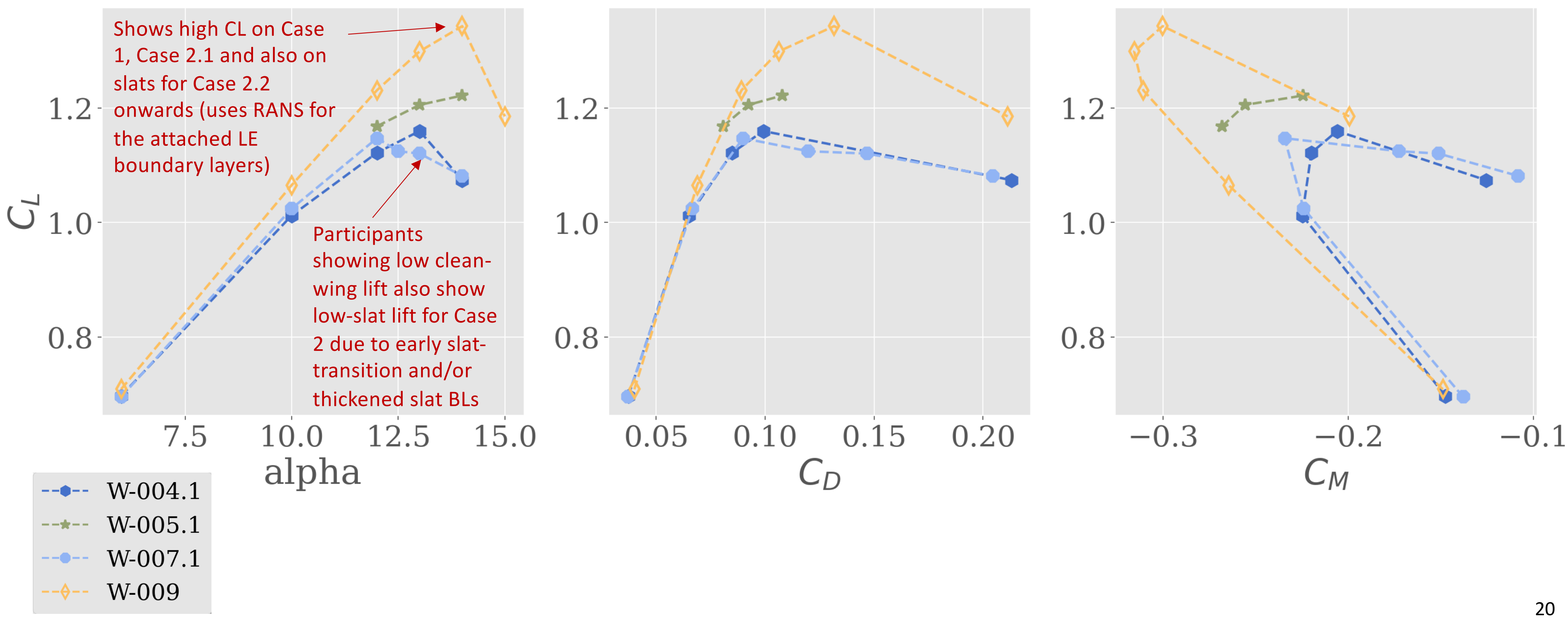


Case 2.1: W-005 Grid Resolution Study



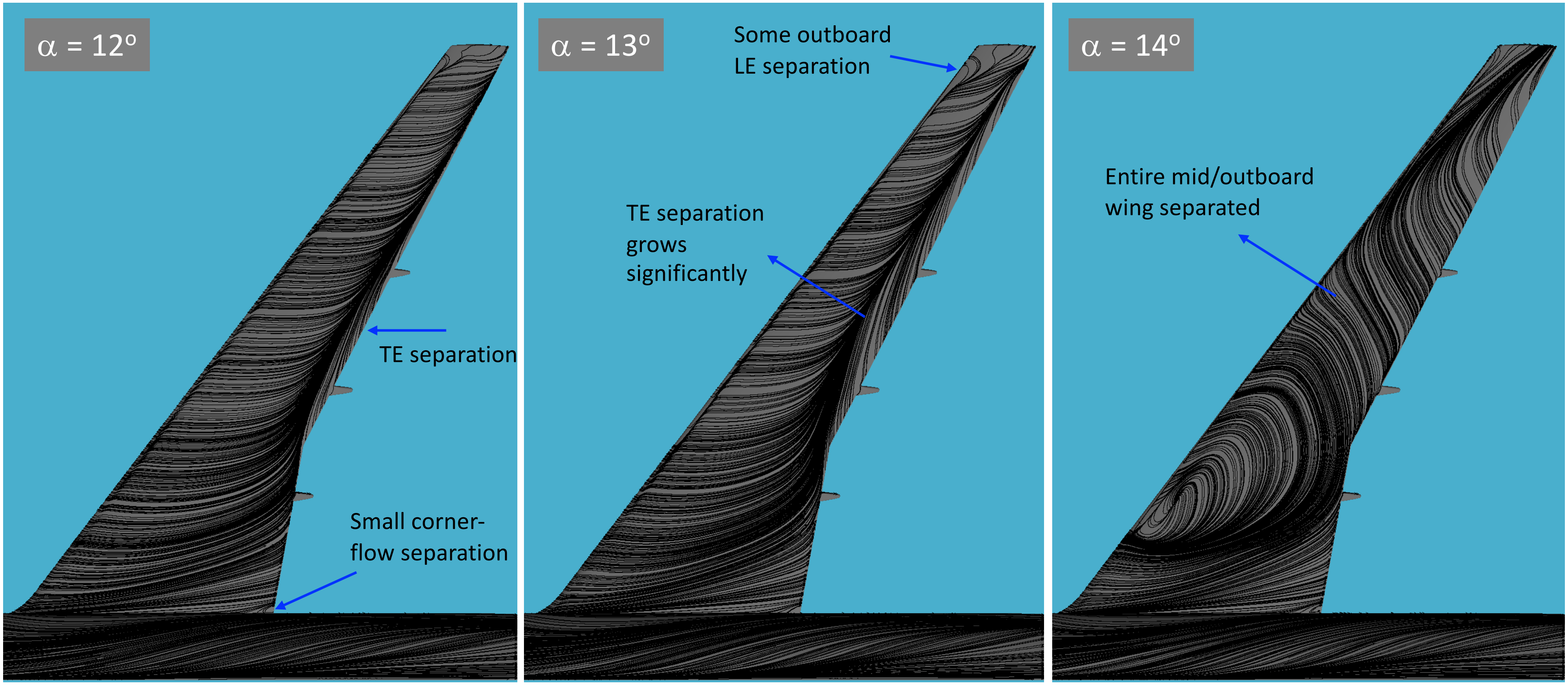
Case 2.1 Integrated F&M – All Submissions

Clean Wings – can "untripped" WMLES be predictive at low/moderate Re?



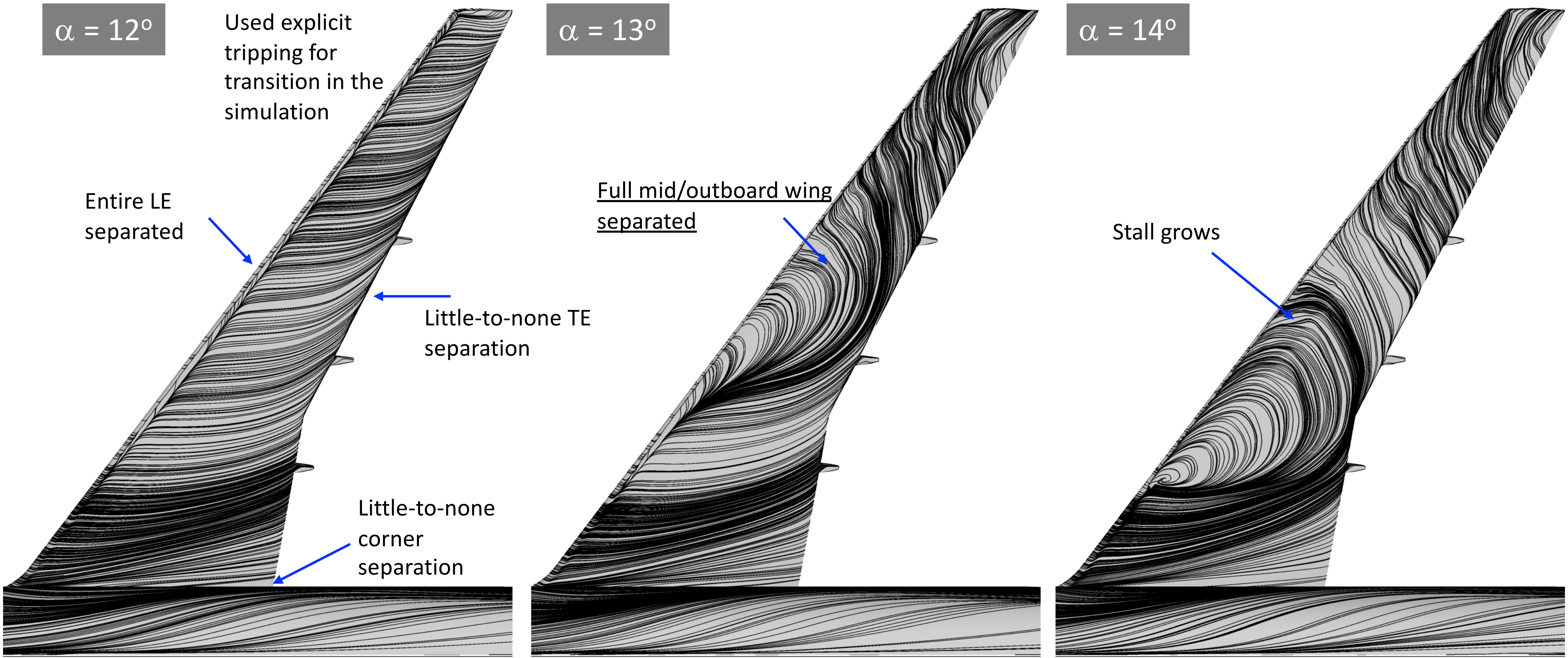
Case 2.1

W-004.1 Streamlines



Case 2.1

W-007 Streamlines



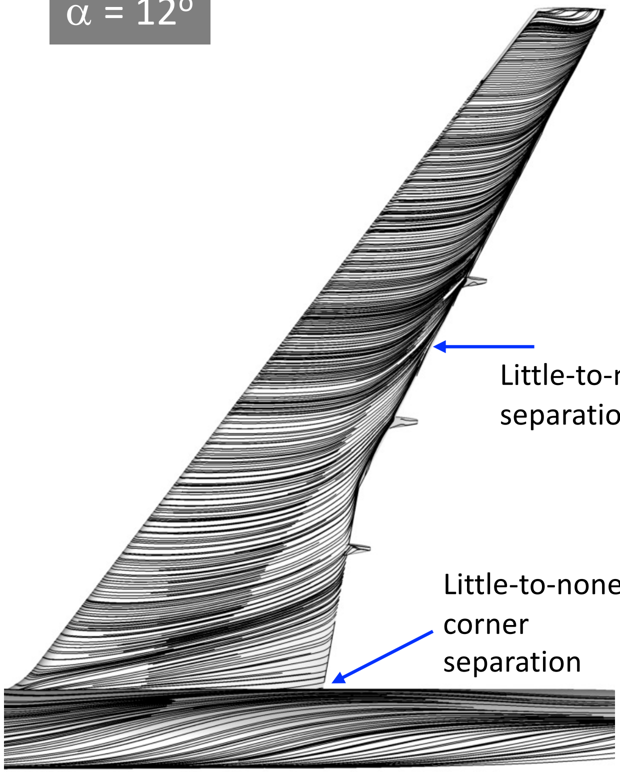
Case 2.1

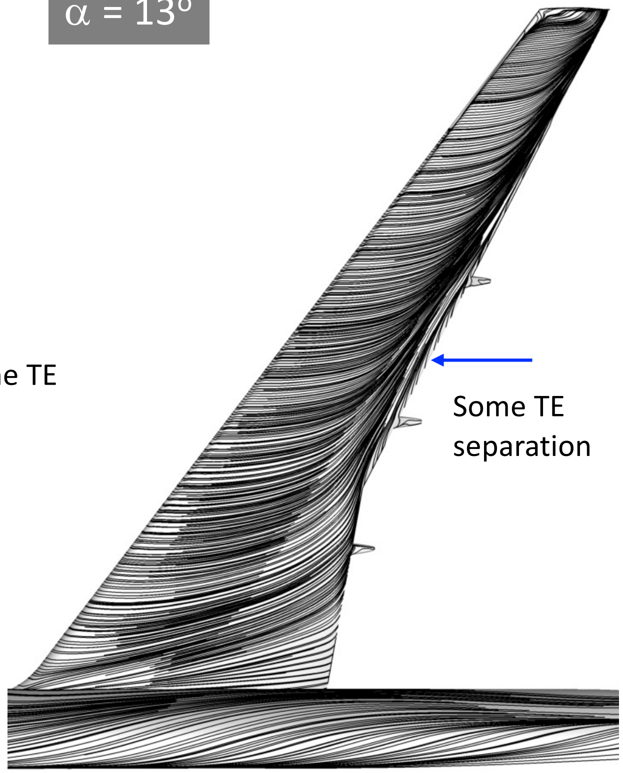
W-005.1 Streamlines

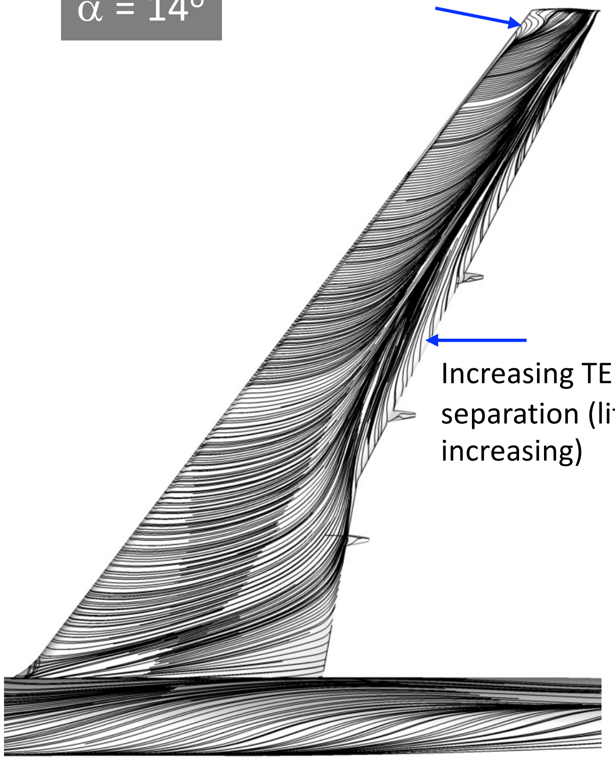
α = 12°

α = 13°

α = 14°

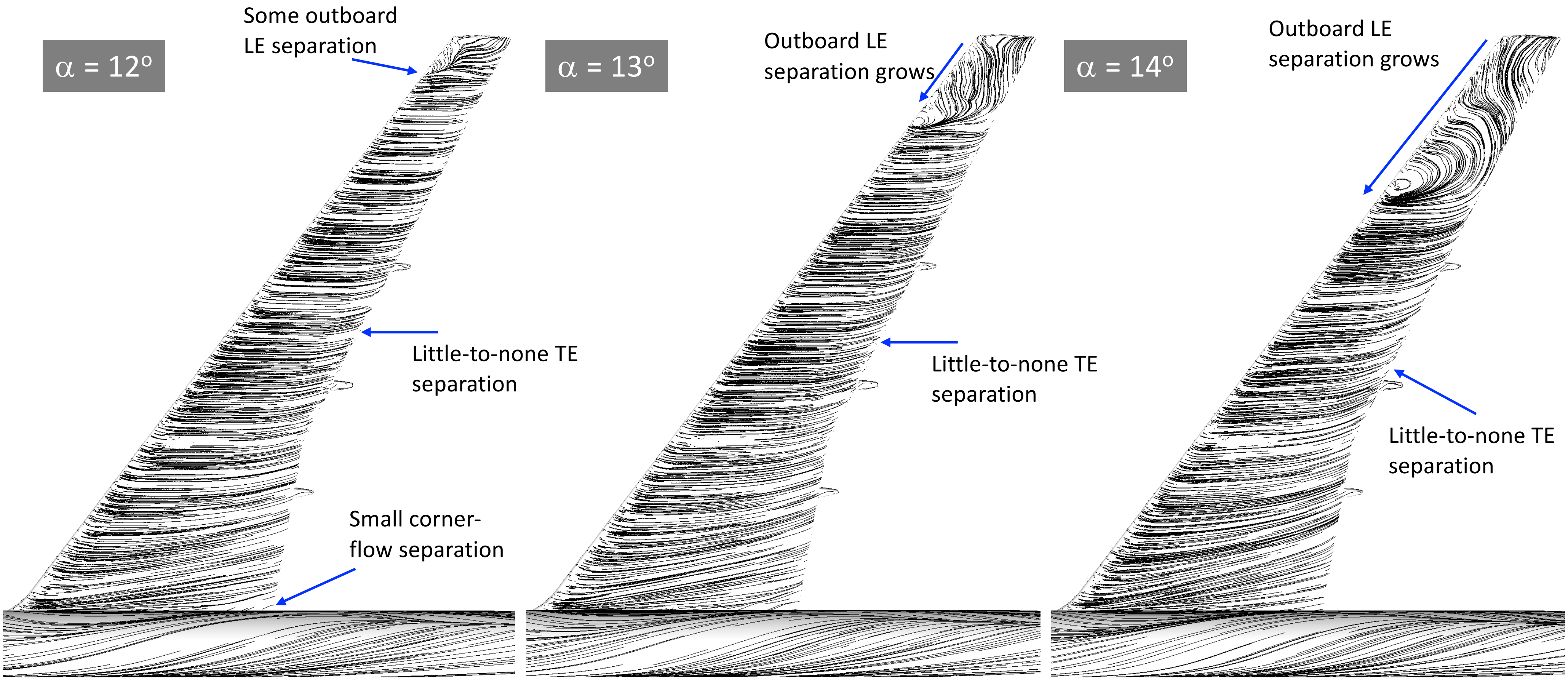




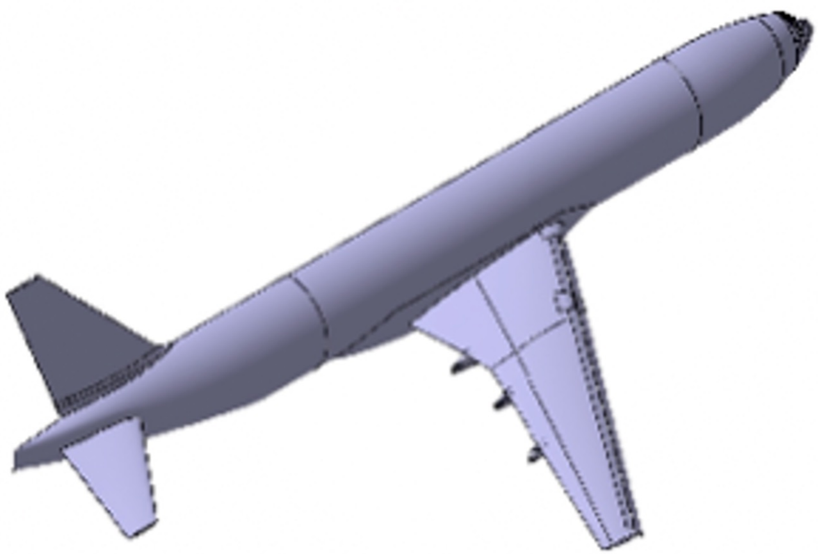


Case 2.1

W-009 Streamlines



Case 2.2



Case 2.2: ONERA_LRM-WBSHV

Angle of Attack (AoA)

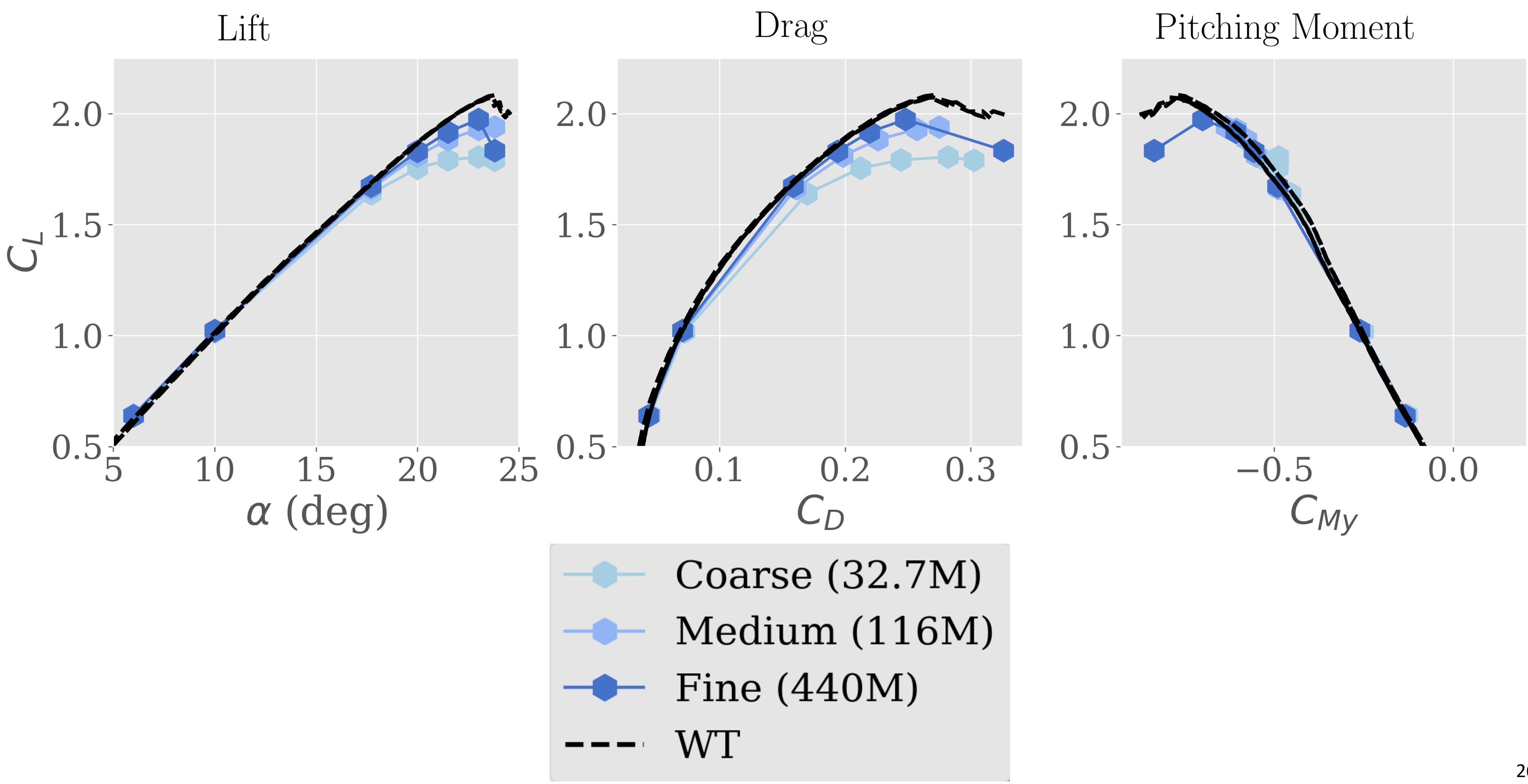
Case 2.1: 6º , 10º , 12º , 13º , 14º
Case 2.2: 6º , 10º , 17.7º , 20º , 21.5º , 23º , 23.8º
Case 2.3: 6º , 10º , 14º , 16º , 17.7º , 20.7º , 23.5º
Case 2.4: 7.6º , 10º , 14º , 16º , 17.7º , 19.7º , 23.6º

Participant ID	Solver	Coarse Grid	Medium Grid	Fine Grid	Blind Submission?
W-001	Adaptive Euler	165K*			NO
W-005.1	FUN3D (FV)	225M		1.73B*	Coarse Grid Only
W-006	hpMusic	57M (DOF)	99M	159M*	YES
W-004.1	CharLES (DSM)	35M	126M	483M*	YES
W-007	LAVA			296M*	NO
W-009	PowerFlow		413M*	1.2B	YES
W-010.1	Volcano ScaLES (Vr)	355M	544M	1.09B*	YES
W-010.3	Volcano ScaLES (DSM)			872M*	NO

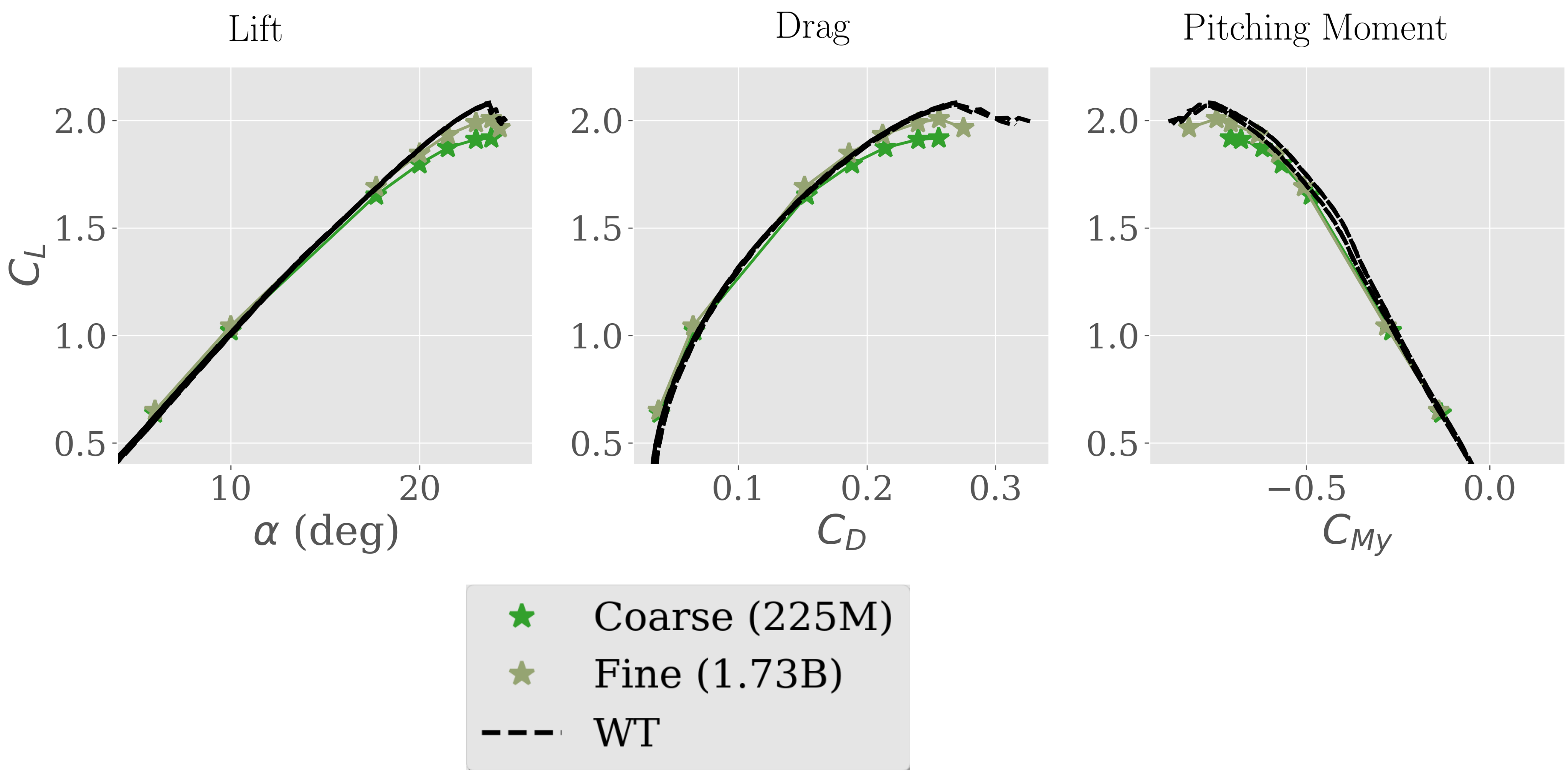
Wind Tunnel (WT) data is provided by ONERA

**Nominal grid used by participants. Presented grid size unless otherwise mentioned.*

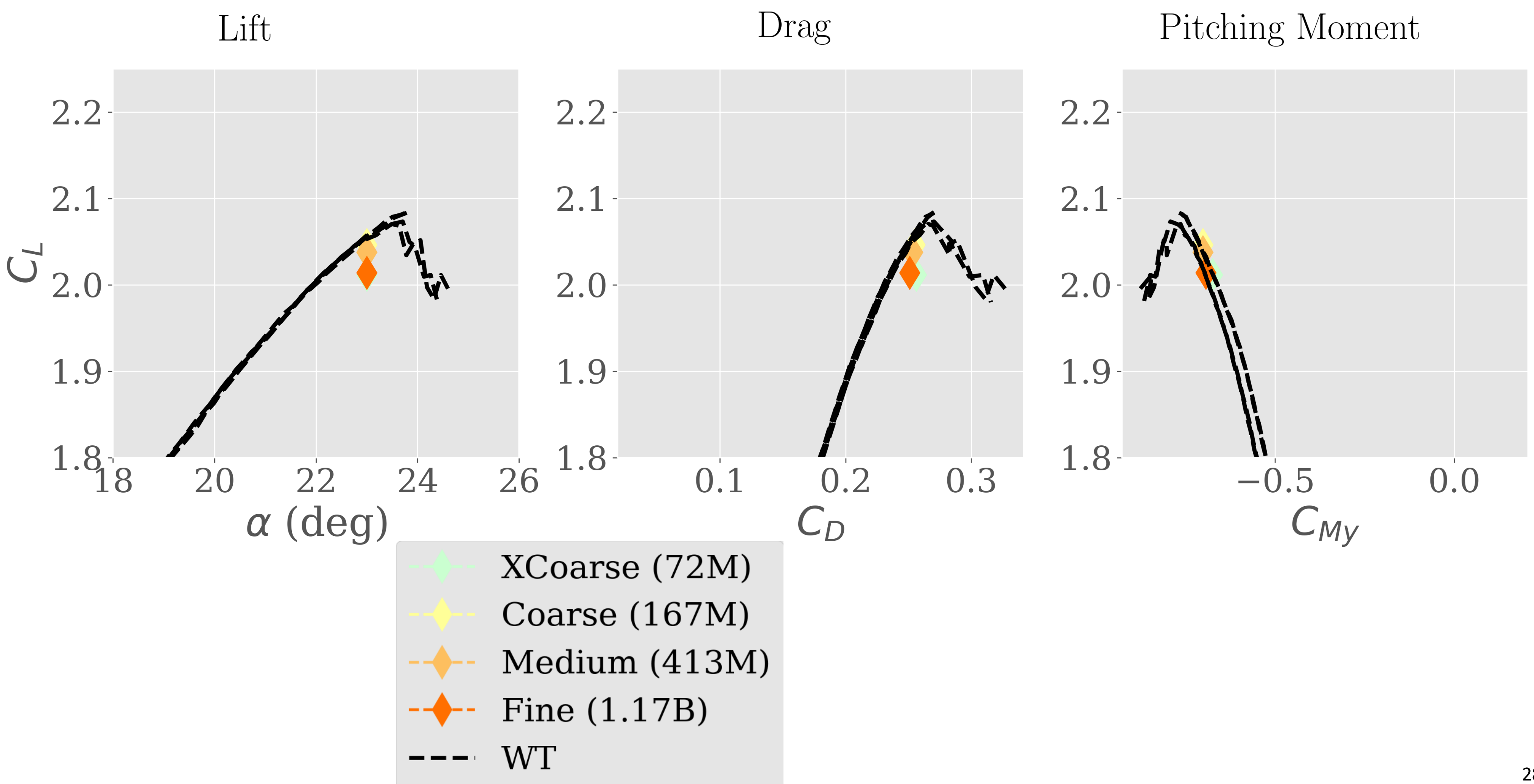
Case 2.2: W-004.1 Grid Resolution Study



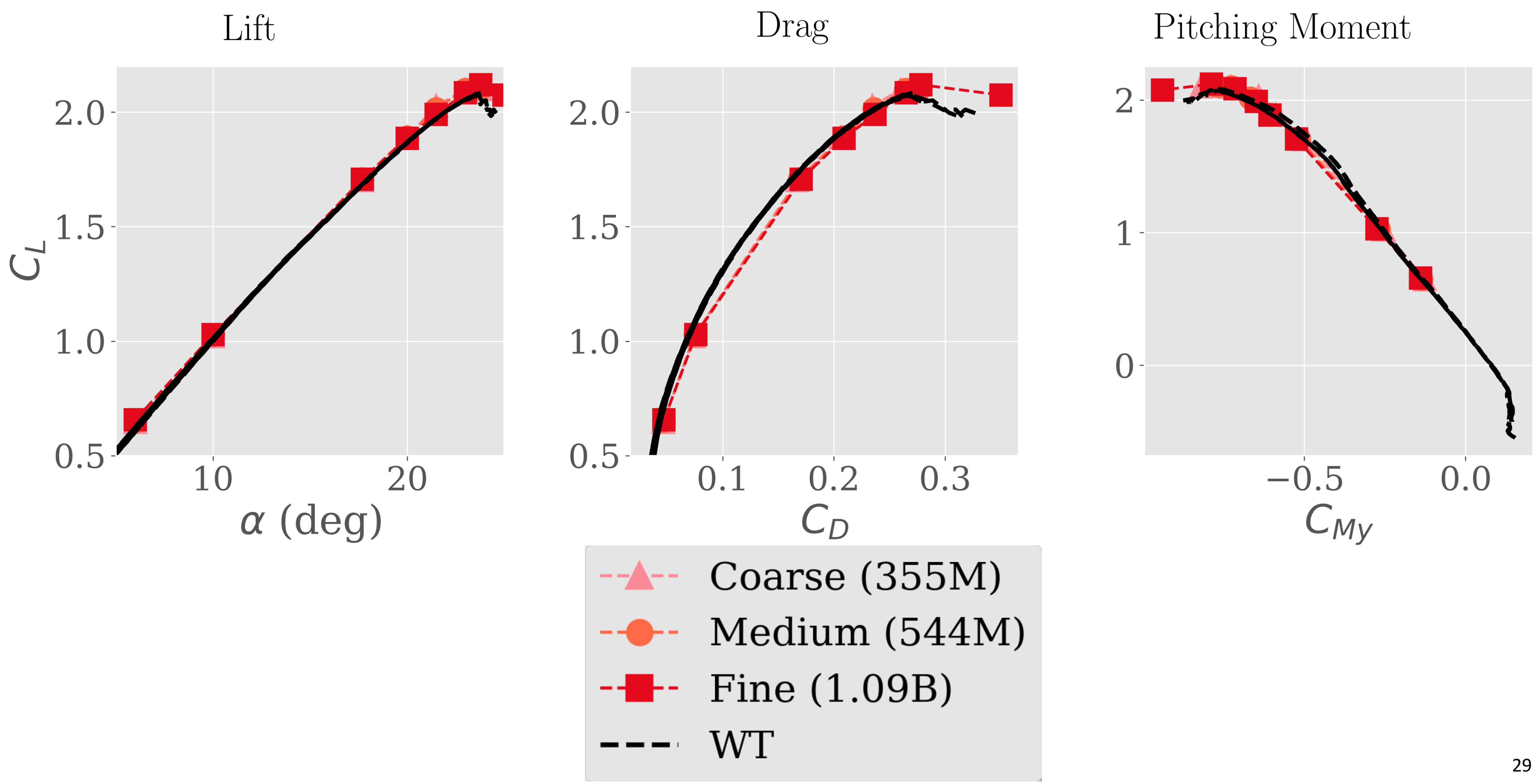
Case 2.2: W-005.1 Grid Resolution Study



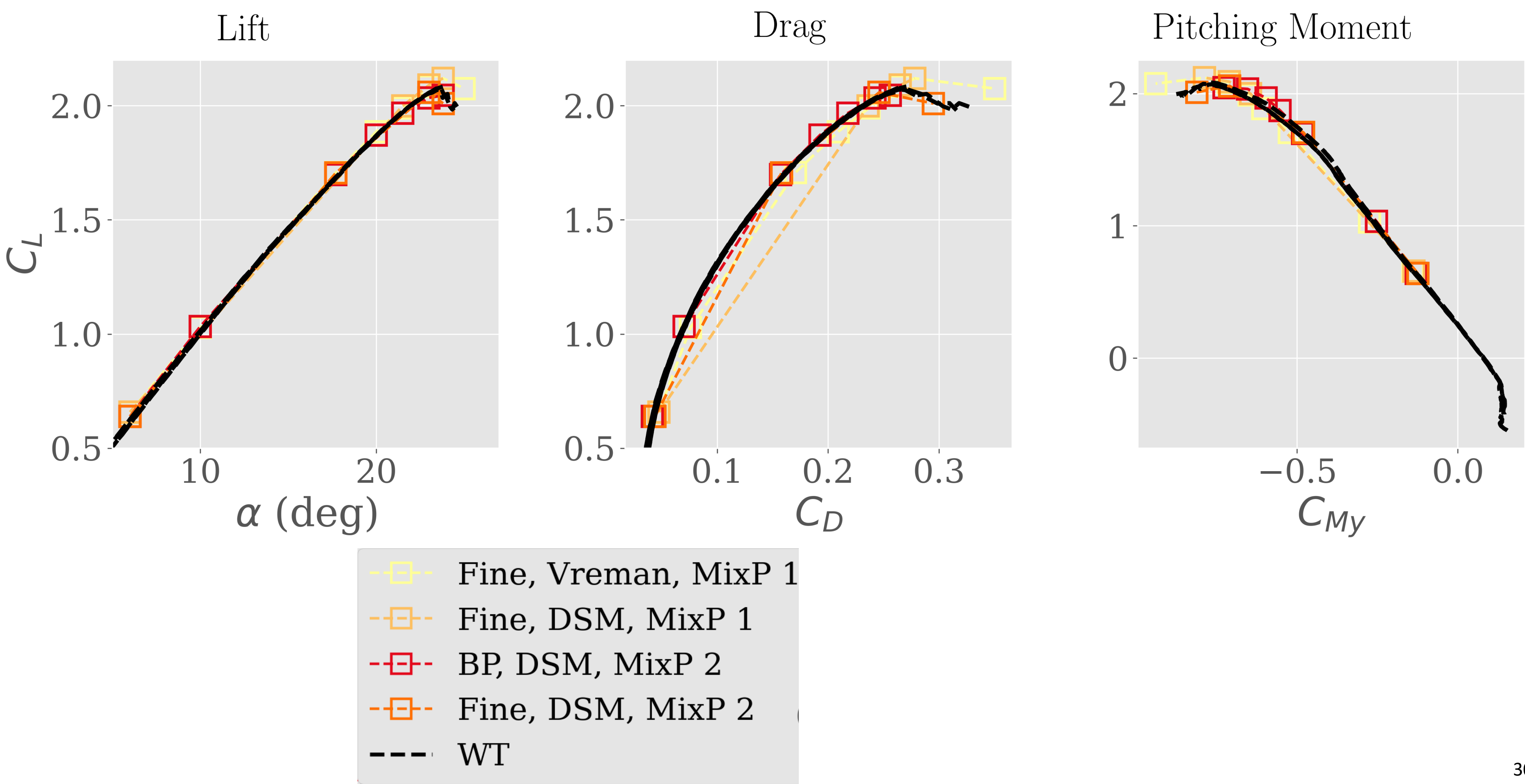
Case 2.2: W-009 Grid Resolution Study



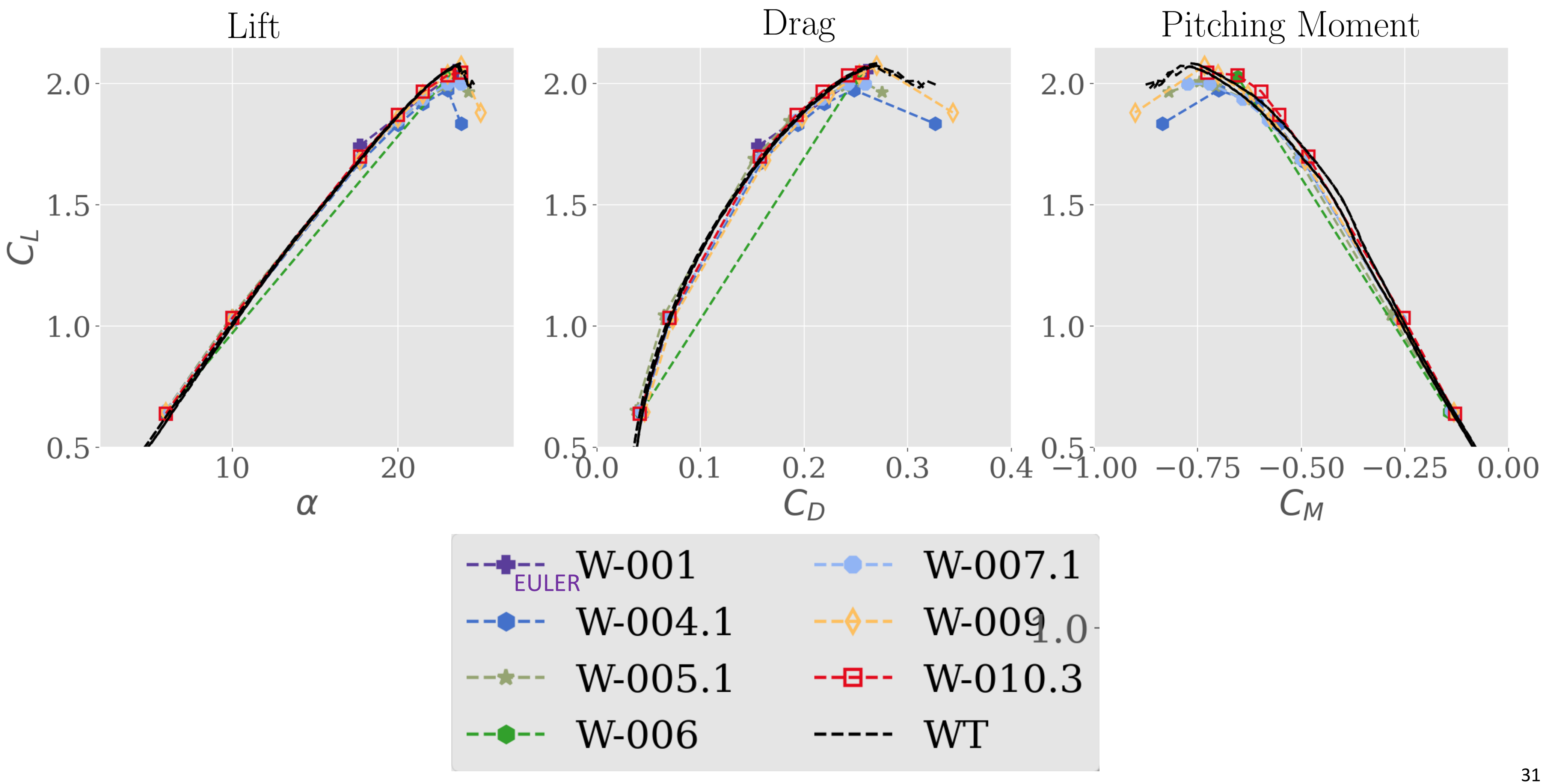
Case 2.2: W-010.1 Grid Resolution Study



Case 2.2: W-010 SGS Closure & Precision Sensitivity

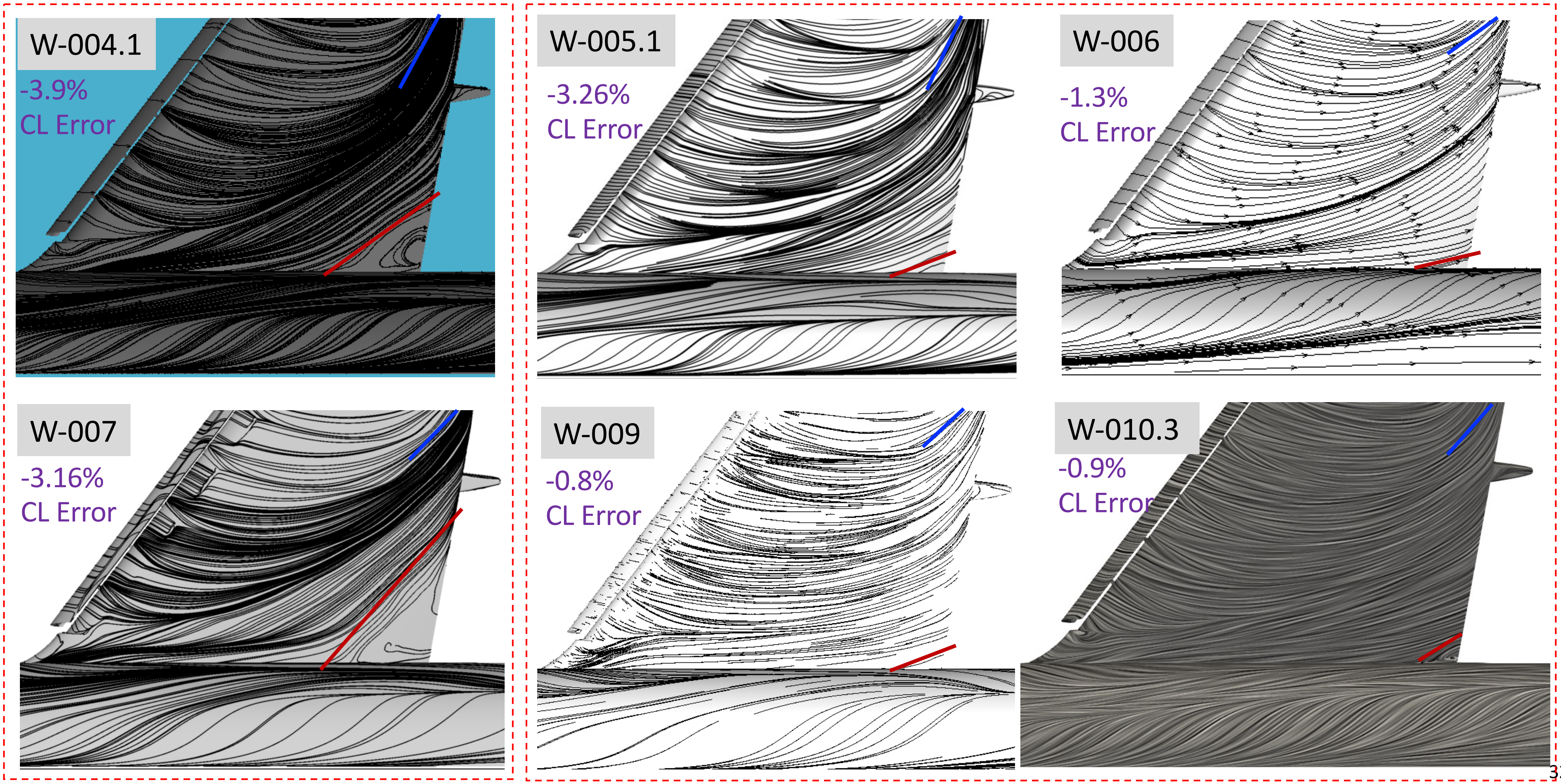


Case 2.2 Integrated F&M - All Submissions



α = 23.0º

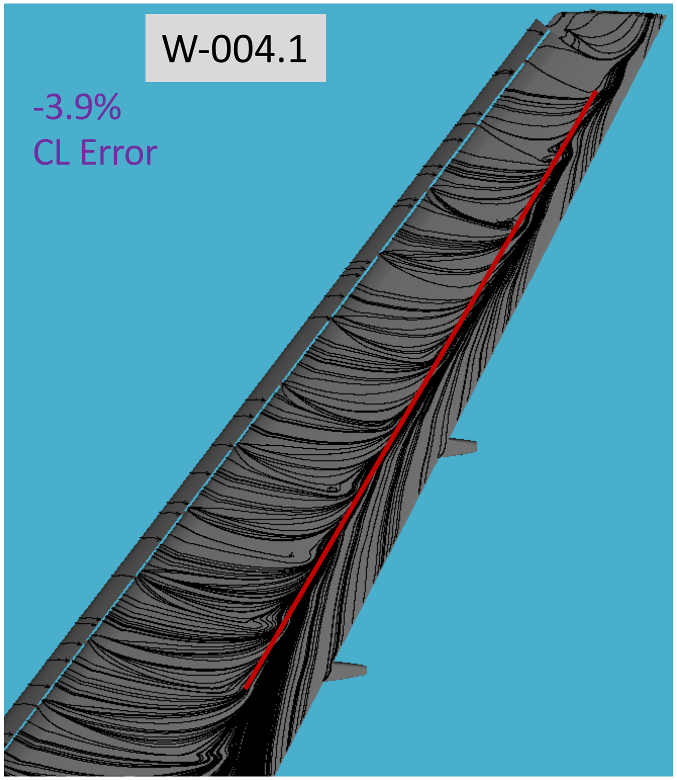
Case 2.2: Streamlines (in-board)

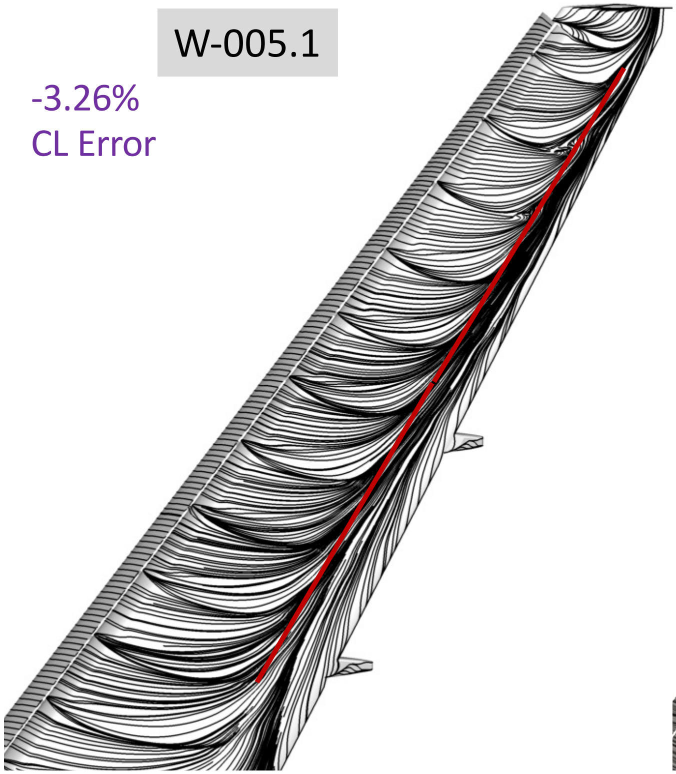


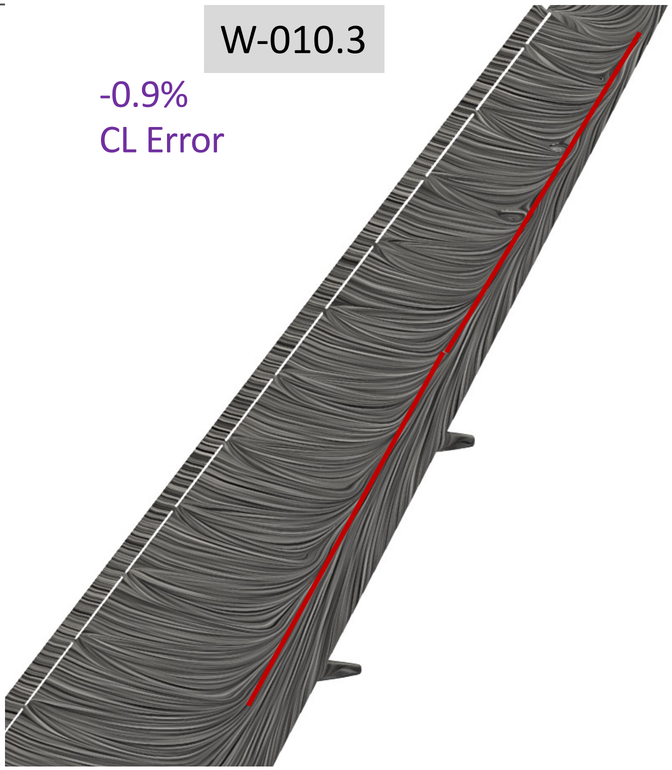
α = 23.0°

Case 2.2: Streamlines (out-board)

decreasing order of separation in trailing edge







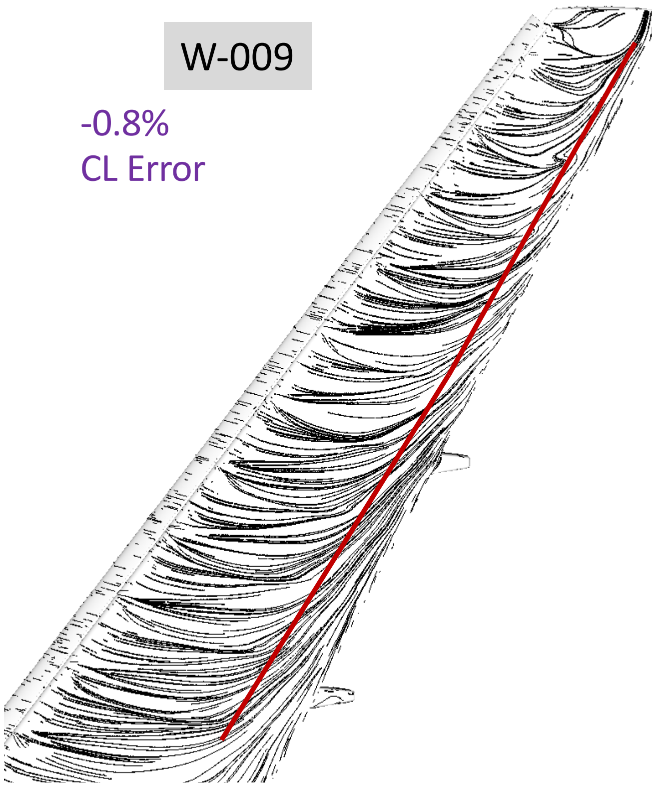
α = 23.0°

Case 2.2: Steamlines (out-board)

decreasing order of separation in trailing edge →

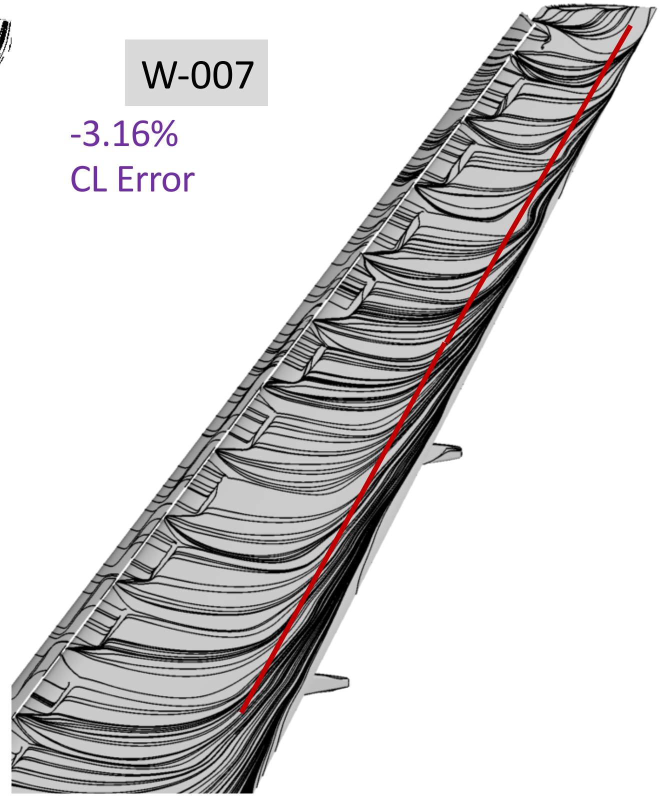
W-009

-0.8%
CL Error



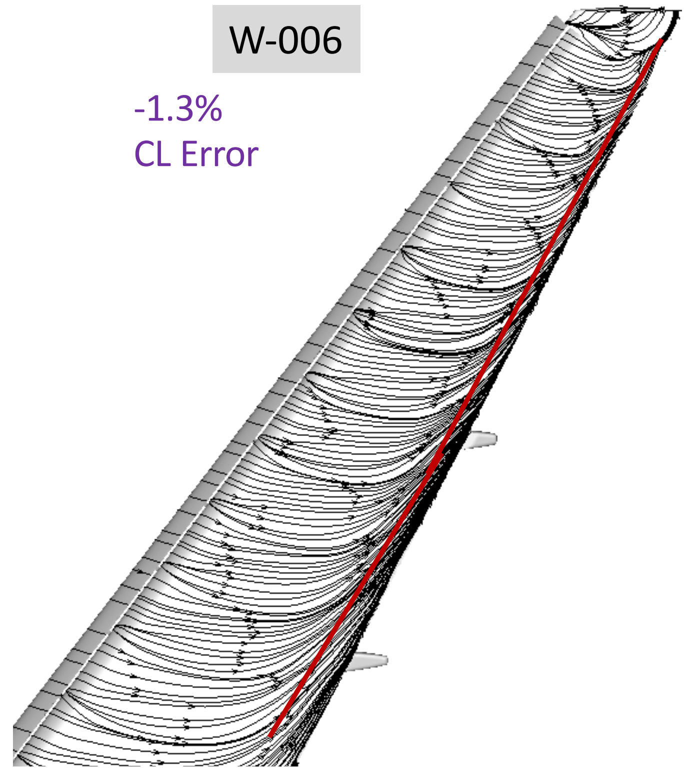
W-007

-3.16%
CL Error



W-006

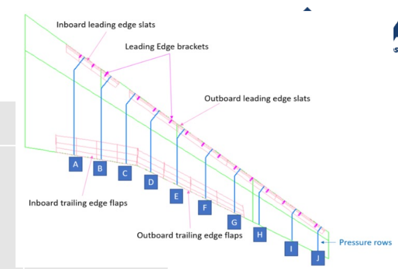
-1.3%
CL Error

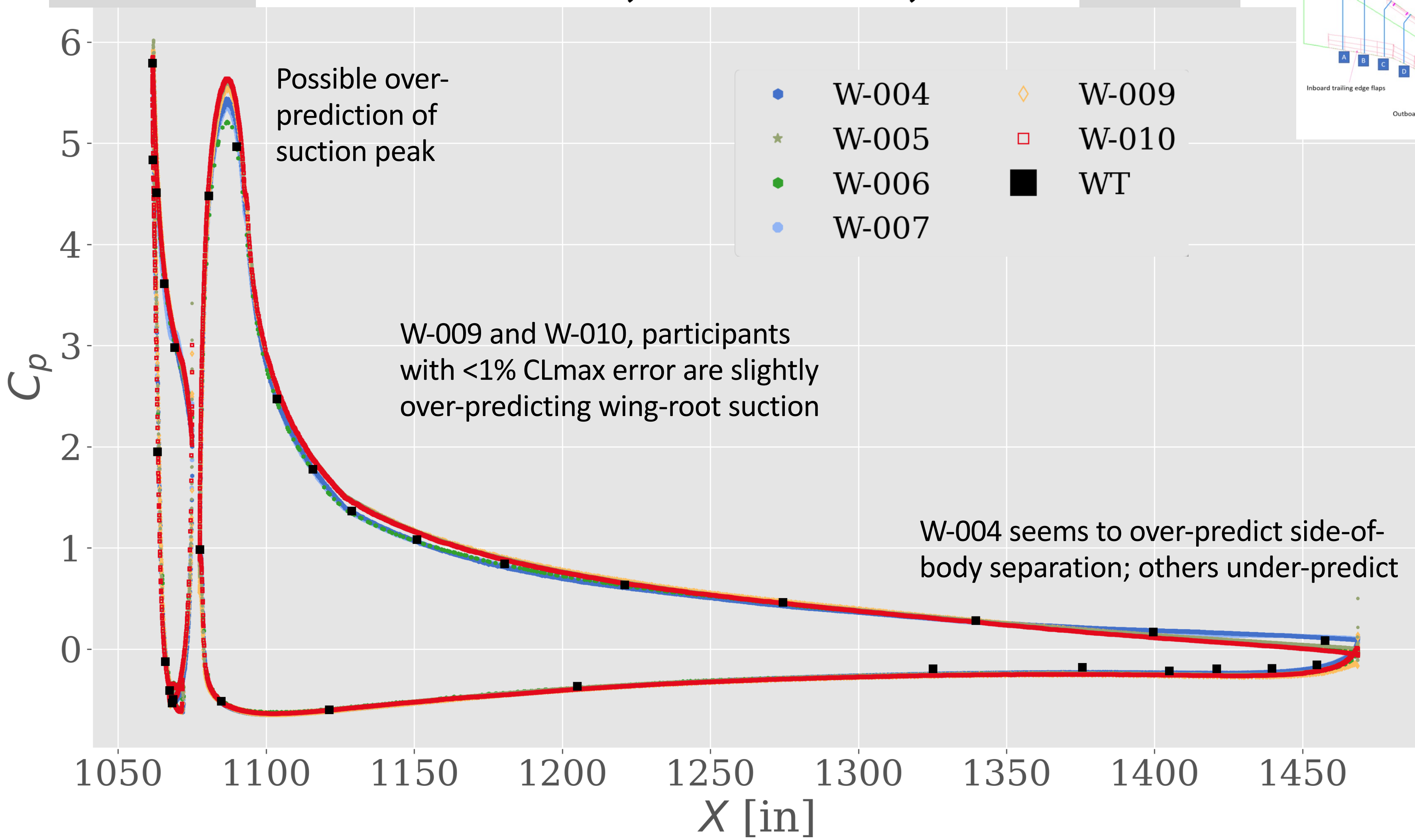


α = 23.0º

Case 2.2: Cp Cuts(in-board)

Row A

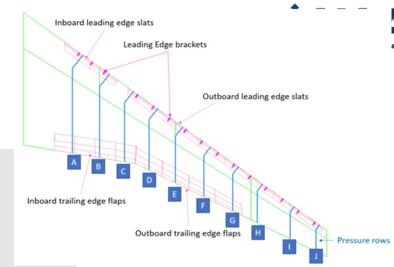


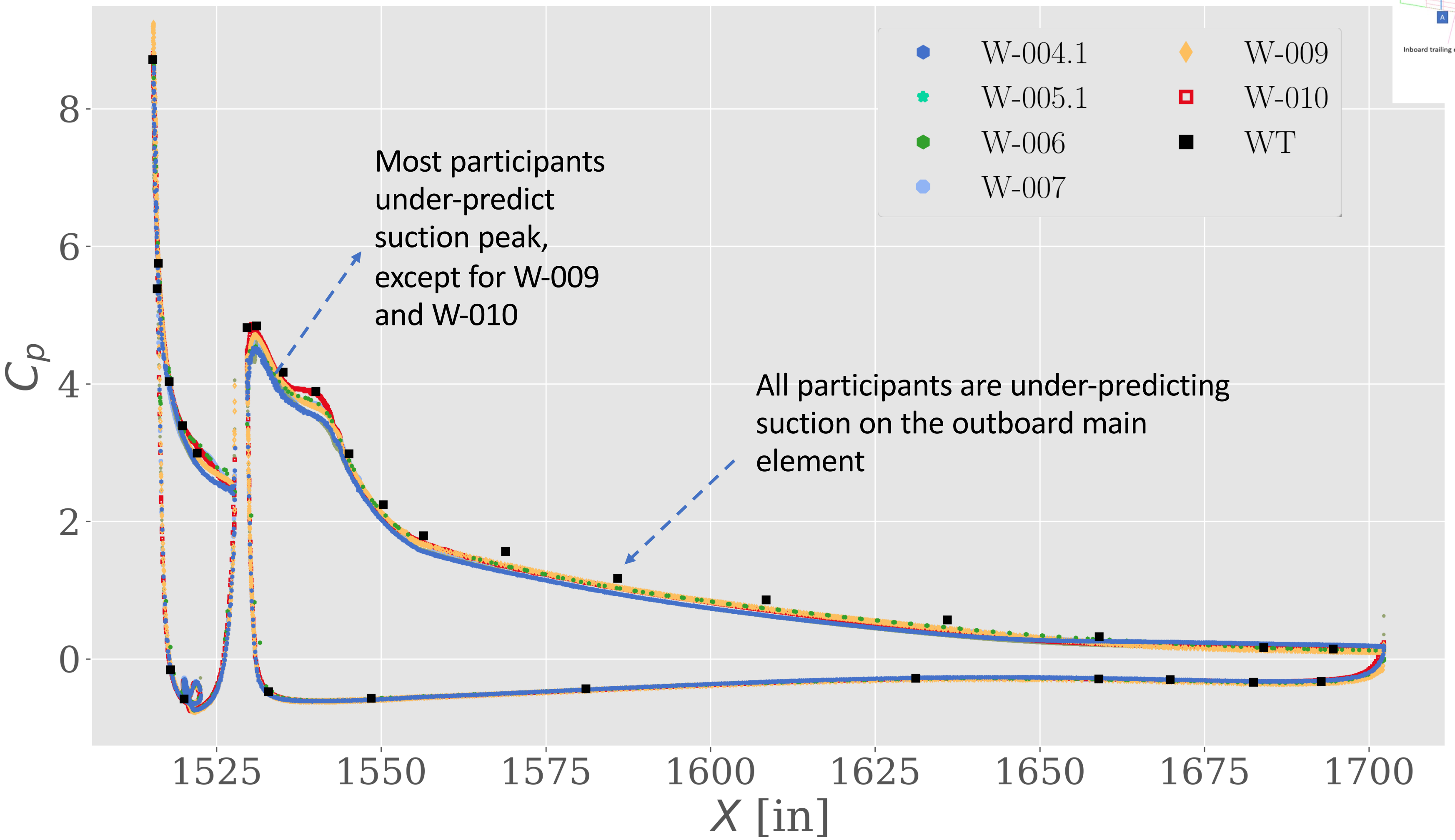


α = 23.0º

Case 2.2: Cp Cuts(out-board)

Row G

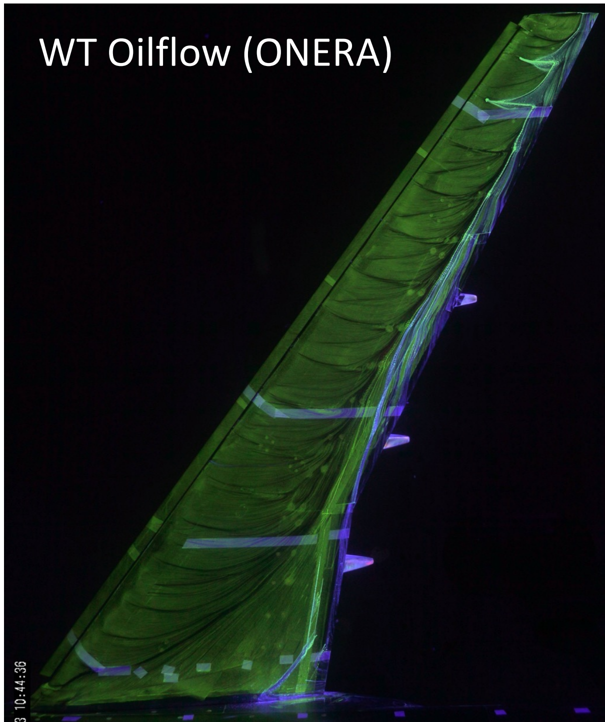




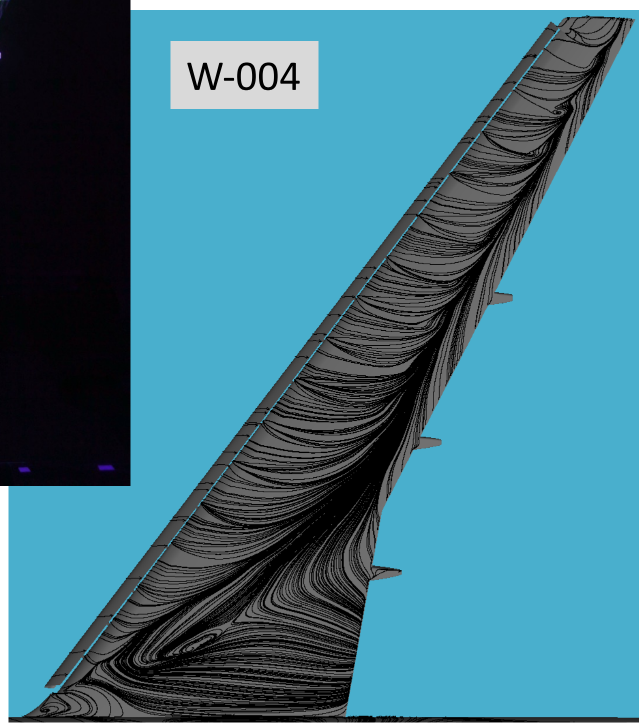
Case 2.2: Streamlines

$\alpha = 23.8^o$

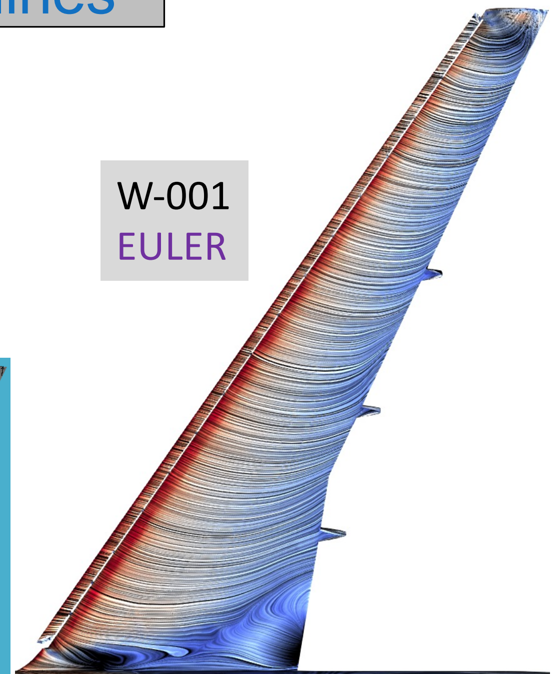
more-complicated – bistable solution likely



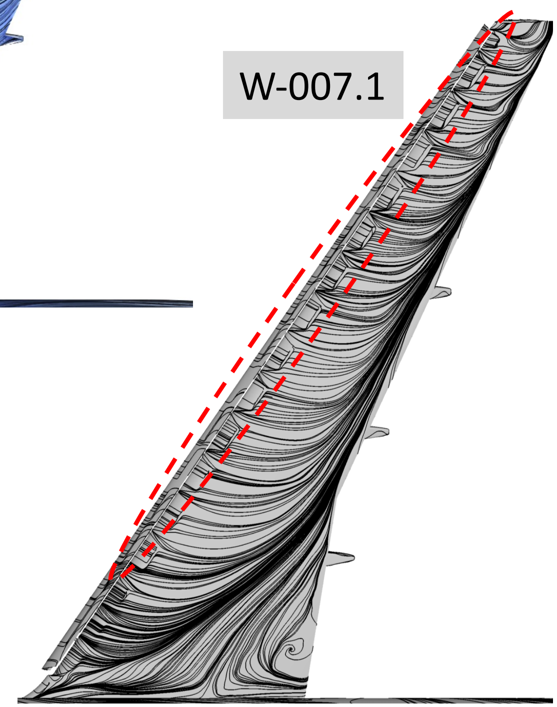
W-004



W-001
EULER

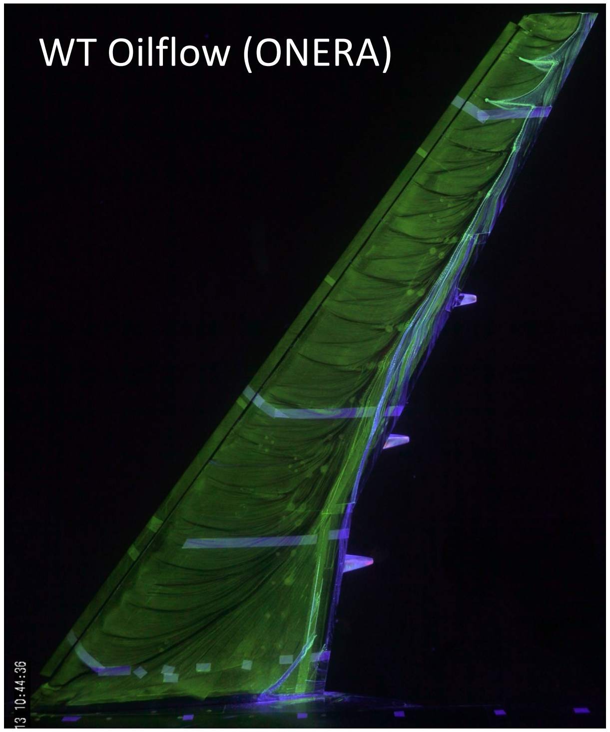


W-007.1

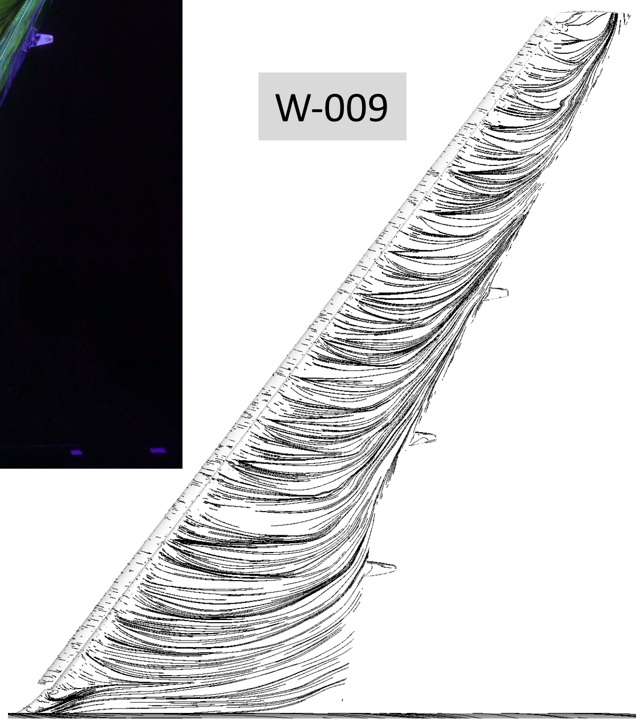


α = 23.8°

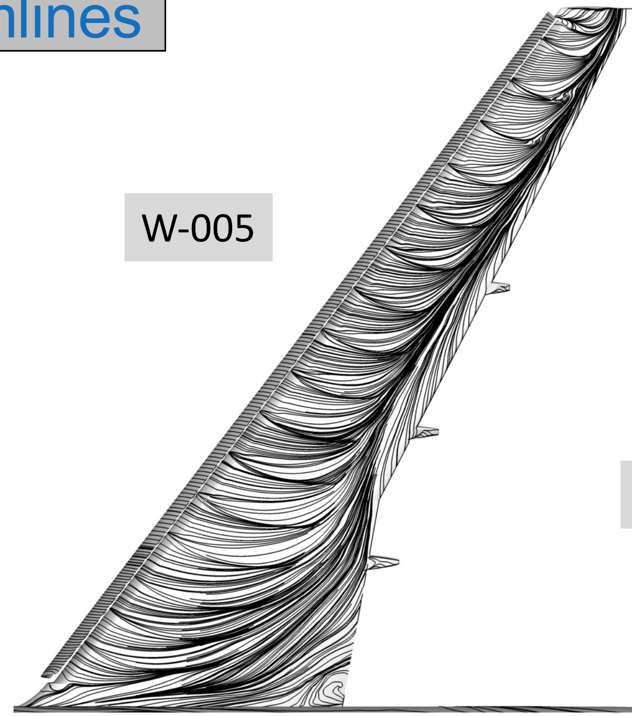
Case 2.2: Steamlines



W-009

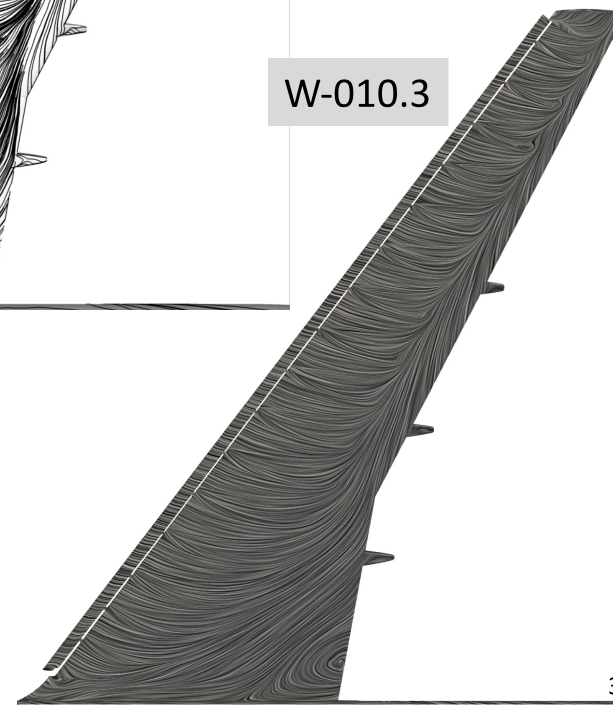


W-005



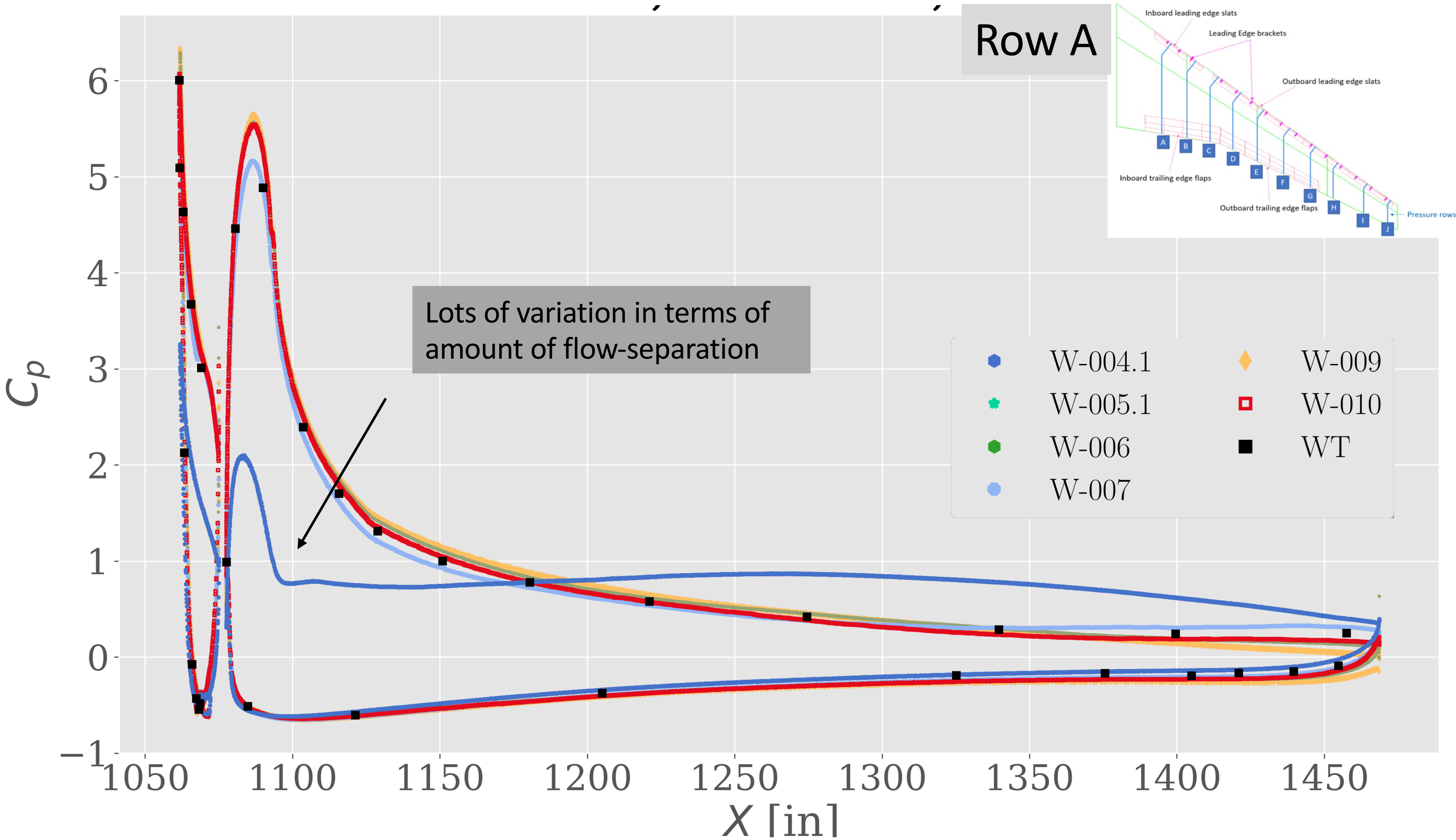
more-complicated – bistable solution likely

W-010.3

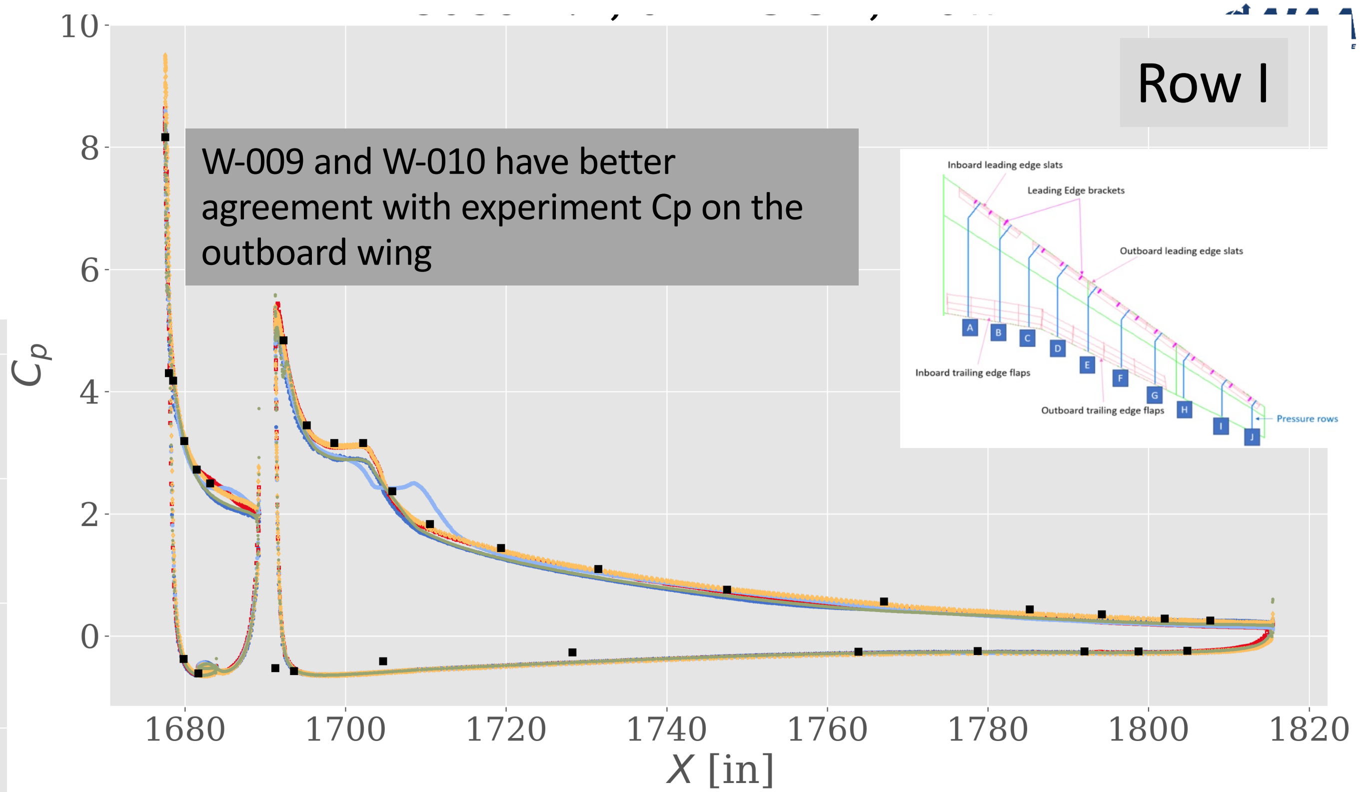


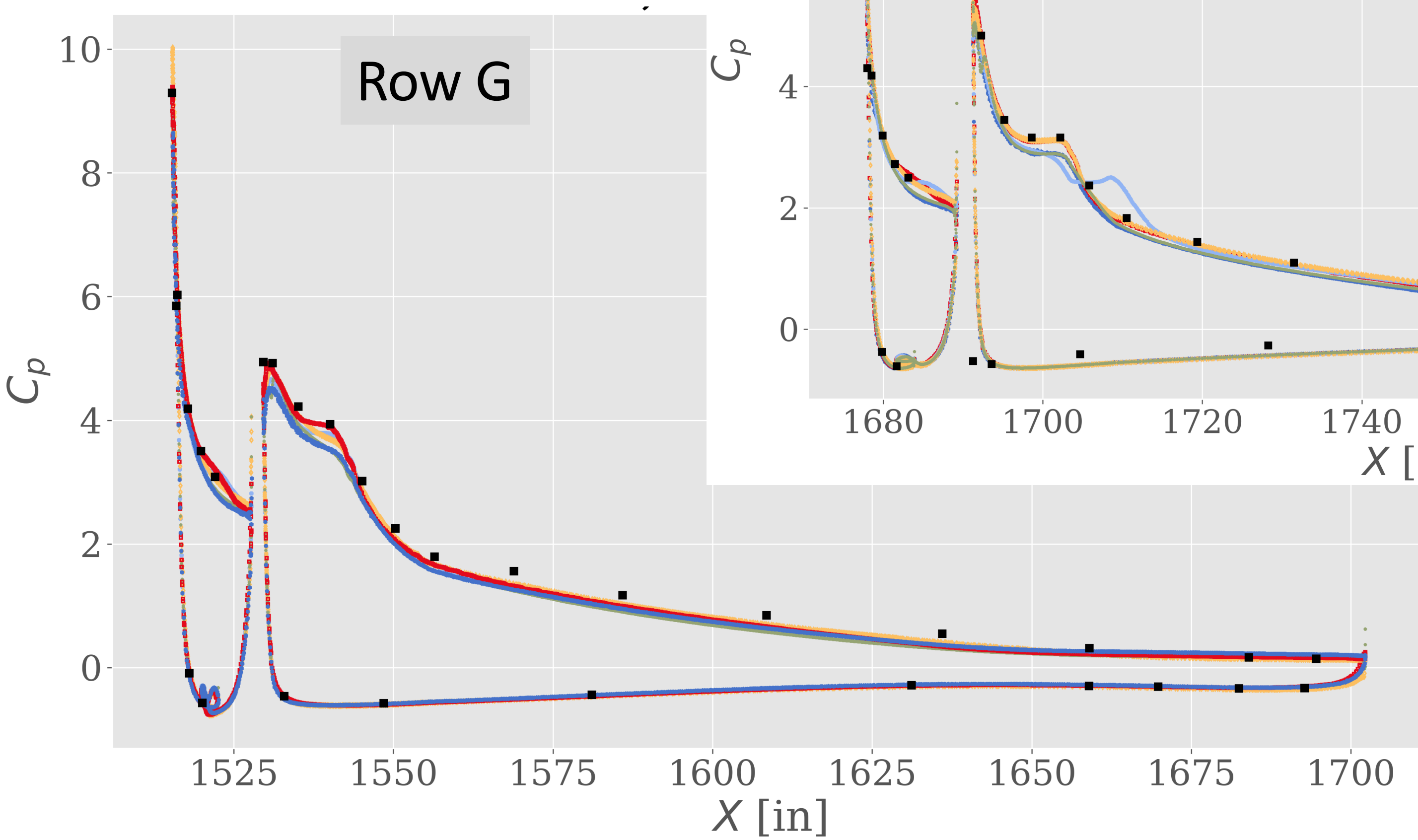
α = 23.8º

Case 2.2: Cp Cuts (in-board)



Case 2.2: Cp Cuts (out-board) - α = 23.8°

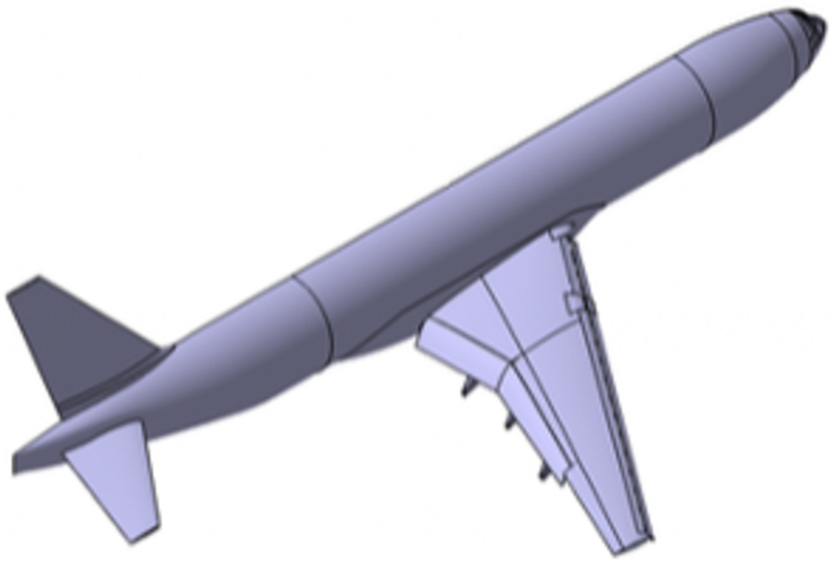




Case 2.2 – Observations

- 5 full angle of attack sweep submissions – Two of them are within 2% error at CLmax
- Some inboard-outboard error cancellation
  - W-004: under-prediction of outboard suction: -3.9% CL error at 23.0 deg.
  - W-005: under-prediction of outboard suction -> -3.26% CL error at 23.0 deg.
  - W-006: Only two angle simulated but shows reasonable inboard CL with small under-prediction outboard - had the lowest overall separated flow on the suction side: -1.3% CL error at 23.0 deg.
  - W-007: under-prediction of outboard suction: -3.16% CL error at 23.0 deg
  - W-009: Some over-prediction of inboard suction with moderate under-prediction of outboard suction: -0.8% CL error at 23.0 deg
  - W-010: Some over-prediction of inboard suction with reasonable agreement in outboard suction: -0.9% CL error at 23.0 deg
- All submissions predict the correct onset of stall
- W-001 (Euler) submission had reasonable CL values but completely inaccurate surface flow (missing TE separation on outboard wing, excess inboard separation) leading to inaccurate CMY

Case 2.3



Case 2.3: ONERA_LRM-WBSFHV

Participant ID	Solver	Coarse Grid	Medium Grid	Fine Grid	Blind Submission?
W-001	Adaptive Euler	165K*			NO
W-005.1	FUN3D (FV)	241M		1.85B*	Coarse Grid Only
W-005.2	FUN3D (FE)	241M*			NO
W-004.1	CharLES (DSM)	38M	138M	527M*	YES
W-007	LAVA			307M*	NO
W-009	PowerFlow	233M	605M*	1.03B	YES
W-010.1	Volcano ScaLES (Vr)	400M	622M	1.17B*	YES
W-010.3	Volcano ScaLES (DSM)			1.03B*	NO

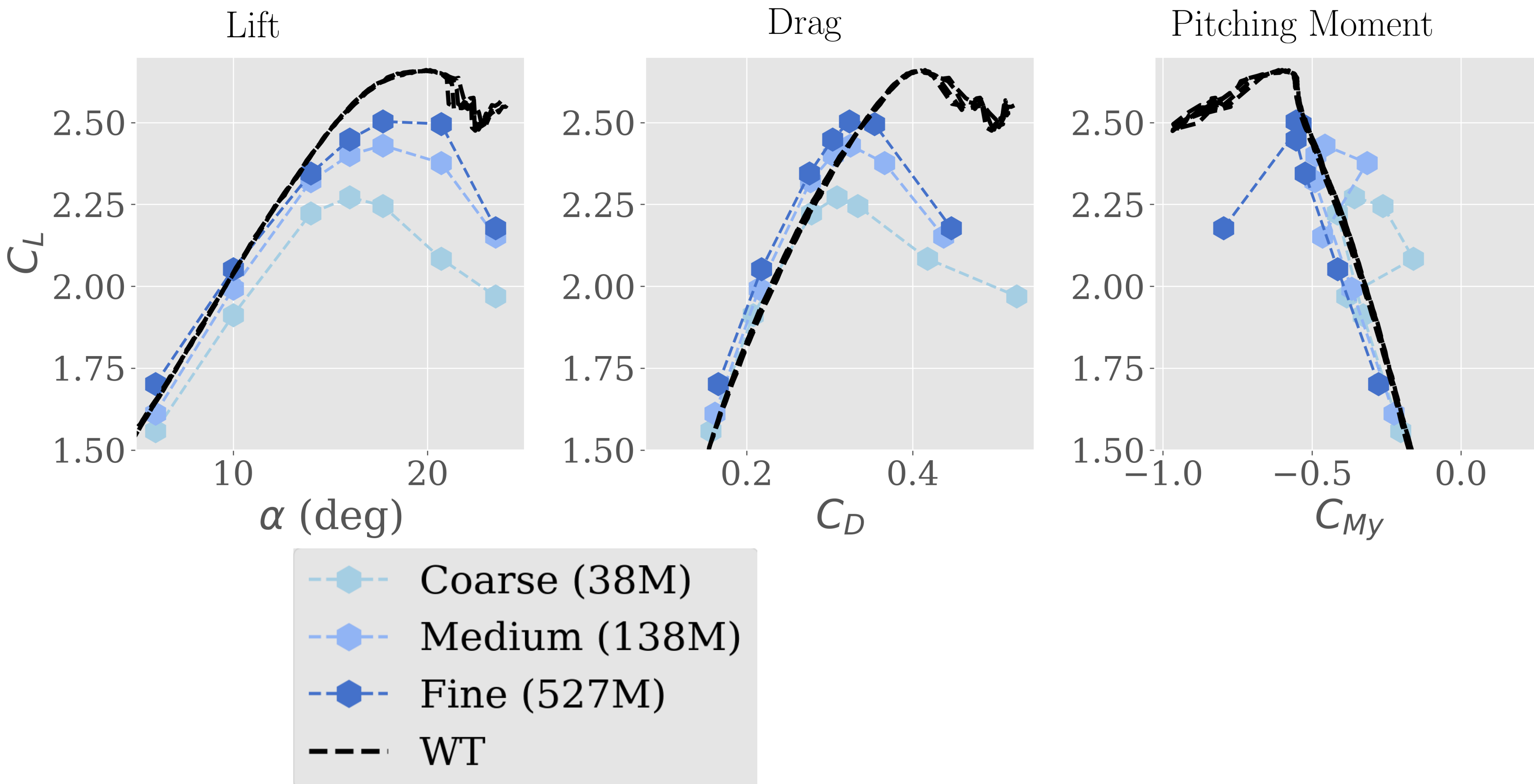
Wind Tunnel (WT) data is provided by ONERA

Angle of Attack (AoA)

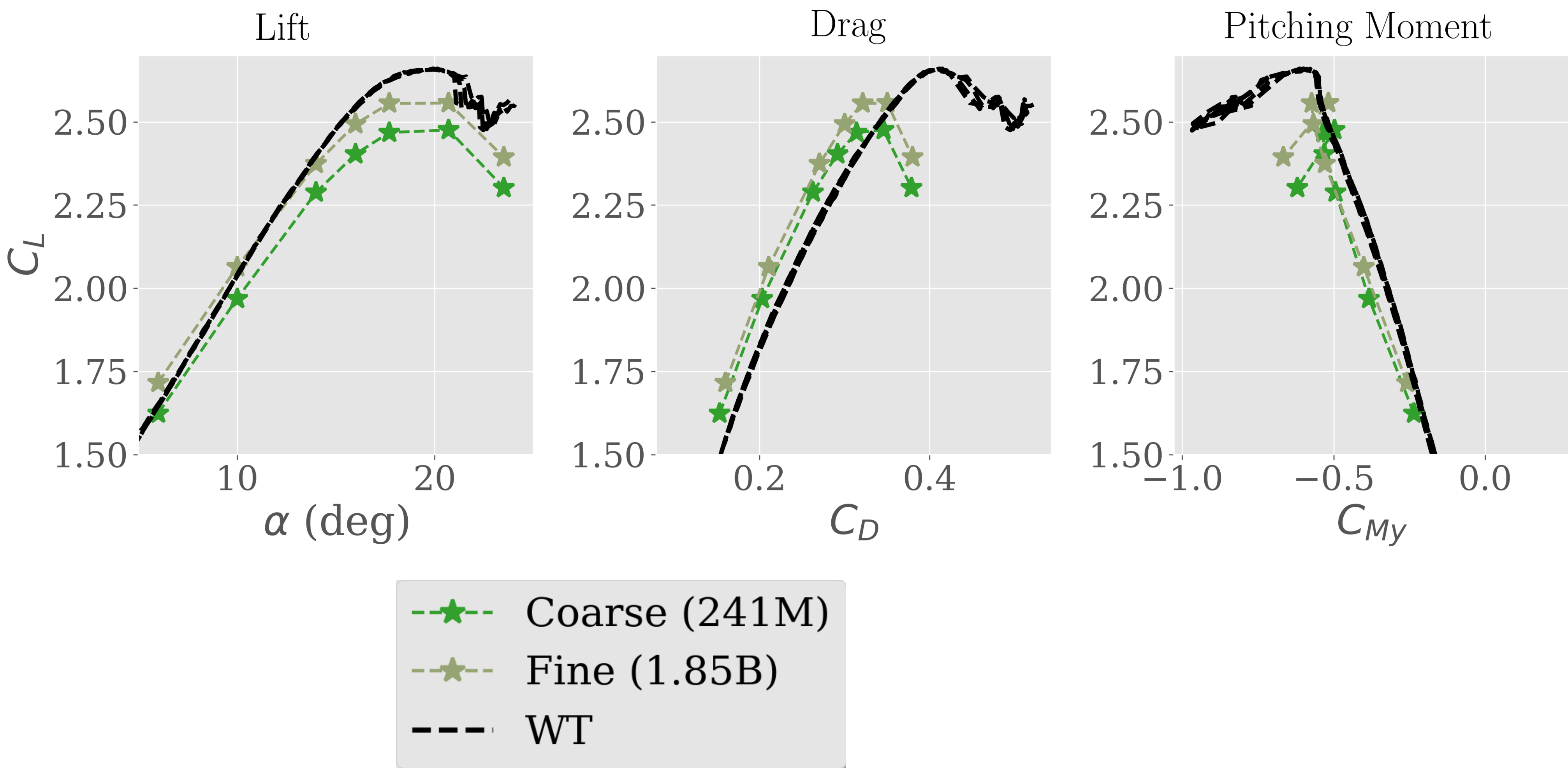
Case 2.1: 6°, 10°, 12°, 13°, 14°
Case 2.2: 6°, 10°, 17.7°, 20°, 21.5°, 23°, 23.8°
Case 2.3: 6°, 10°, 14°, 16°, 17.7°, 20.7°, 23.5°
Case 2.4: 7.6°, 10°, 14°, 16°, 17.7°, 19.7°, 23.6°

Nominal grid used by participants. Presented grid size unless otherwise mentioned.

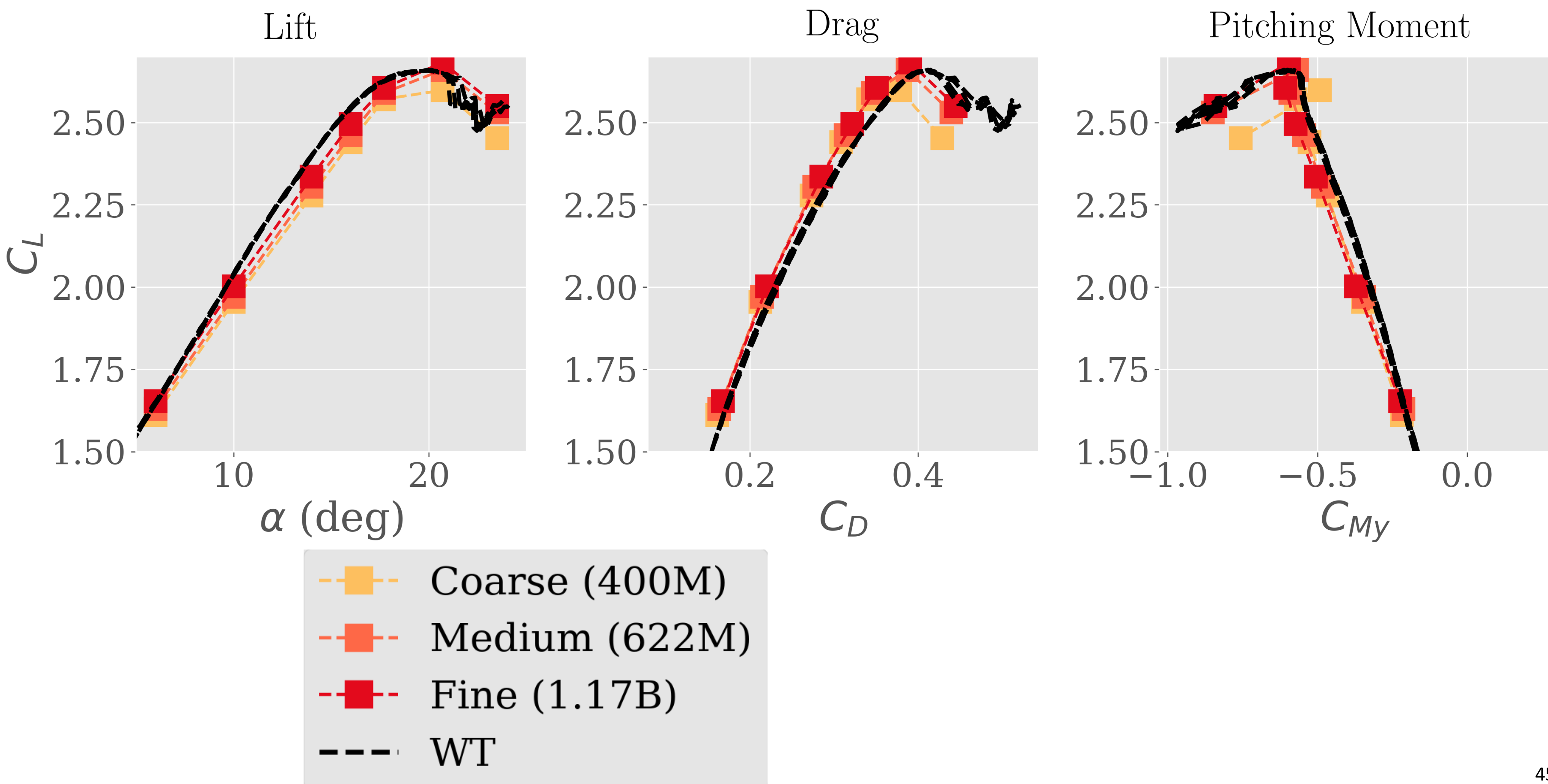
Case 2.3: W-004.1 Grid Resolution Study



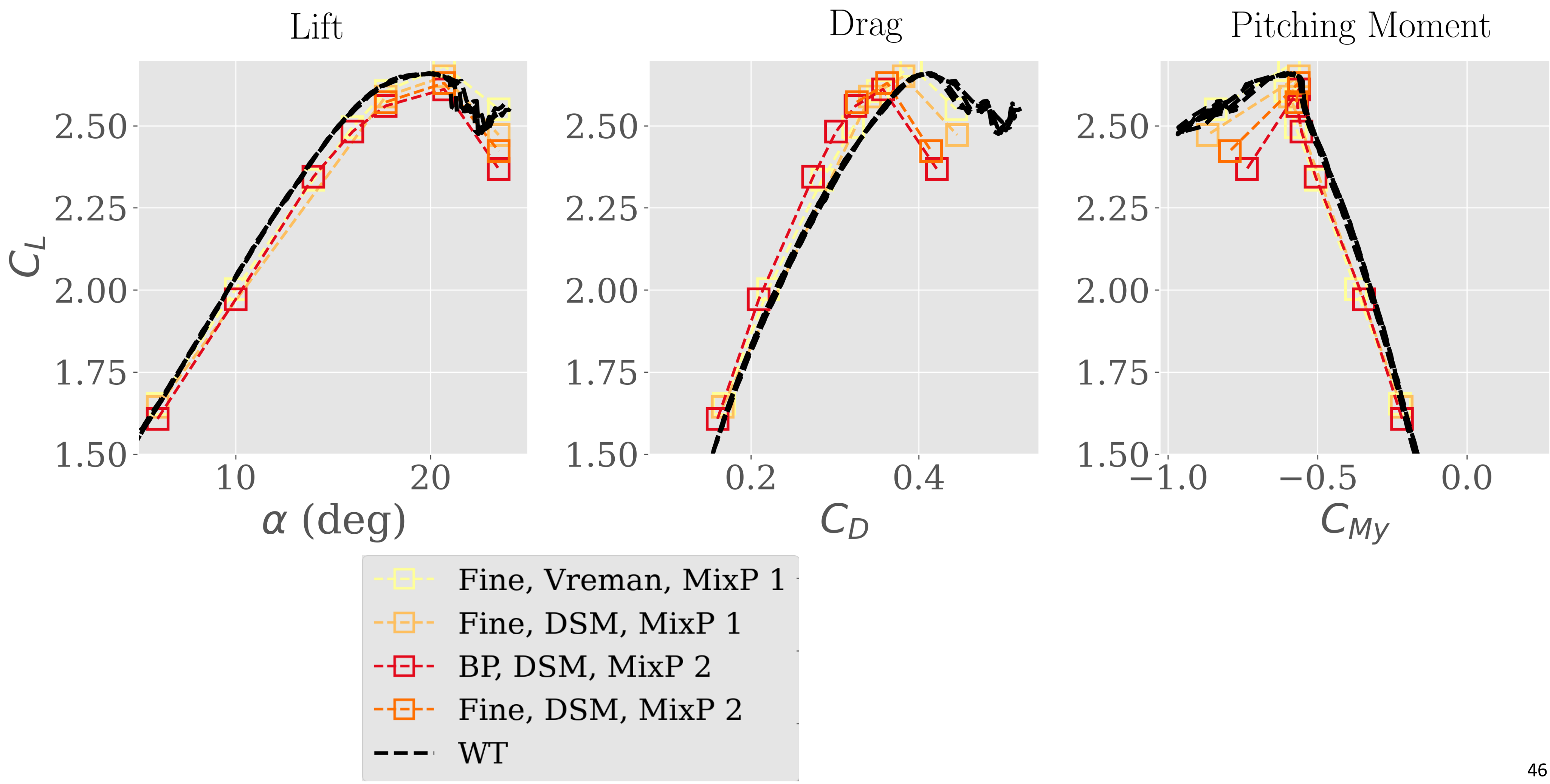
Case 2.3: W-005 Grid Resolution Study



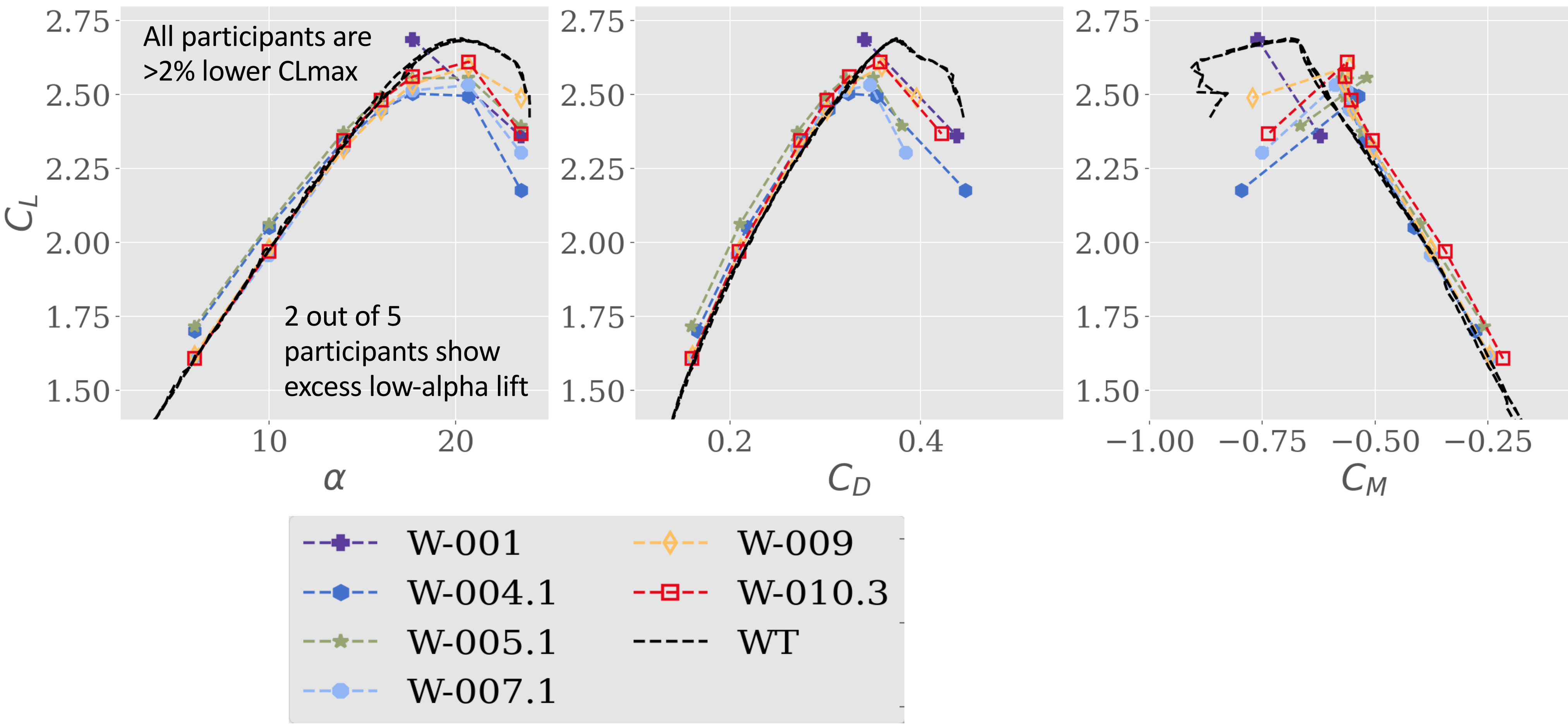
Case 2.3: W-010.1 Grid Resolution Study



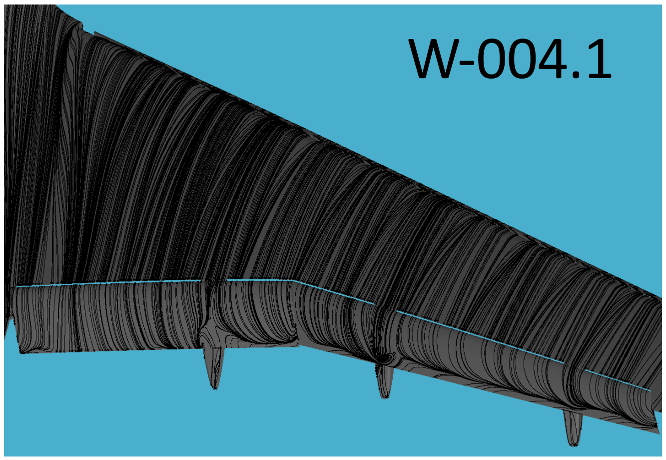
Case 2.3: W-010 SGS Closure & Precision Sensitivity



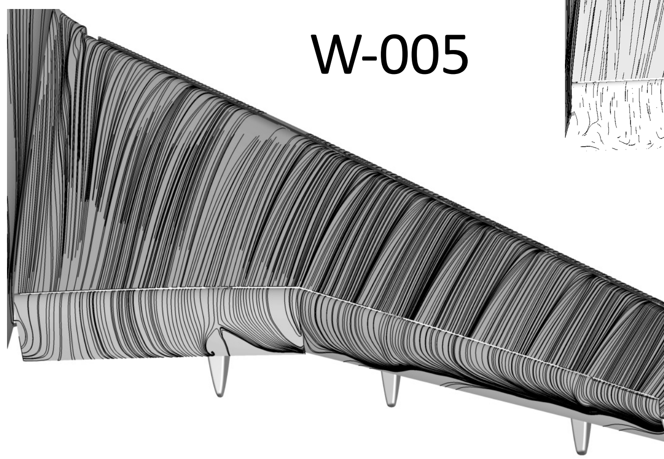
Case 2.3 Integrated F&M – All Submissions



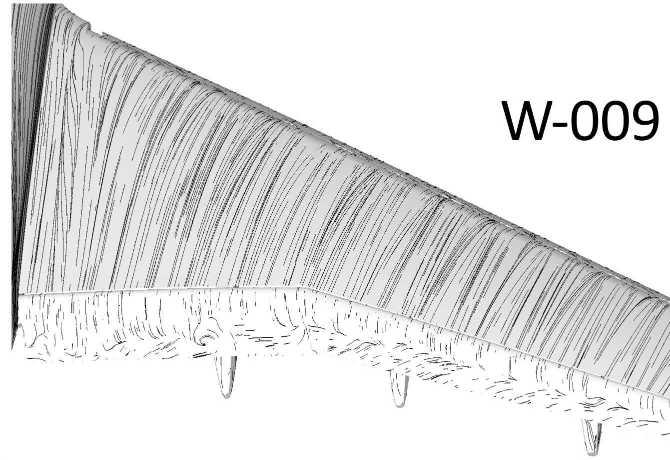
Case 2.3: Streamlines $\alpha = 6.0^{\circ}$



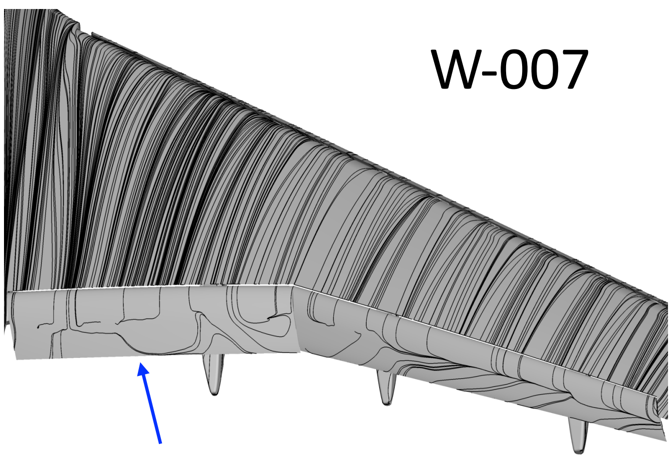
W-005



W-009

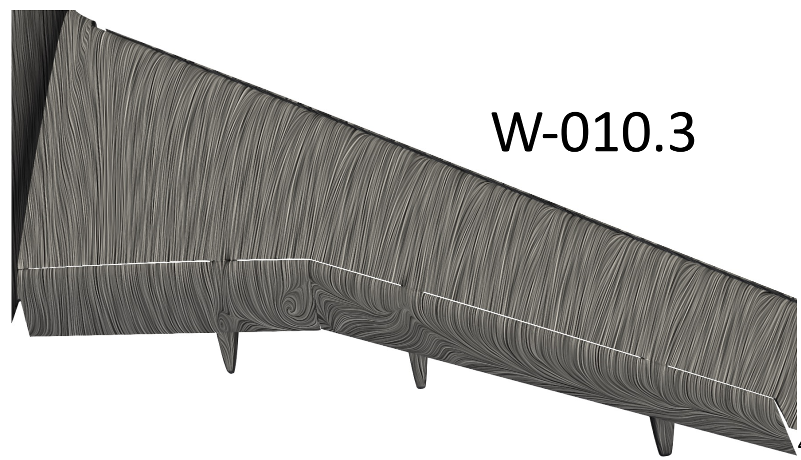


W-007



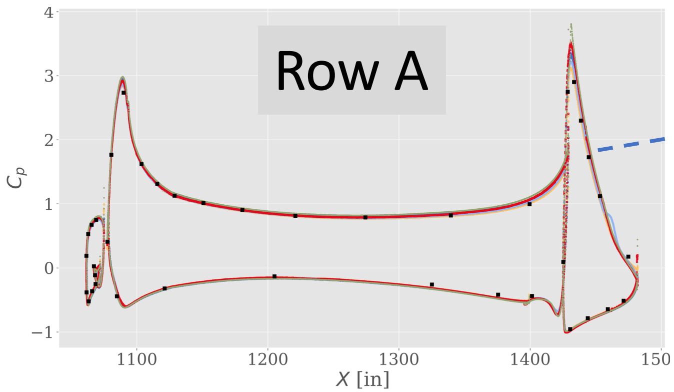
Shows separated flow on inboard flap

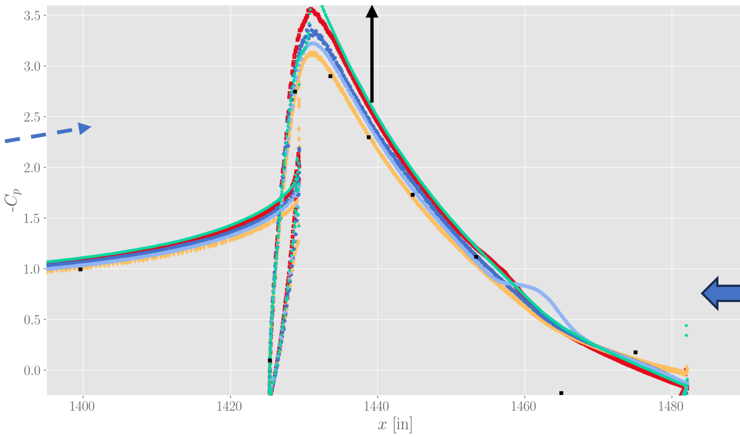
W-010.3

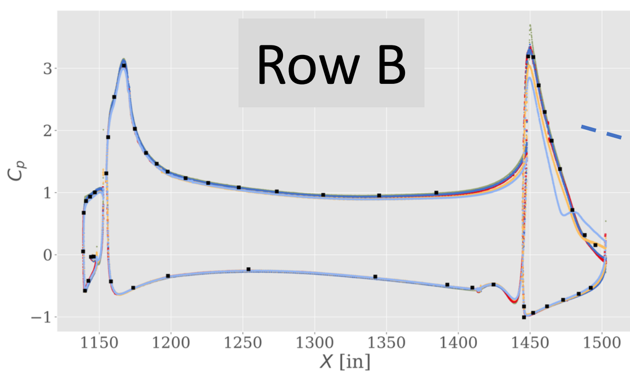


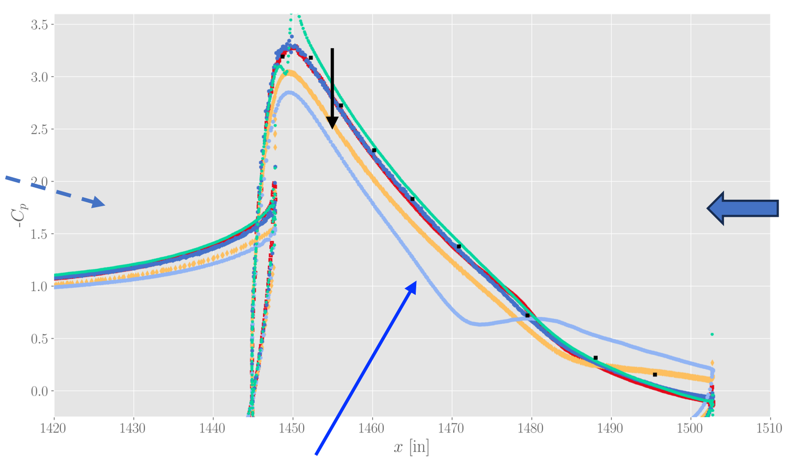
$\alpha = 6.0^o$

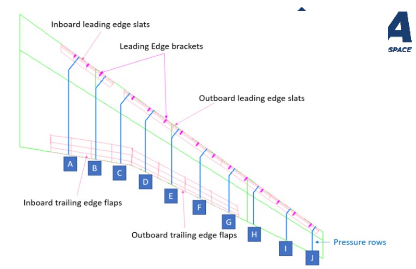
Case 2.3: Cp Cuts(in-board)











- W-004, W-005, W-007 and W-010 overpredict suction
- W-009 is accurate

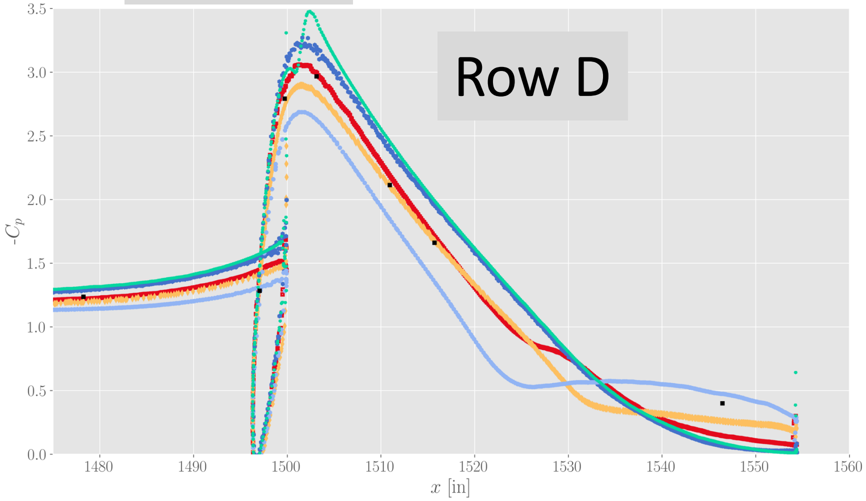
For in-board flap contribution to lift:
- W-004 overpredicts
- W-005 overpredicts
- W-007 has error cancellation – underpredicts
- W-009 underpredicts
- W-010 overpredicts

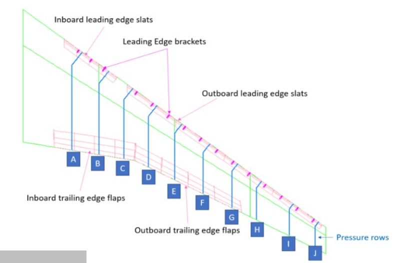
- W-004 and W-010 are accurate
- W-005 over-predicts suction peak
- W-007 & W-009 underpredict suction

Caused on spurious inboard flap separation (experiment shows no evidence inboard flap separation in cp)

α = 6.0°

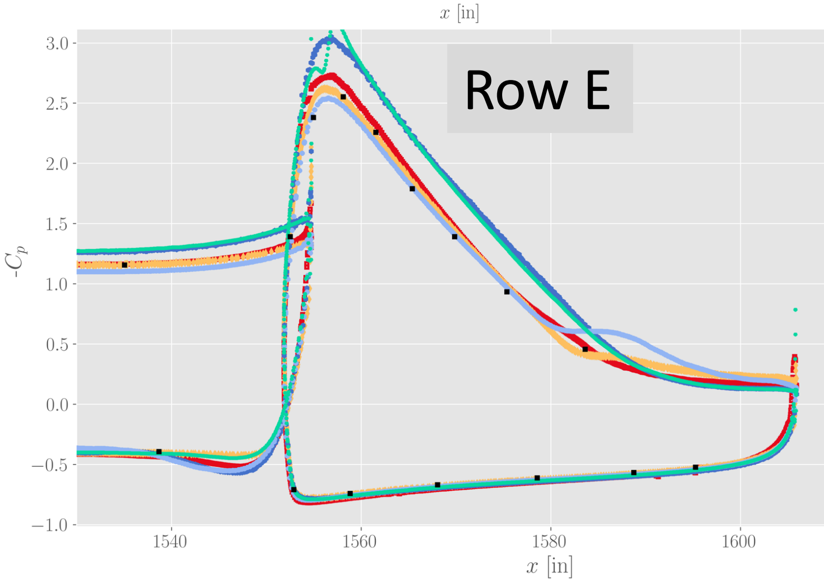
Case 2.3: Cp Cuts(out-board flaps)

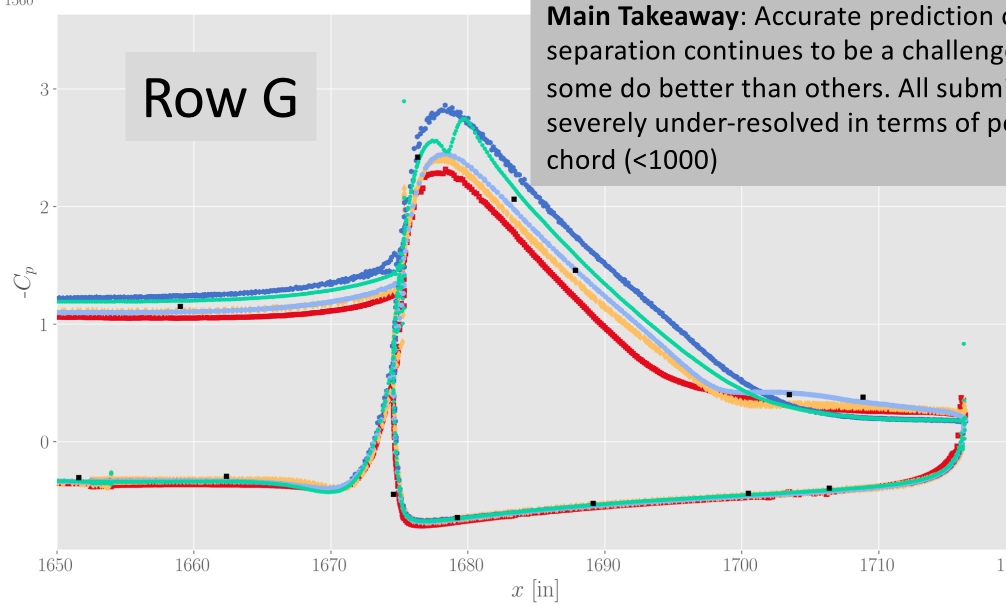




For out-board flap contribution to lift:

- W-004 and W-005 have large overprediction
- W-007 and W-009 have slight underprediction



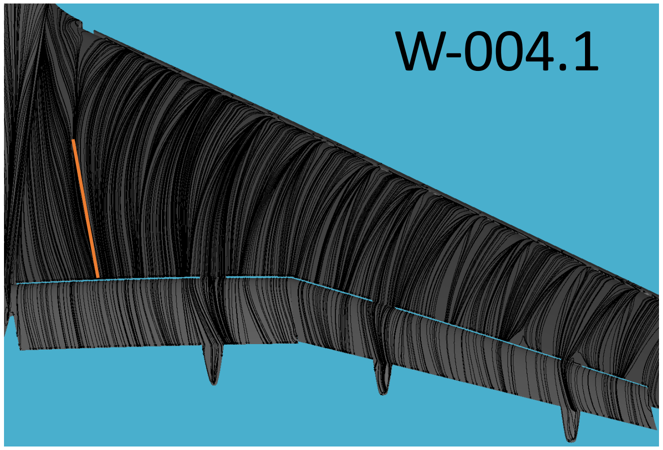


Main Takeaway: Accurate prediction of flap separation continues to be a challenge, although some do better than others. All submissions are severely under-resolved in terms of points-per-chord (<1000)

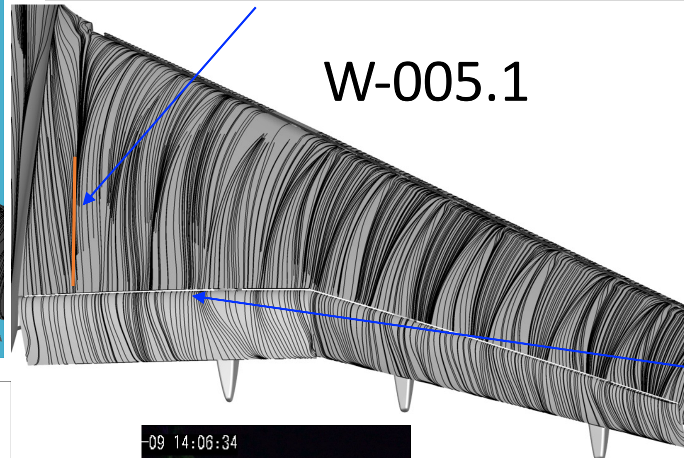
Case 2.3 – Low angle of attack Observations

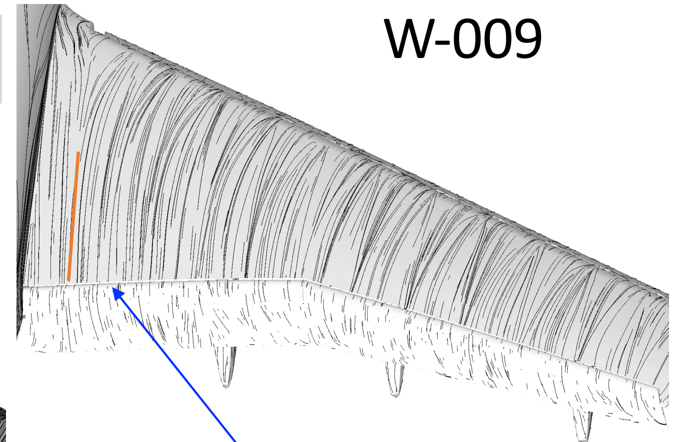
- Flap-separation dominates the low-alpha integrated loads
- W-009 appears to be reasonably accurate with little error-cancellation; potentially underpredicts the lift from inboard flap due to excess separation
- W-010 is reasonably accurate but shows more inboard-outboard flap error cancellation (higher lift on inboard flap, lower lift on outboard flap); hence predicts a more nose-up moment
- W-007 consistently underpredicts flap suction but has quite accurate overall-lift; refinement study is missing – current grid has coarsest flap resolution out of all participants
- W-004 and W-005 are overpredicting flap lift – much higher overprediction for the outboard flap than for the inboard flap
- All submissions are **severely under-resolved** on the flap in terms of "points-per-flap-chord" (<1000)
- These findings carry over to lower angles of attack for Case 2.4

Case 2.3: Streamlines $\alpha = 20.7^{\circ}$

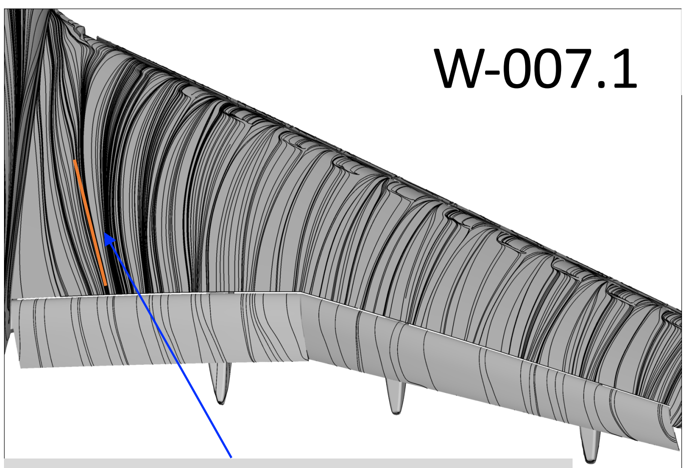


Participant's grid refinement suggested straightening of this streamline with refinement

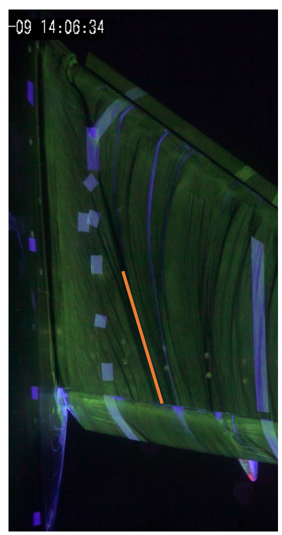


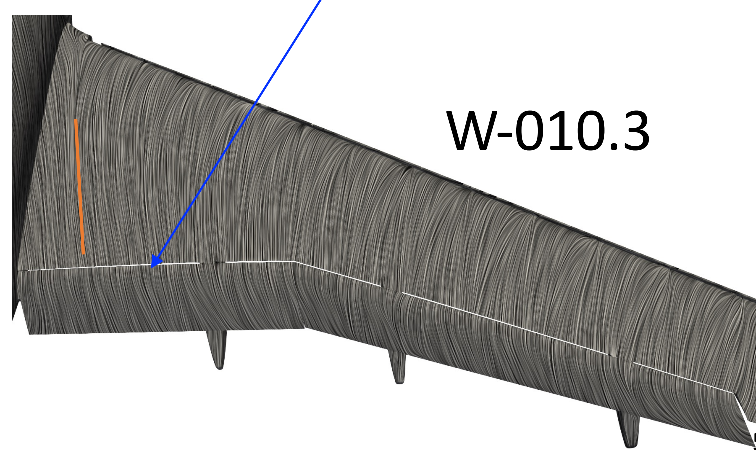


Overpredict inboard flap suction peaks

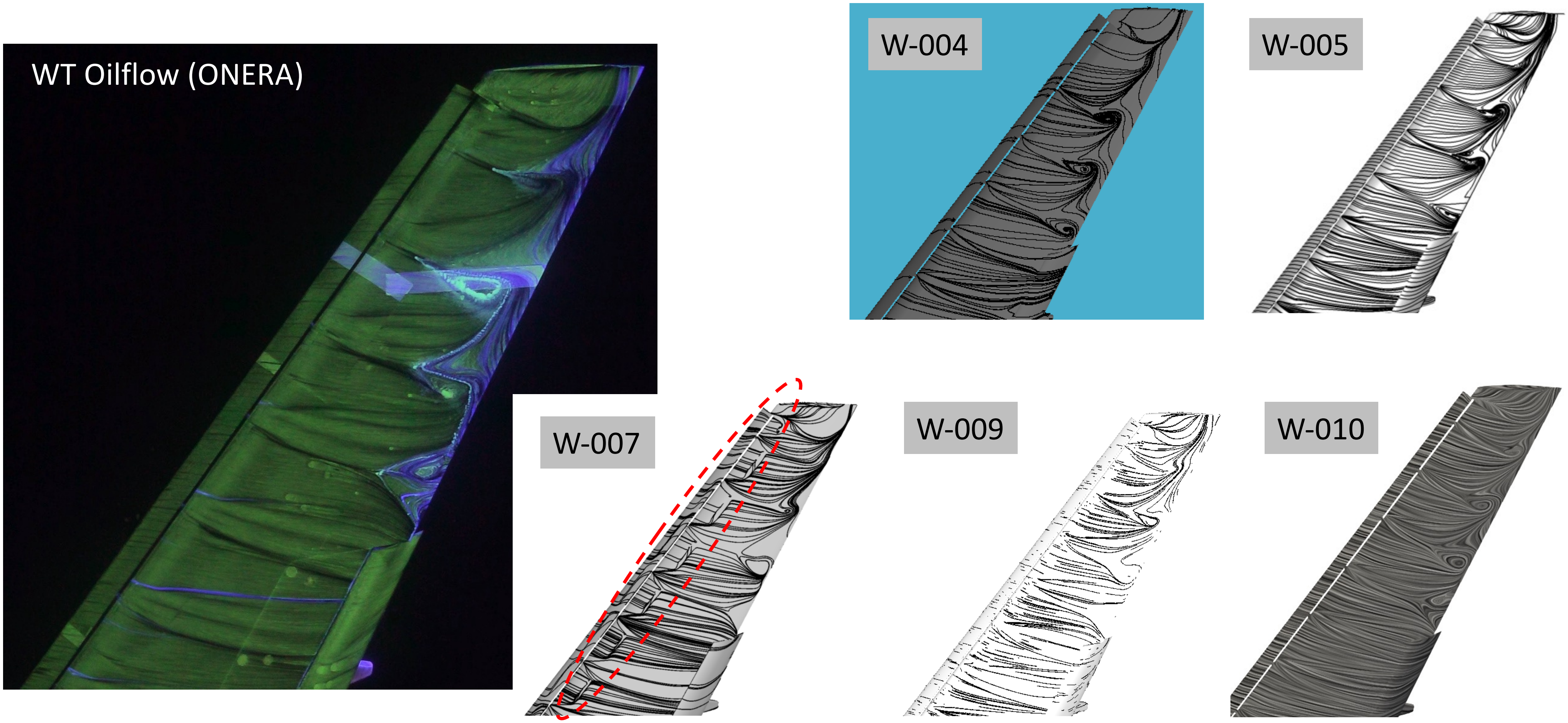


Wedge-shape formed by the streamline starting at the slat cut-out appears to be more consistent for W-004.1 and W-007





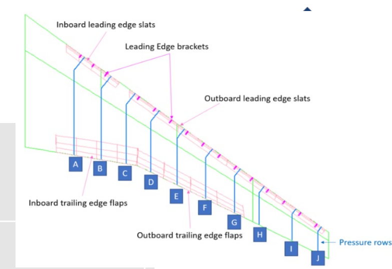
Case 2.3: Oilflow vs Streamlines $\alpha = 20.7^{o}$

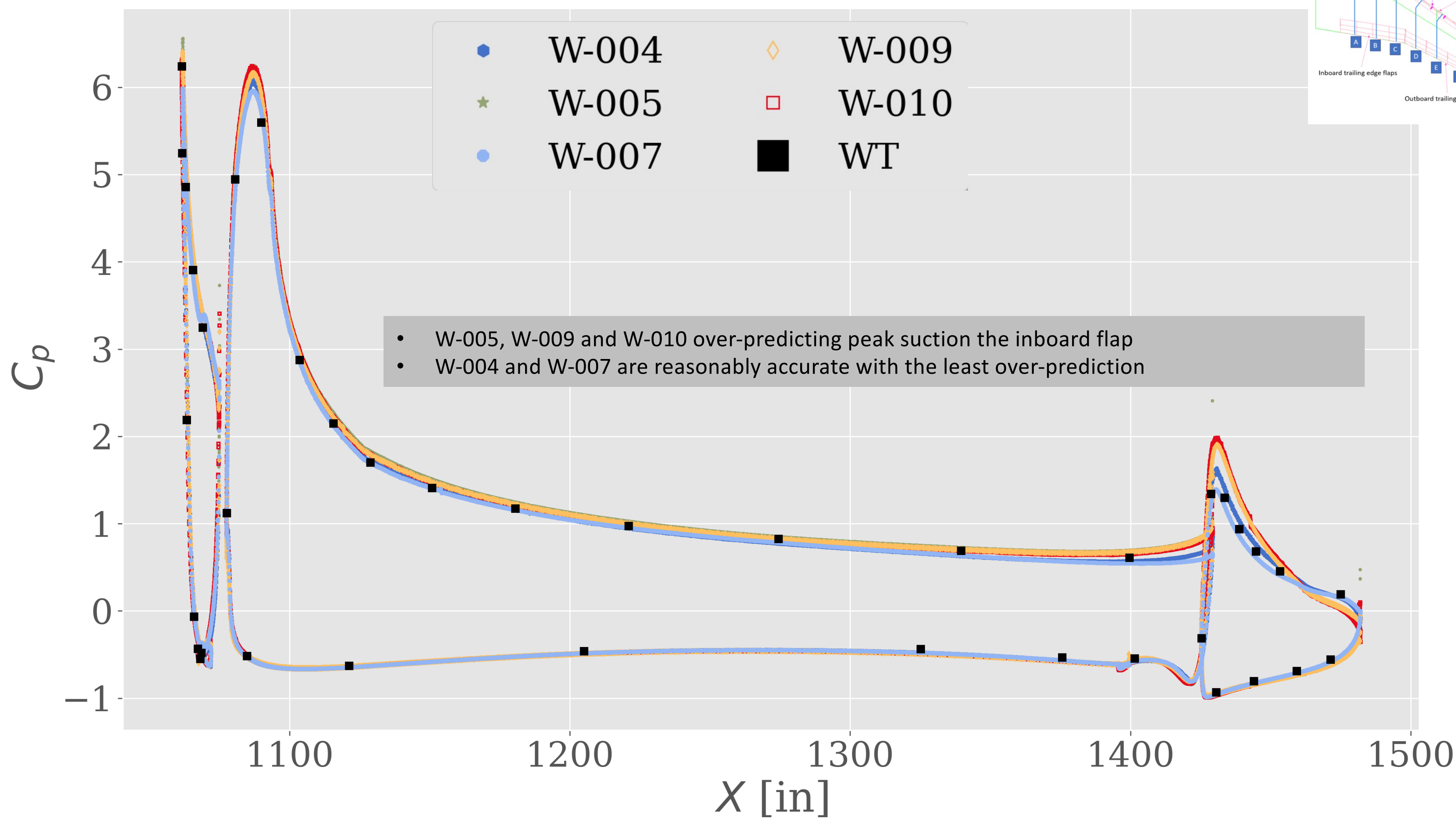


α = 20.7º

Case 2.3: Cp Cuts(in-board)

Row A

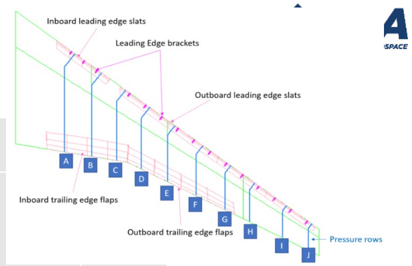


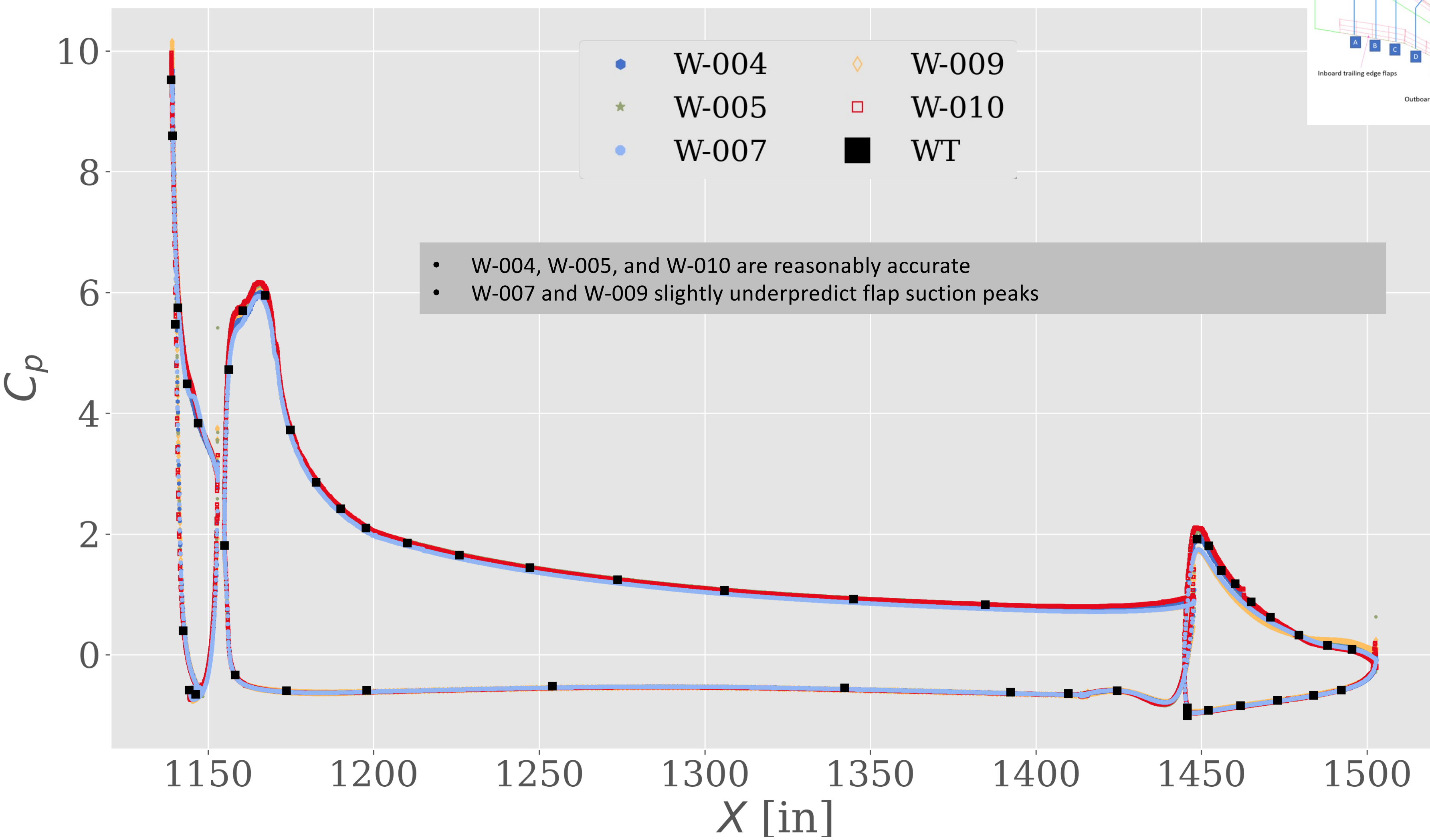


α = 20.7°

Case 2.3: Cp Cuts(in-board)

Row B



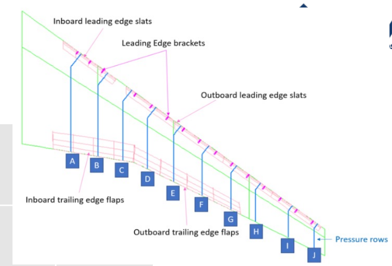


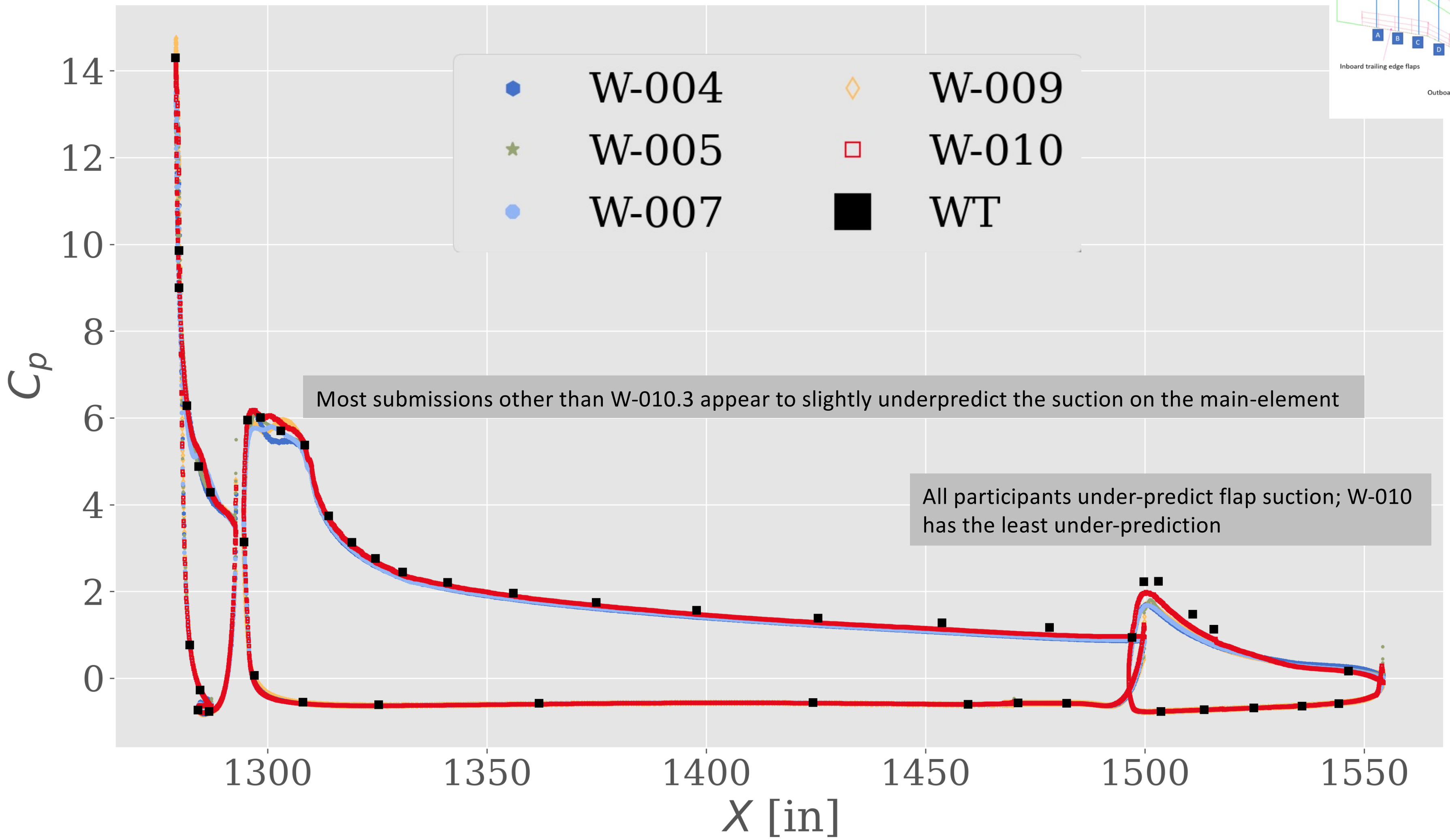
- W-004, W-005, and W-010 are reasonably accurate
- W-007 and W-009 slightly underpredict flap suction peaks

α = 20.7°

Case 2.3: Cp Cuts(mid-board)

Row D





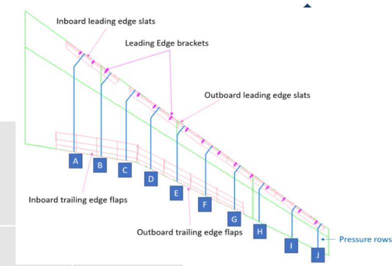
Most submissions other than W-010.3 appear to slightly underpredict the suction on the main-element

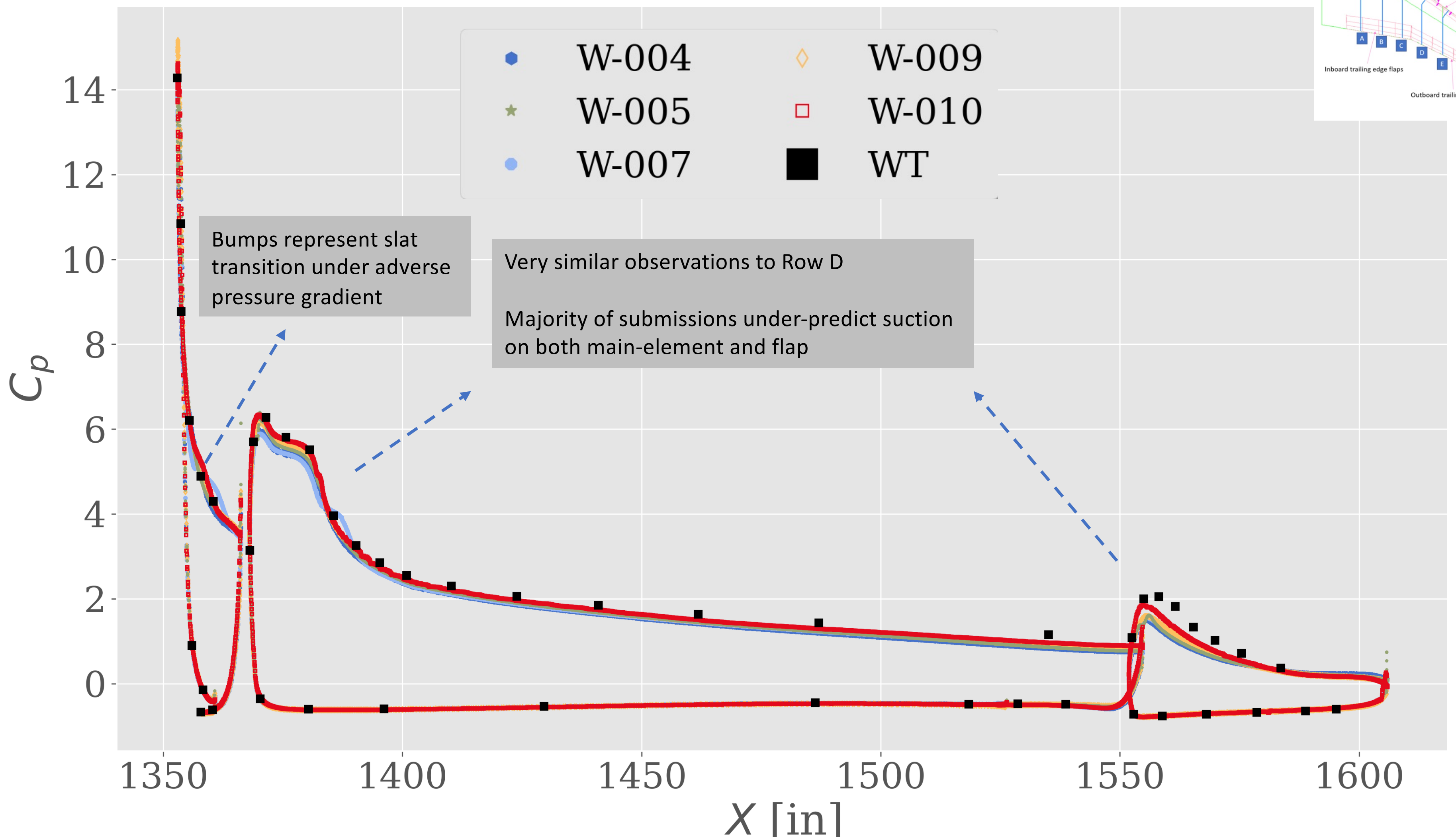
All participants under-predict flap suction; W-010 has the least under-prediction

α = 20.7°

Case 2.3: Cp Cuts(out-board)

Row E

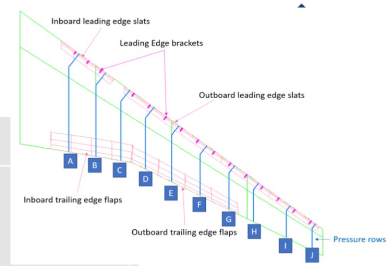


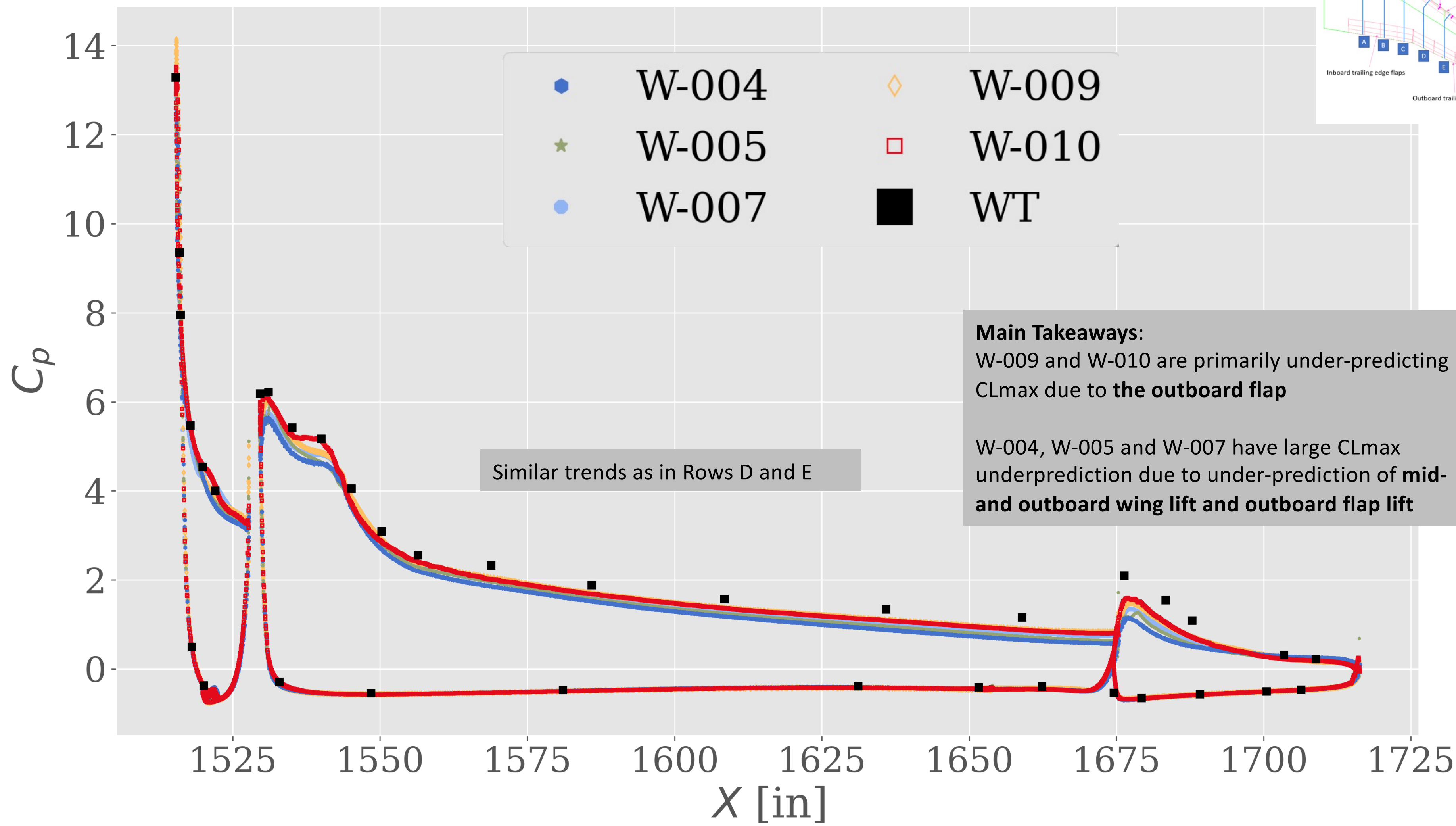


α = 20.7°

Case 2.3: Cp Cuts(out-board)

Row G





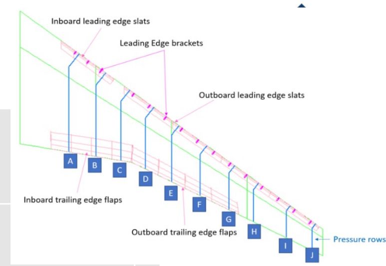
Main Takeaways:
W-009 and W-010 are primarily under-predicting CLmax due to **the outboard flap**

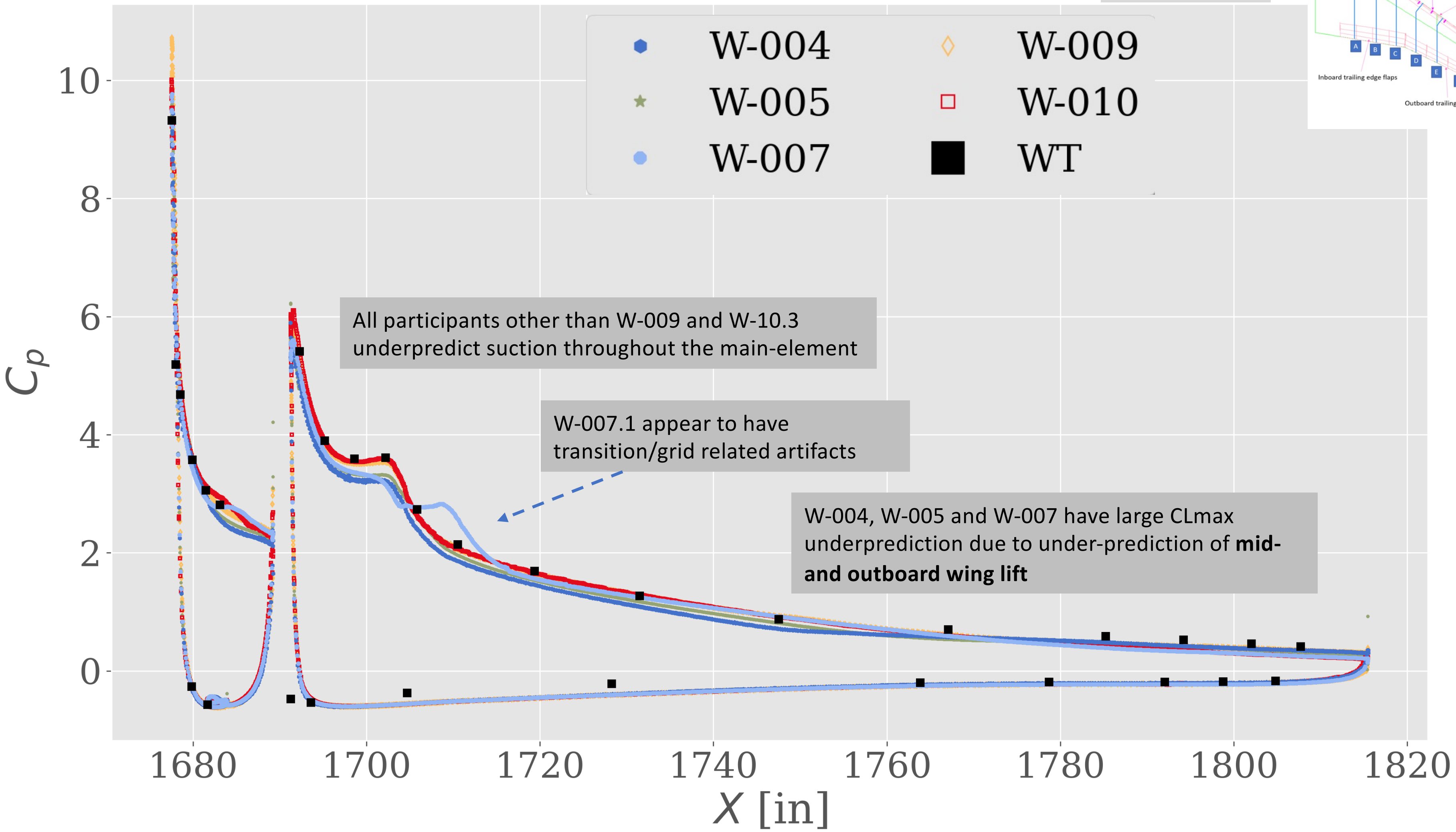
W-004, W-005 and W-007 have large CLmax underprediction due to under-prediction of **mid- and outboard wing lift and outboard flap lift**

α = 20.7°

Case 2.3: Cp Cuts(out-board)

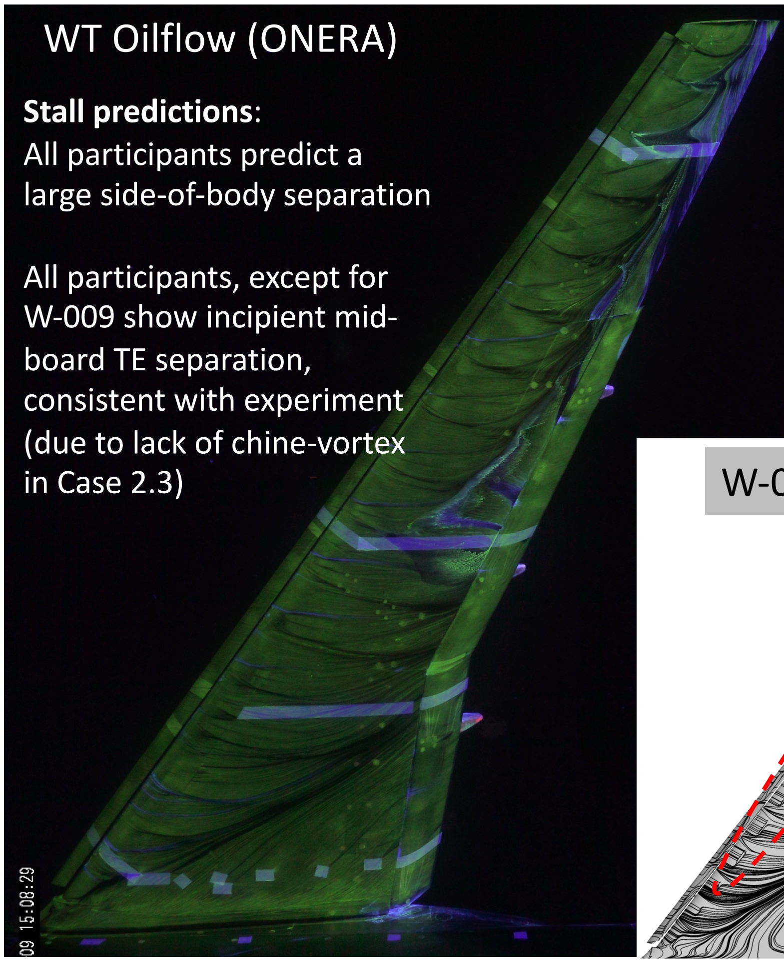
Row I





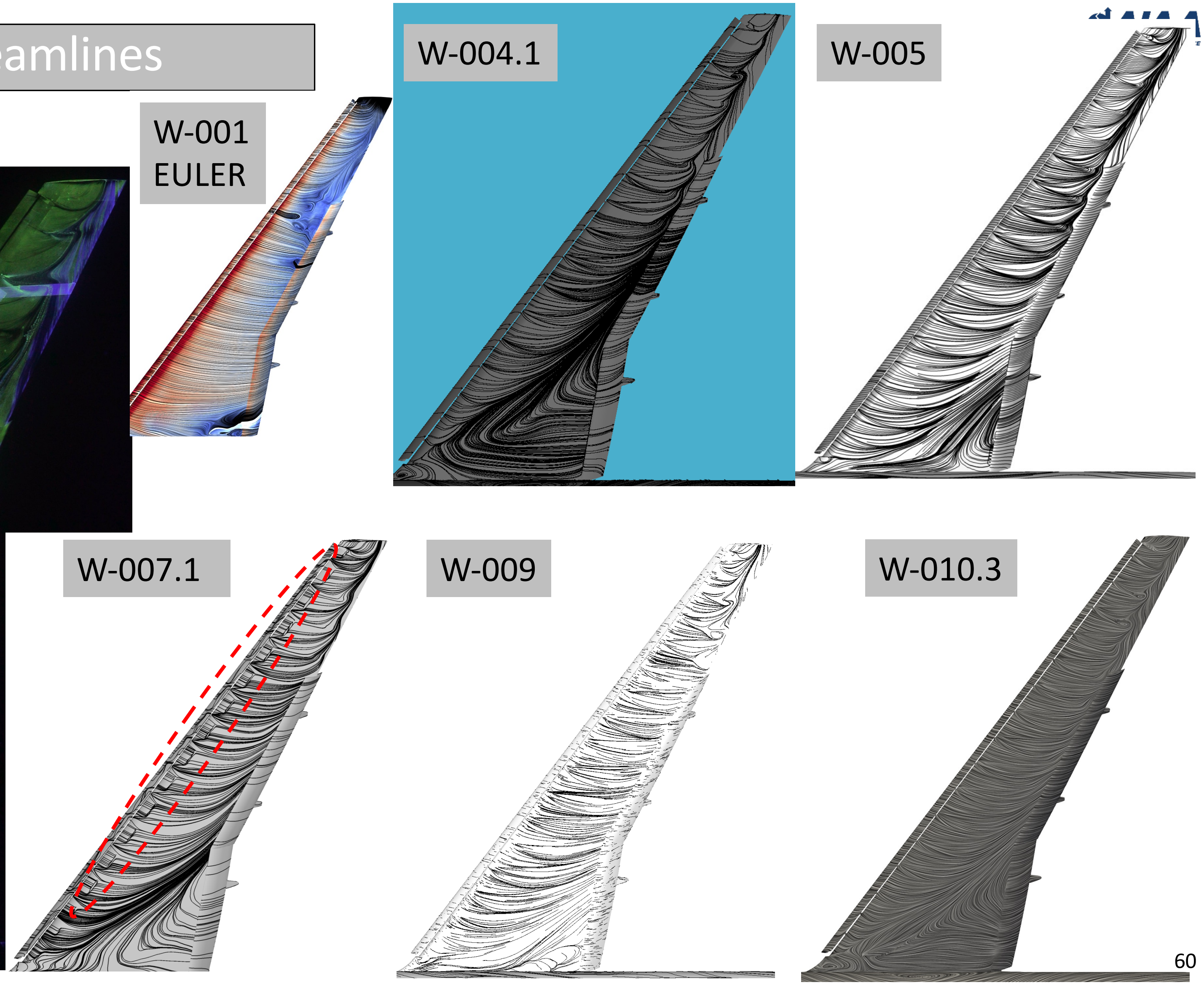
Case 2.3: Oilflow vs Streamlines

α = 23.5°



Stall predictions:
All participants predict a large side-of-body separation

All participants, except for W-009 show incipient mid-board TE separation, consistent with experiment (due to lack of chine-vortex in Case 2.3)



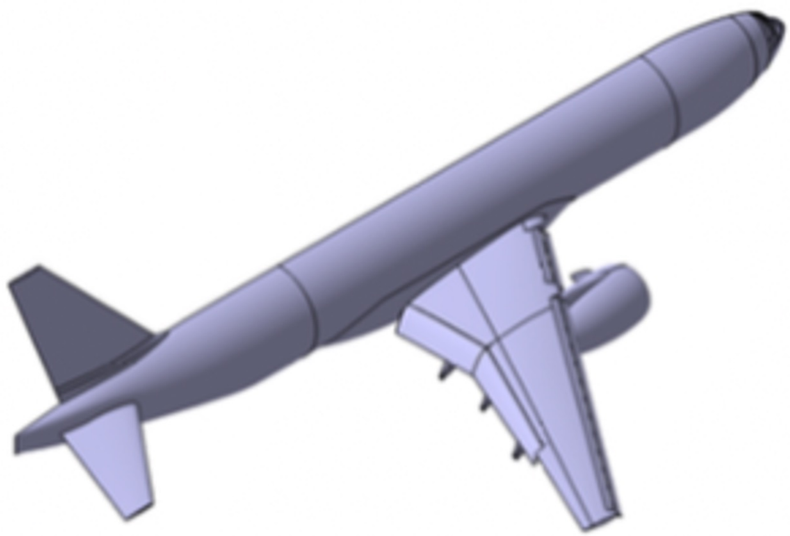
Case 2.3 – High Angle of Attack Observations

- 5 – submissions for full AoA sweep; only 1 submissions within reasonable error margin at CLmax:
  - Caveat: W-010 submission has less CLmax error but does show some inboard-outboard error cancellation; lift is correct but pitching moment is too nose-up
  - W-010 as well as W-009 and W-005 show over-prediction of inboard flap suction peaks
  - W-004.1 and W-007 show better agreement for wing-root suction peaks; but show large underpredictions for the outboard wing
  - All submissions (including W-010) show under-prediction of lift on the outboard flap -> consistent with systematically excess nose-up pitching moment in all submissions

- All submissions show correct qualitative stall-onset mechanism – with separation occurring at the wing-root

- W-001 (Euler) is substantially less accurate compared to other WMLES participants

Case 2.4



Case 2.4: ONERA_LRM-LDG-HV

Participant ID	Solver	Coarse Grid	Medium Grid	Fine Grid	Blind Submission?
W-001	Adaptive Euler	228K*			YES
W-005.1	FUN3D (FV)	304M	998M	2.33B*	YES
W-005.2	FUN3D (FEM)	131M*			YES
W-005.3	FUN3D(FV)			419M*	NO
W-006	hpMusic	72M (DOF)	126M*	201M	YES
W-012	NSU3D	131M*			YES
W-013	SU2	131M*			YES
W-014	FLUENT			986M*	NO
W-004.1	CharLES (DSM)	168M	645M*	2.53B	YES
W-004.2	CharLES (Vr)		645M*		YES
W-007	LAVA	147M	325M	573M*	YES
W-009	PowerFLOW			575M*	YES
W-010.1	Volcano ScaLES (Vr)	436M	678M	1.26B*	YES
W-010.3	Volcano ScaLES (DSM)			1.08B*	YES

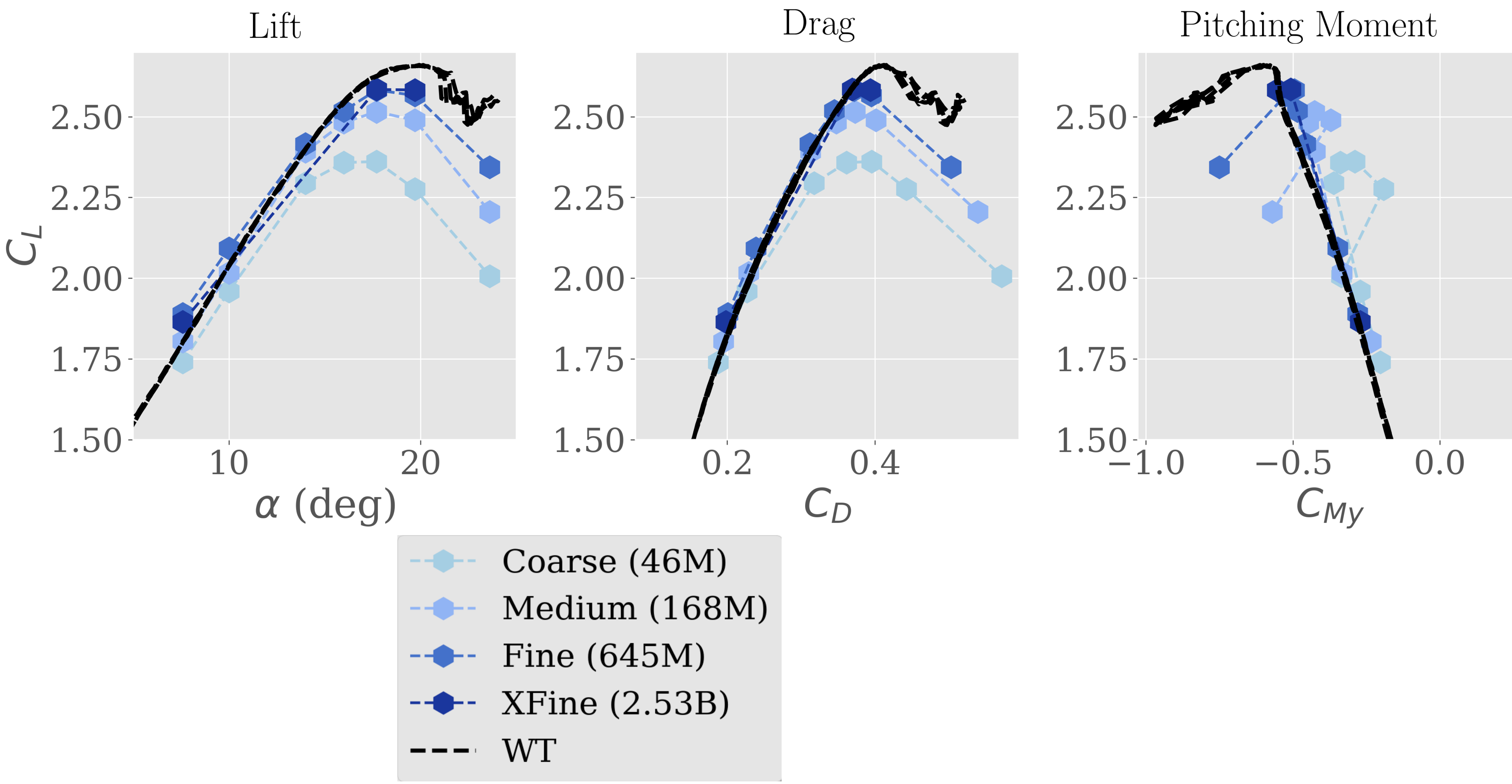
Angle of Attack (AoA)

Case 2.1: 6º , 10º , 12º , 13º , 14º
Case 2.2: 6º , 10º , 17.7º , 20º , 21.5º , 23º , 23.8º
Case 2.3: 6º , 10º , 14º , 16º , 17.7º , 20.7º , 23.5º
Case 2.4: 7.6º , 10º , 14º , 16º , 17.7º , 19.7º , 23.6º

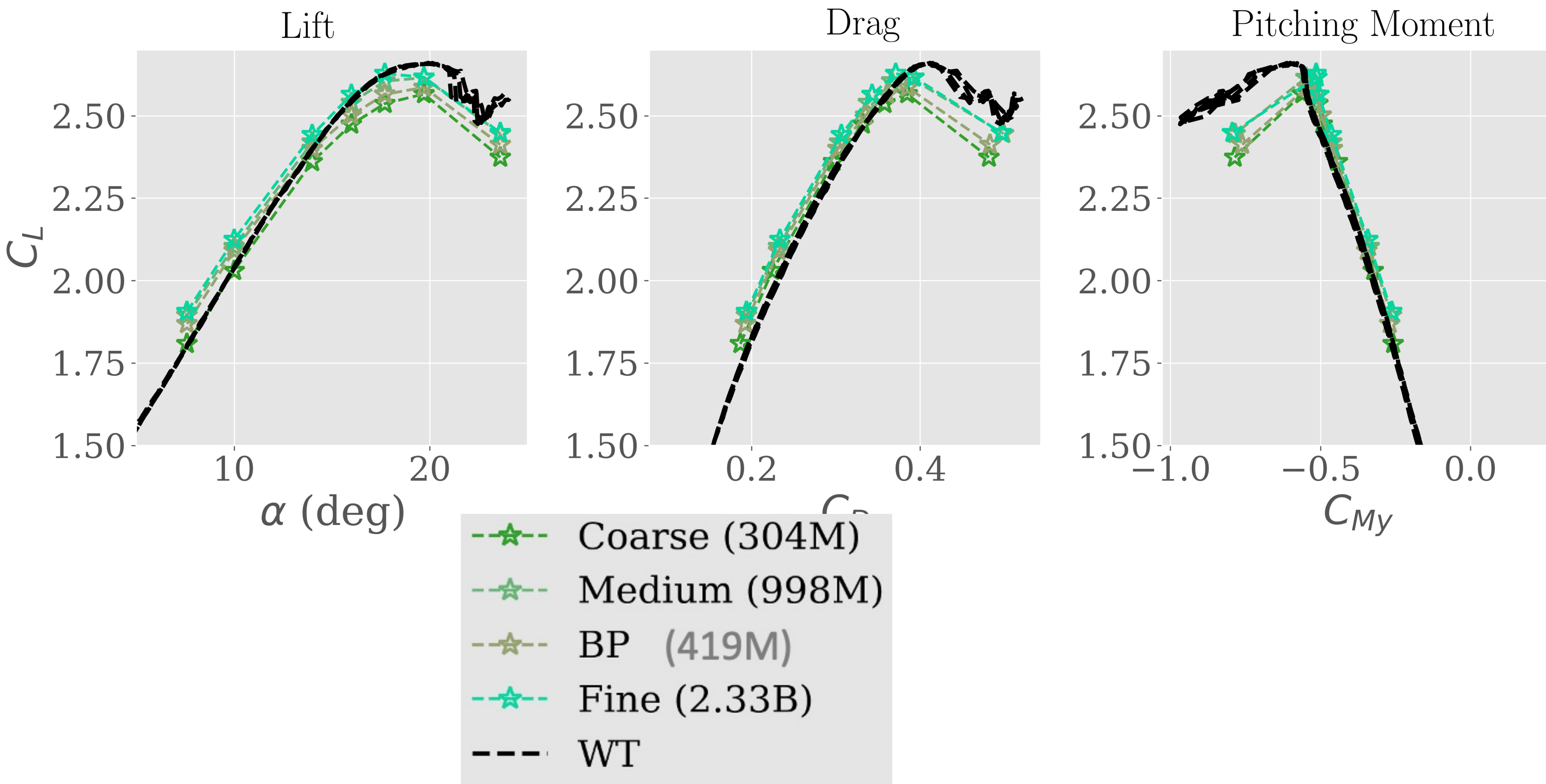
Wind Tunnel (WT) data is provided by ONERA

**Nominal grid used by participants. Presented grid size unless otherwise mentioned.*

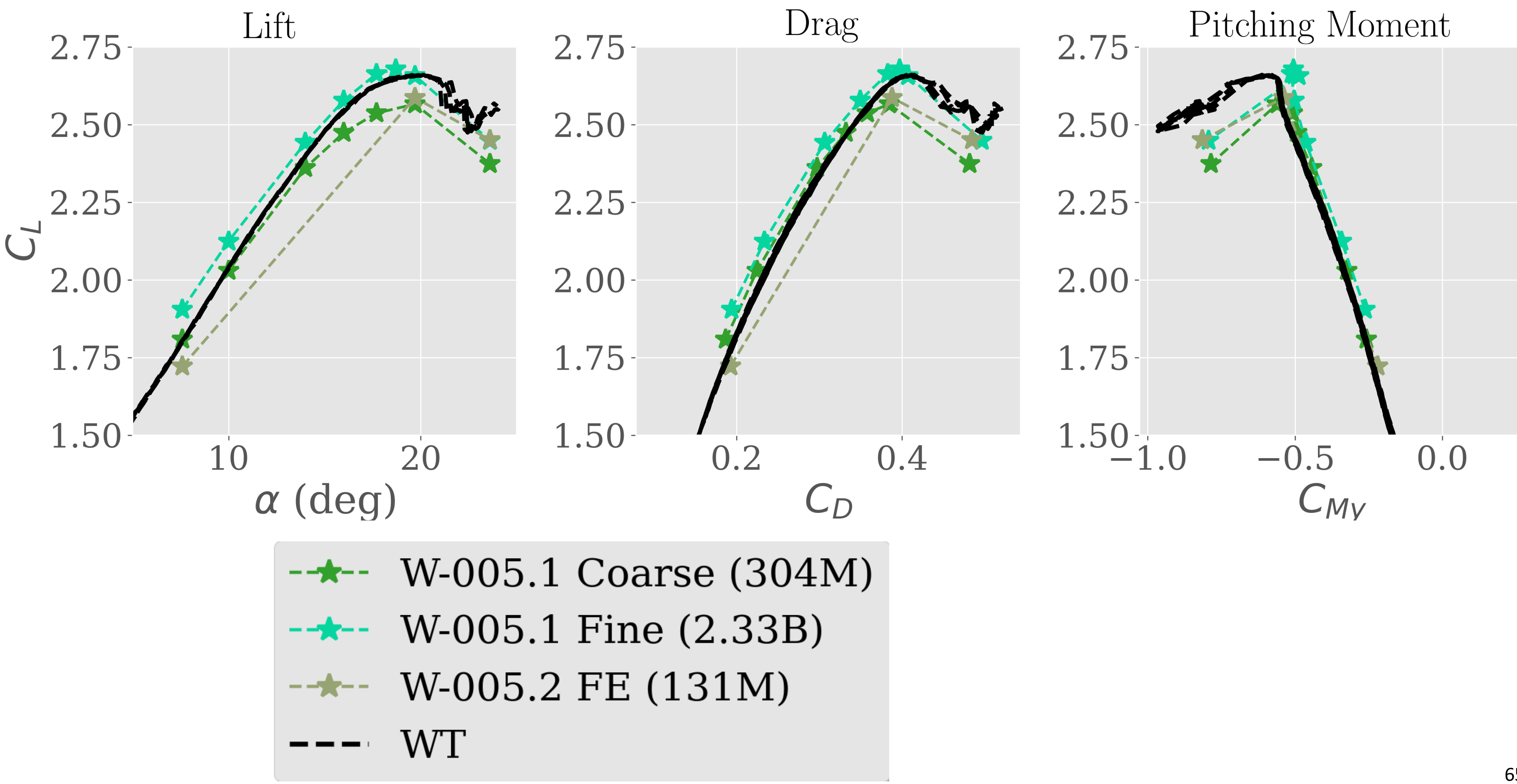
Case 2.4: W-004.1 Grid Resolution Study



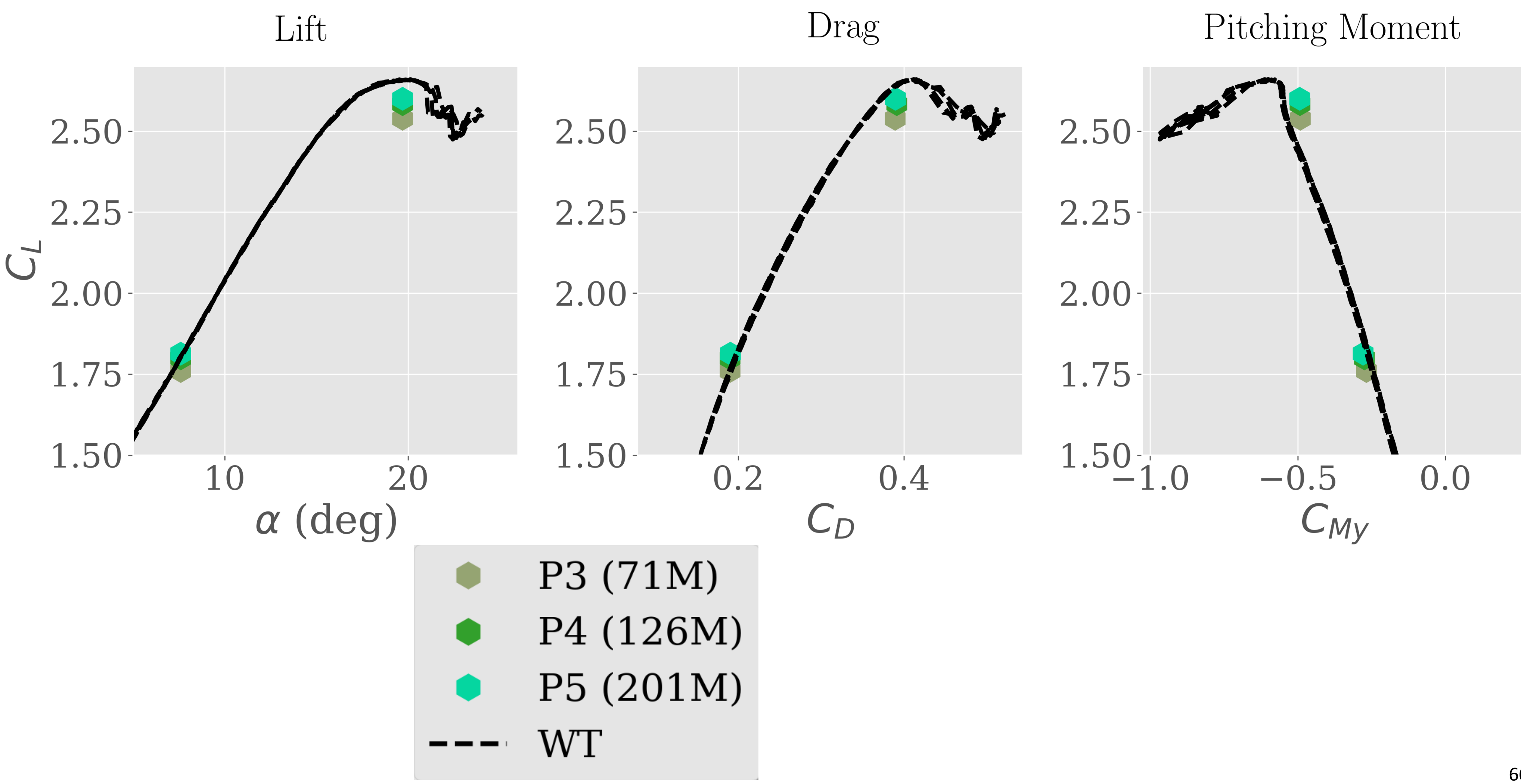
Case 2.4: W-005 Grid Resolution Study



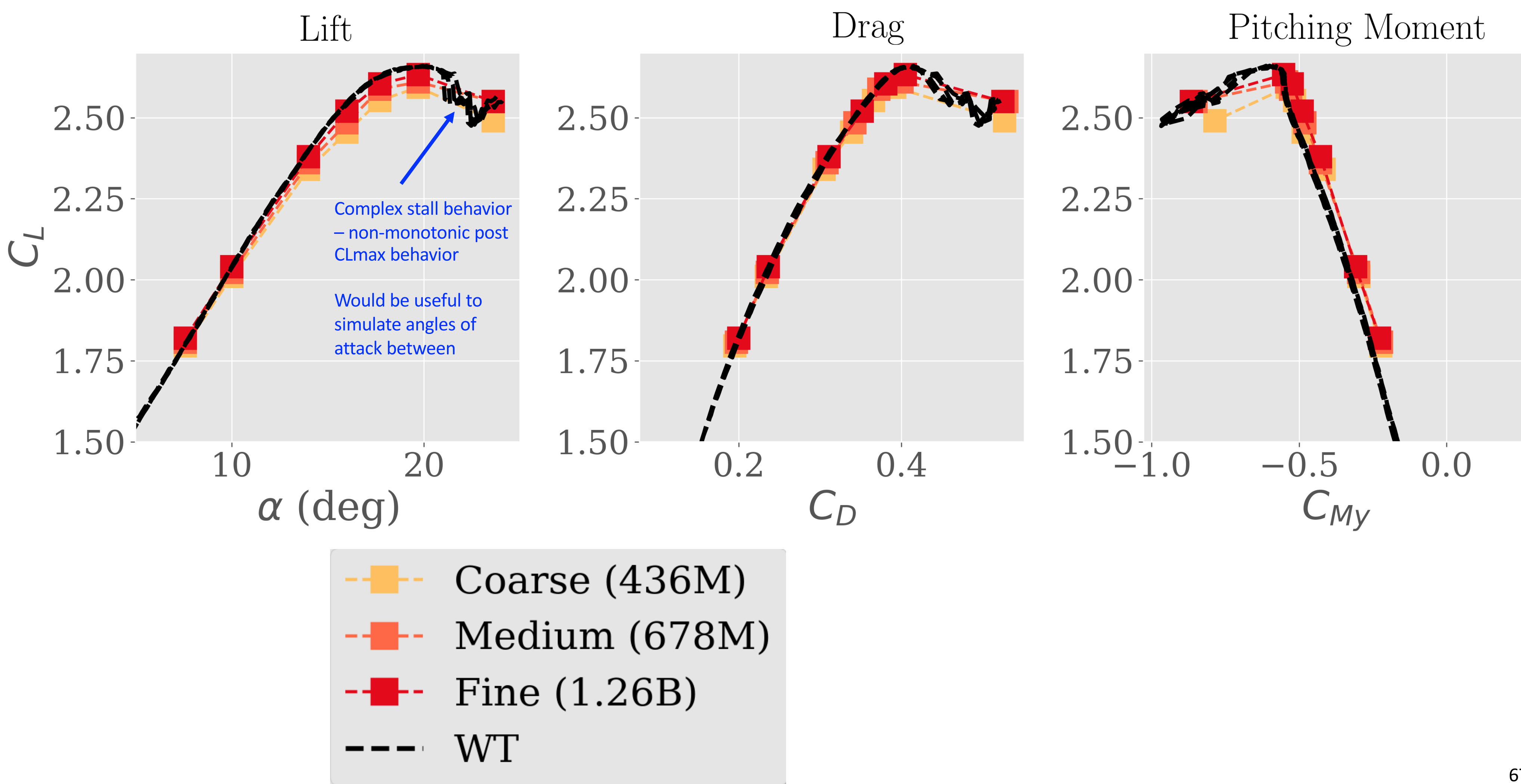
Case 2.4: W-005.1 (Finite Volume) vs W-005.2 (Finite Element)



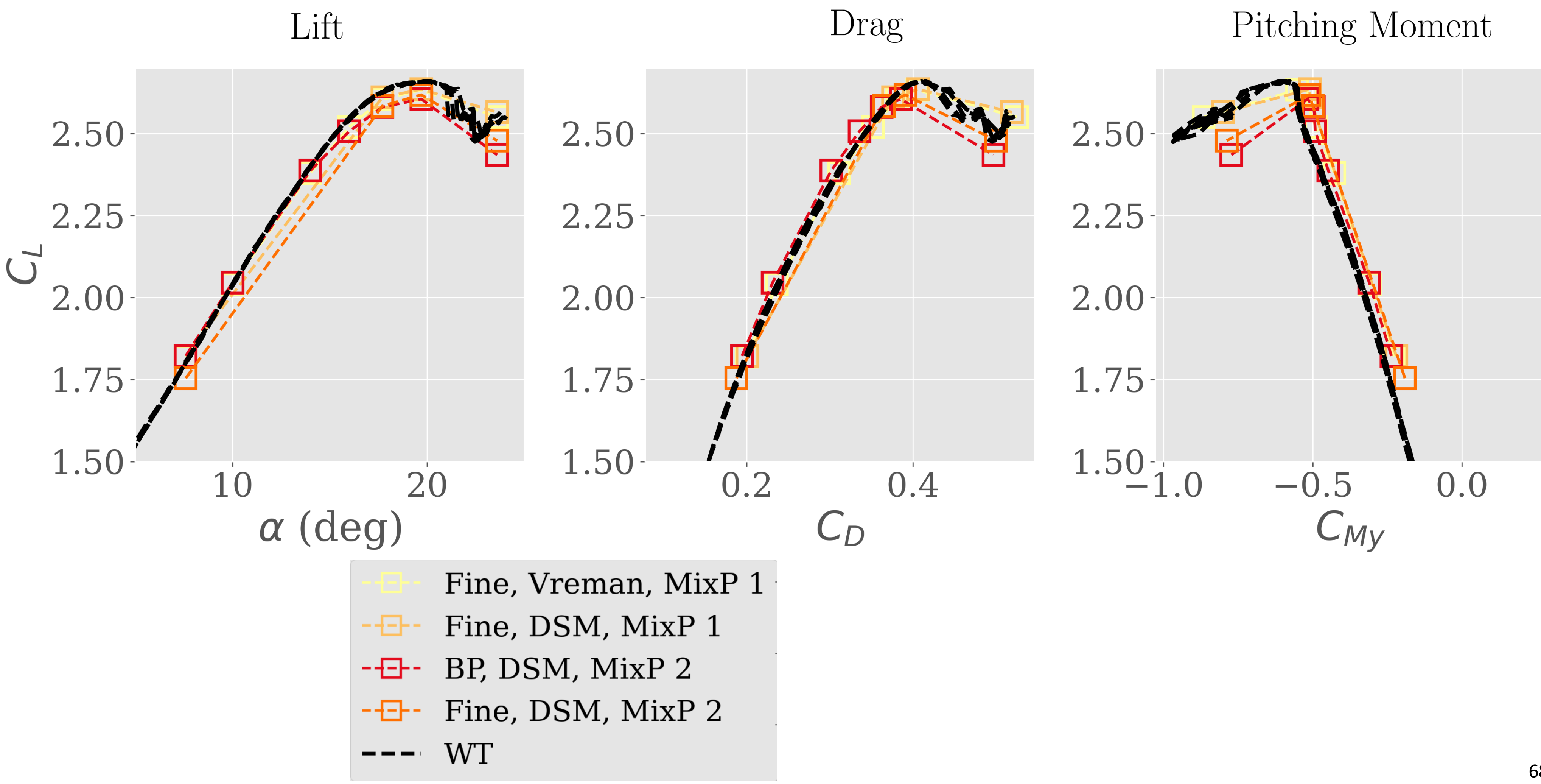
Case 2.4: W-006 Grid Resolution Study



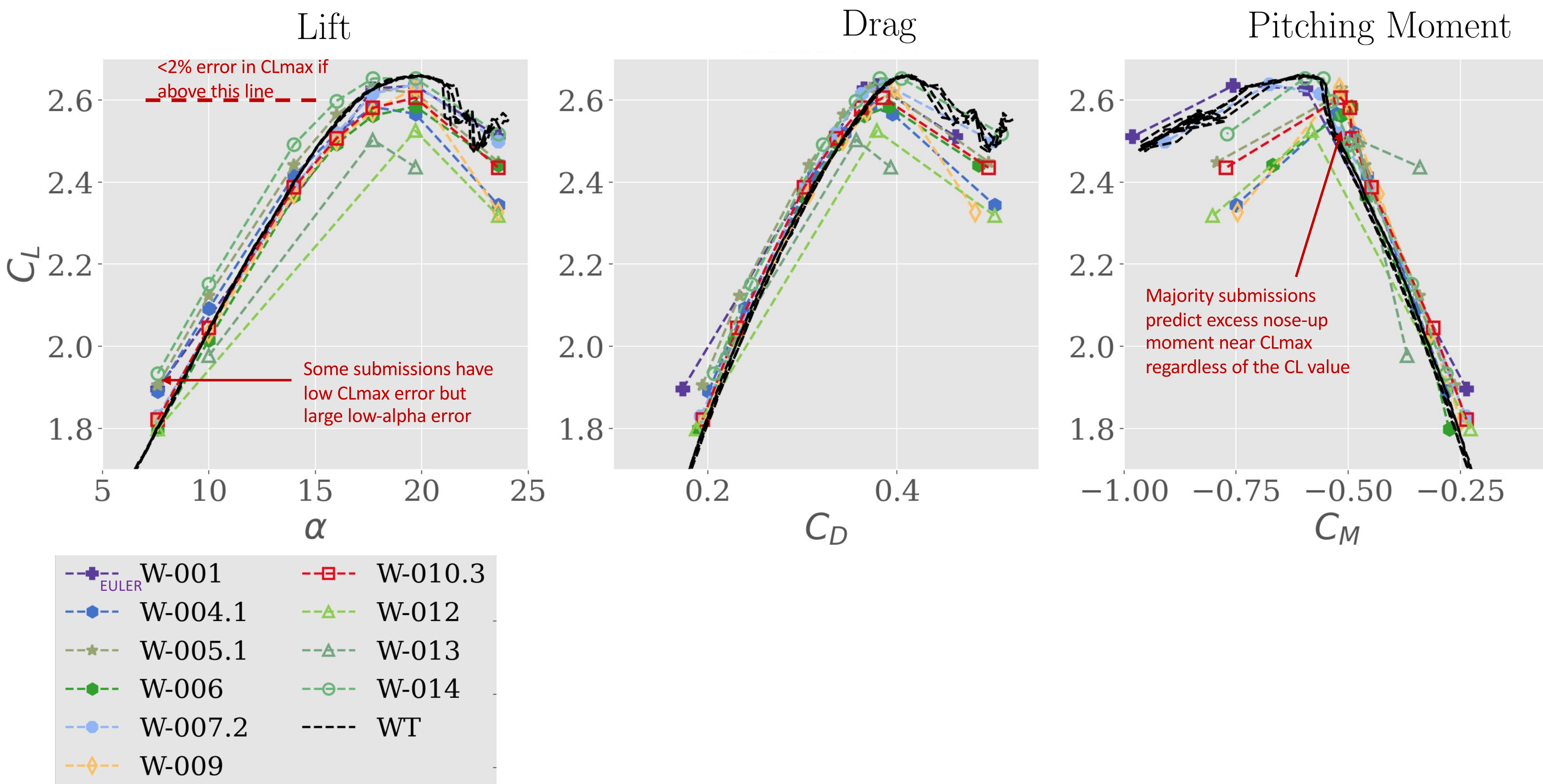
Case 2.4: W-010.1 Grid Resolution Study



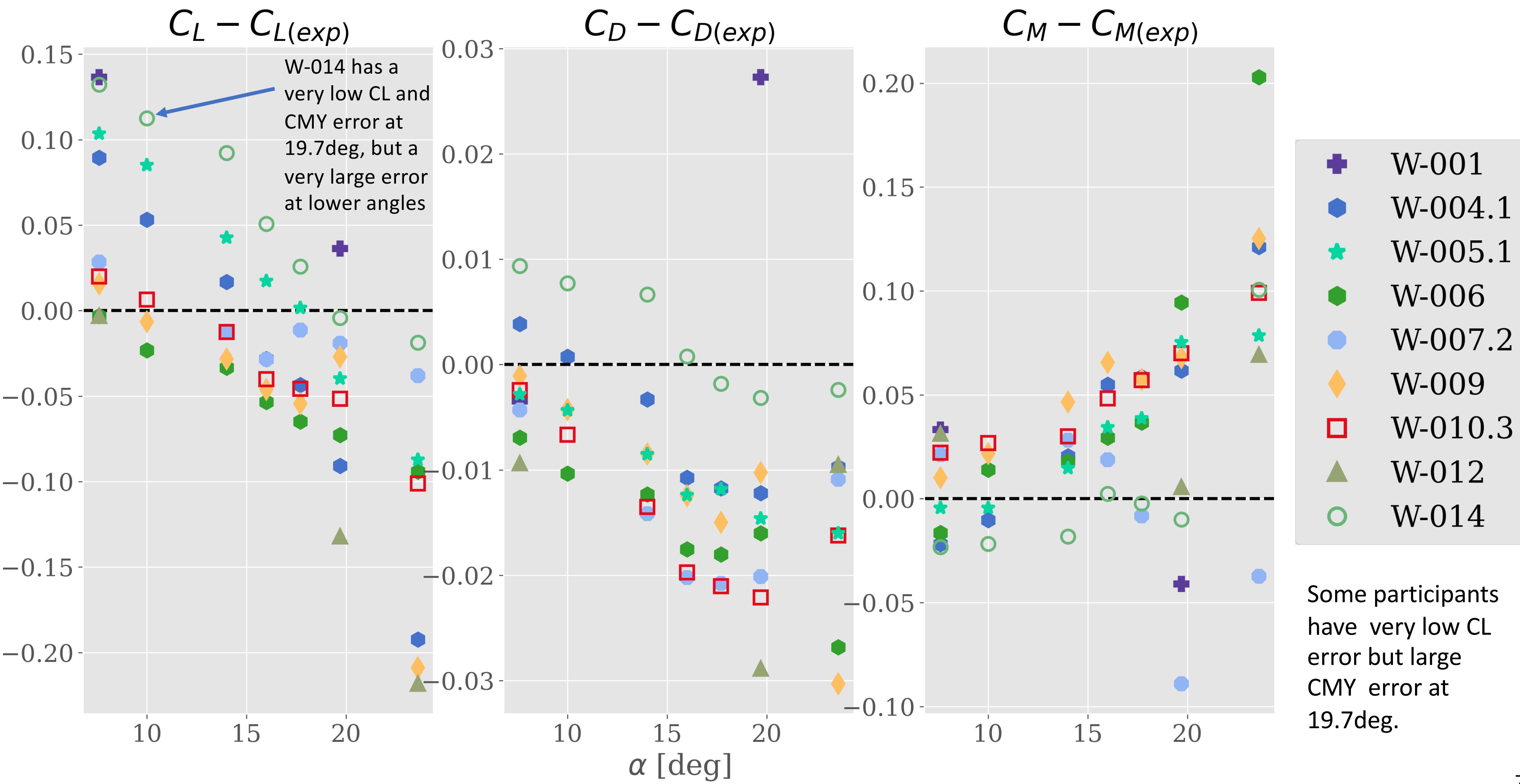
Case 2.4: W-010 SGS Closure & Precision Sensitivity



Case 2.4 Integrated F&M – All Submissions

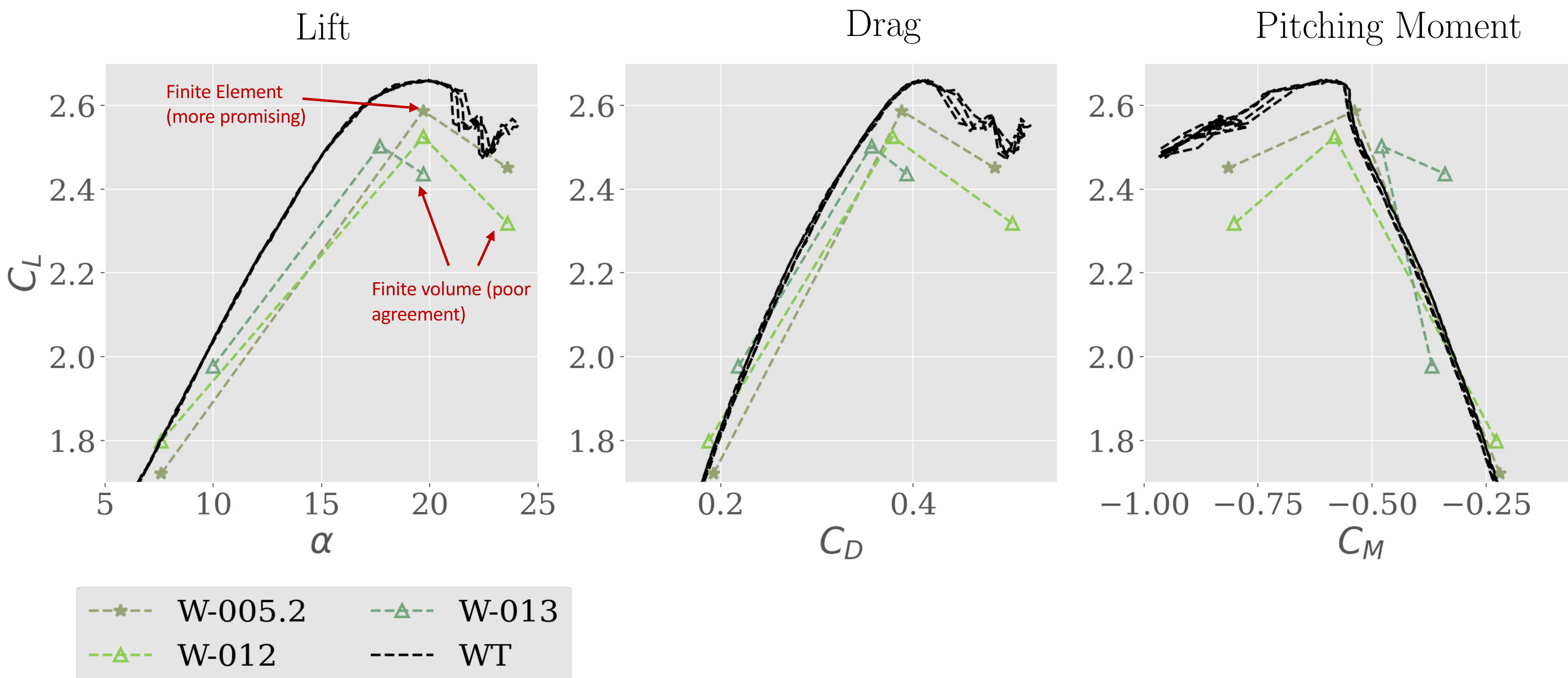


Δ Difference: (Prediction – Experiment)



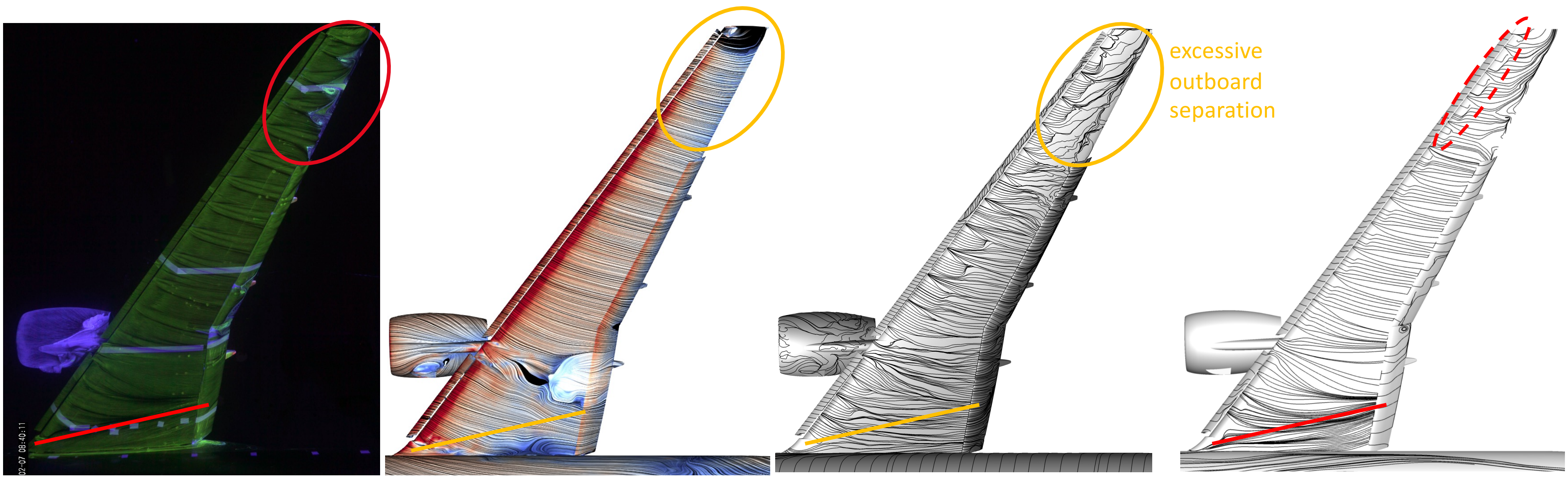
Some participants have very low CL error but large CMY error at 19.7deg.

Submissions using coarse-committee grid (mixed element, 131M)



Case 2.4: Oilflow vs Streamlines. α = 19.7° Coarse Grid Solutions

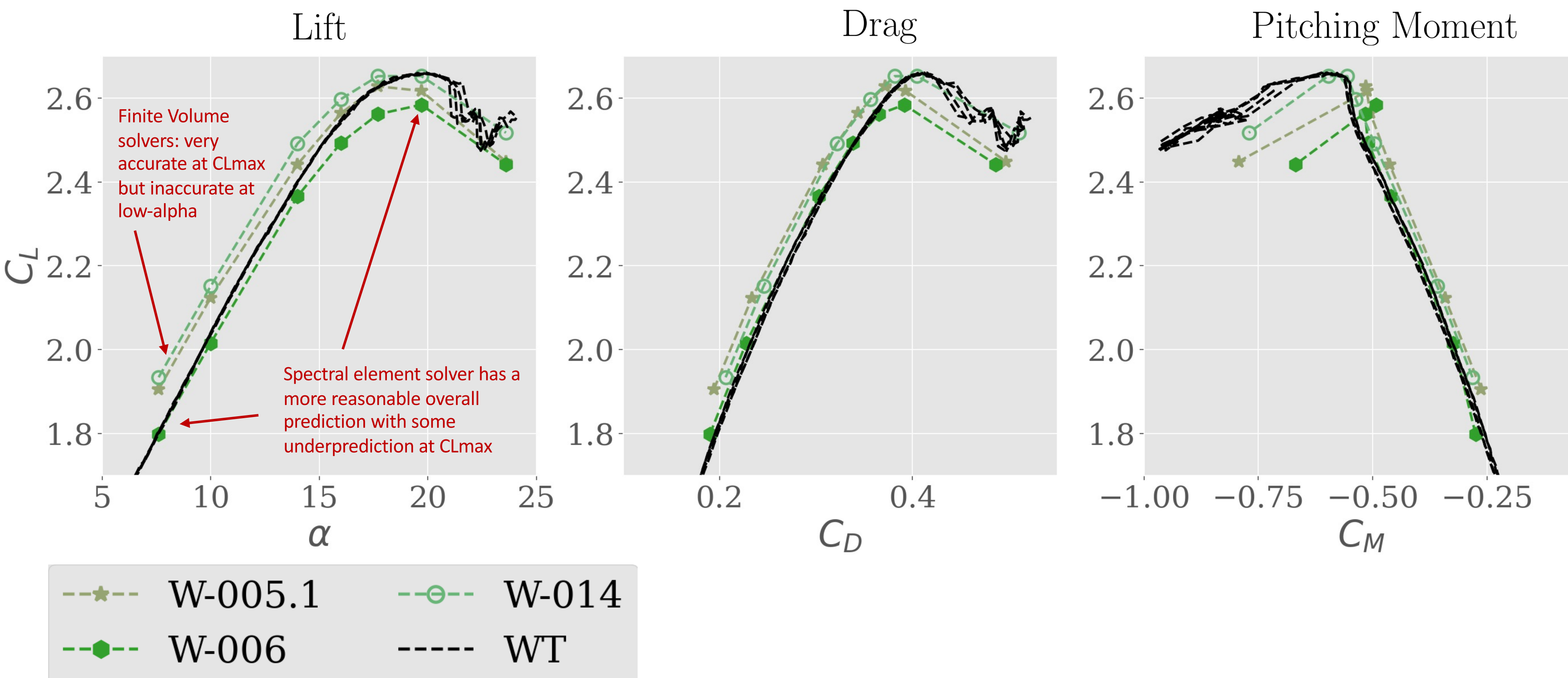
WT Oilflow(ONERA) | W-001 EULER | W-013 Coarse Grid (132M) | W-012 Coarse Grid (132M)



Inaccurate flow patterns

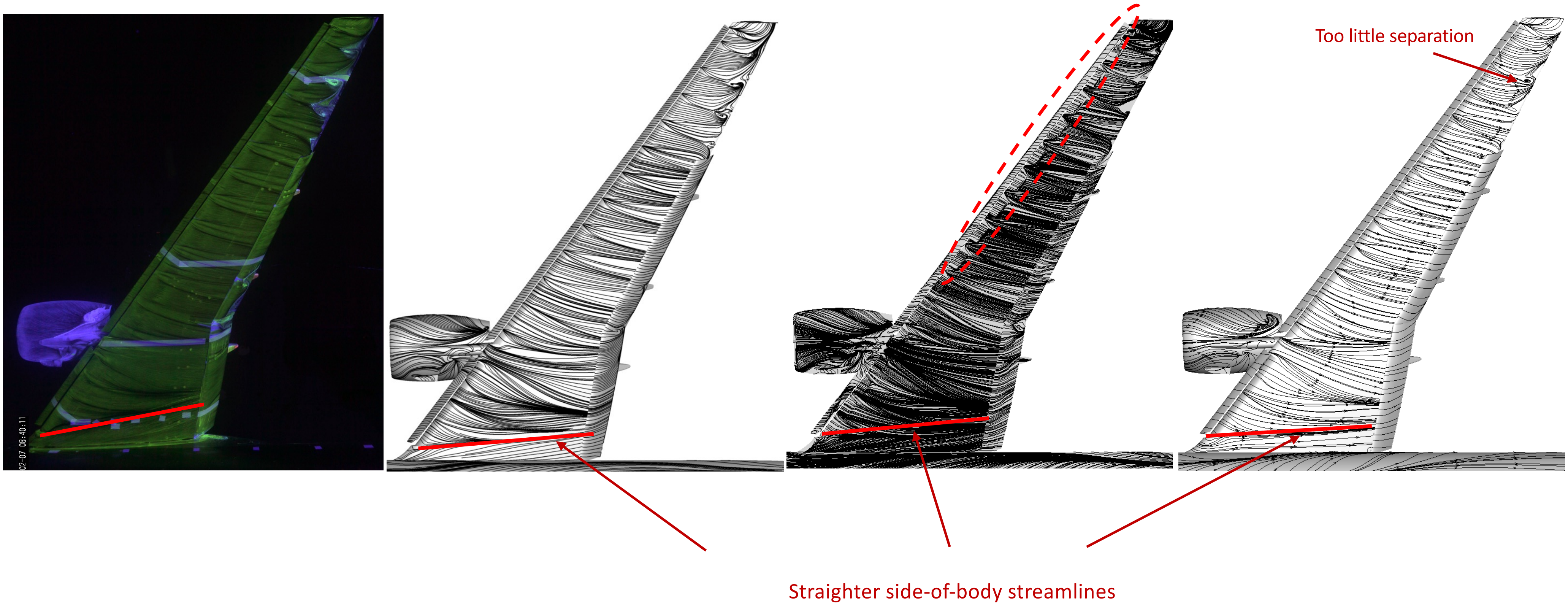
Tendency to have accurate separation patterns - need to run on finer grids

Submissions using Mixed element grids (Implicit time-stepping)

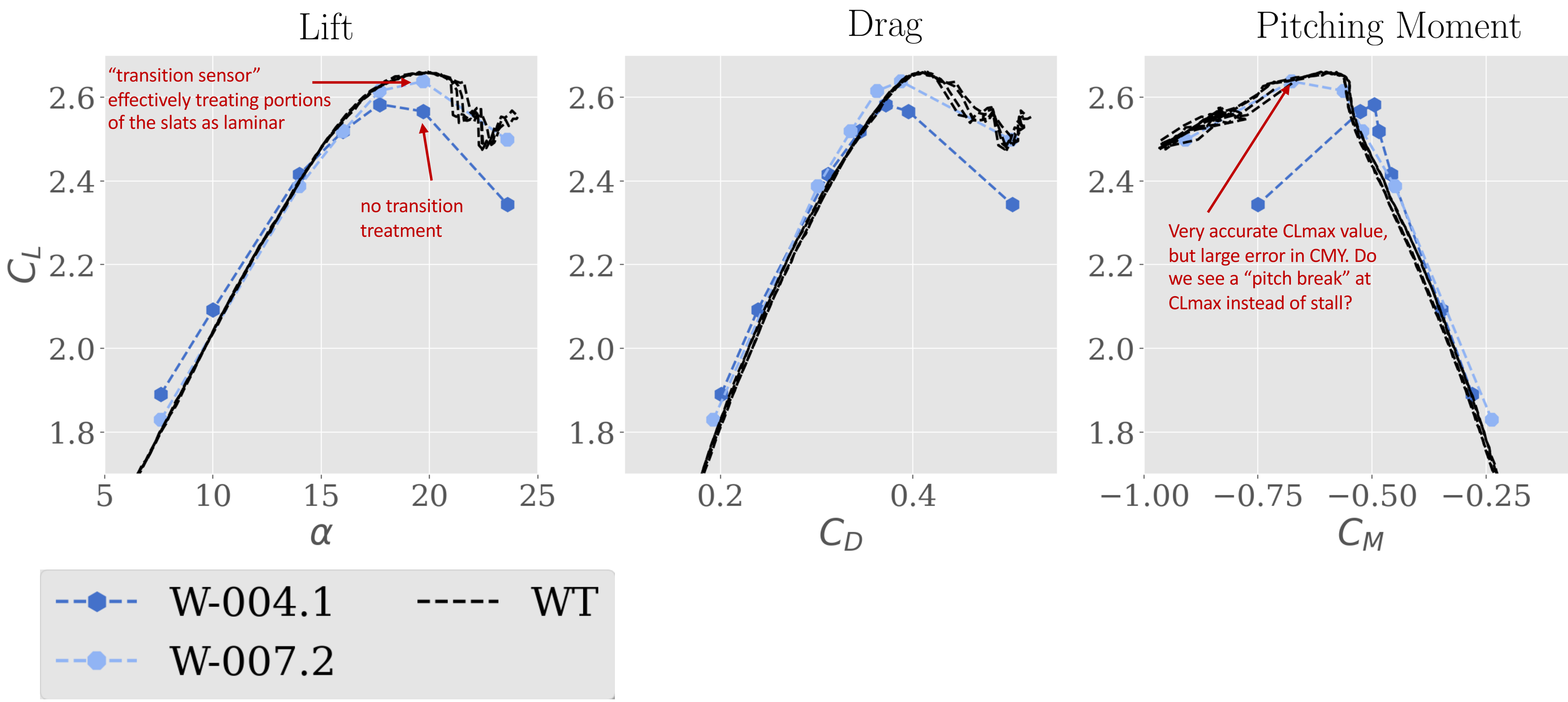


Case 2.4: Oilflow vs Streamlines $\alpha = 19.7^{o}$ Implicit & Mixed Element Grids

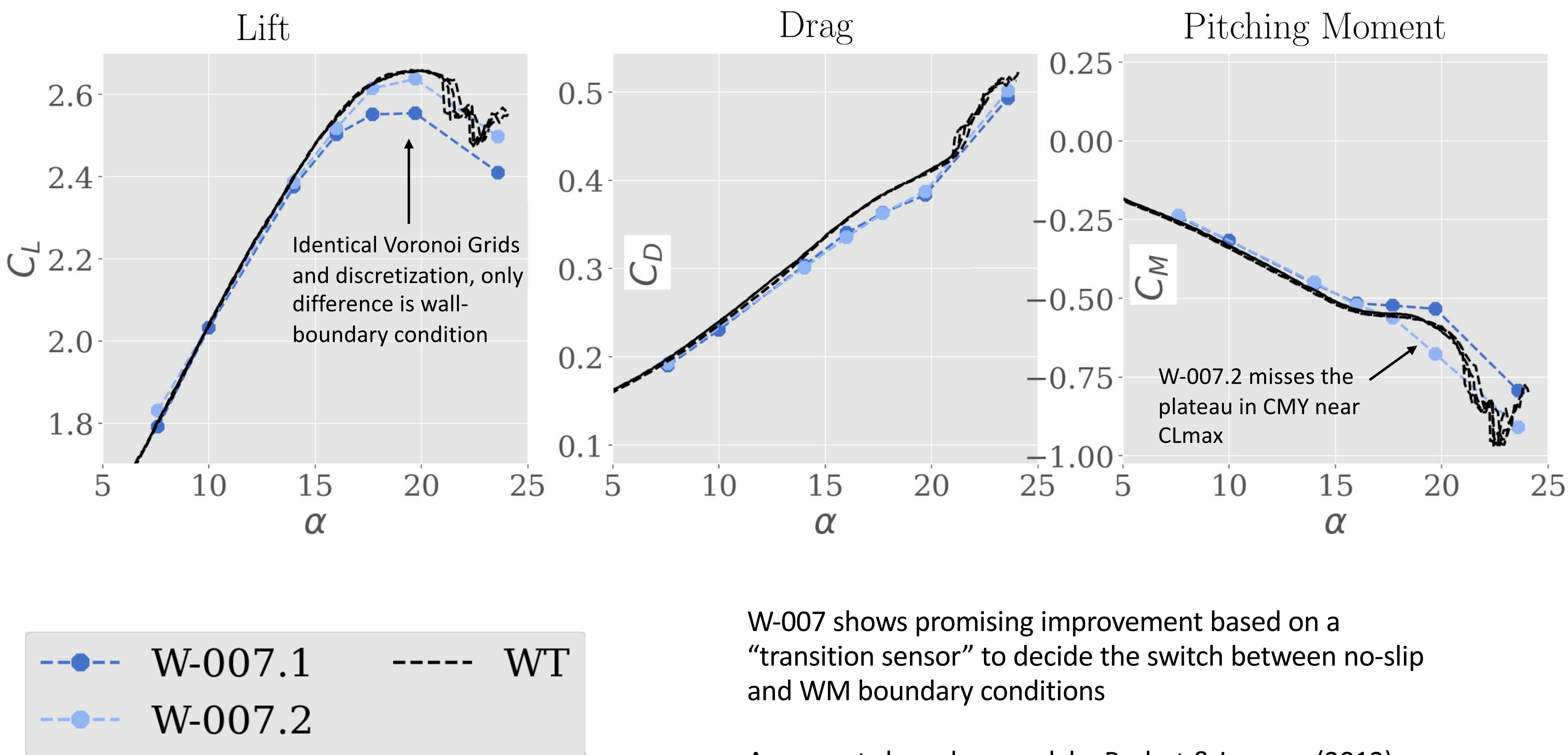
WT Oilflow(ONERA) | W-005.1 (FV) | W-014 (FV) | W-006 (High-Order)



Submissions using Voronoi grids (Explicit time-stepping)



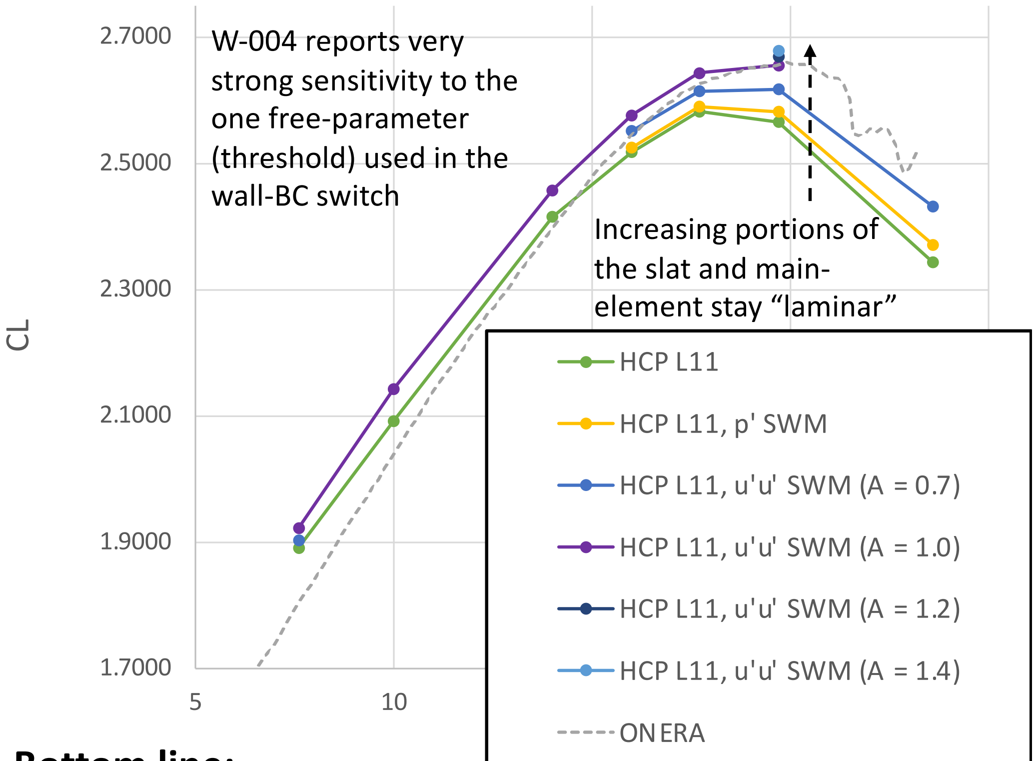
Transition Treatment: W-007 Voronoi Grid

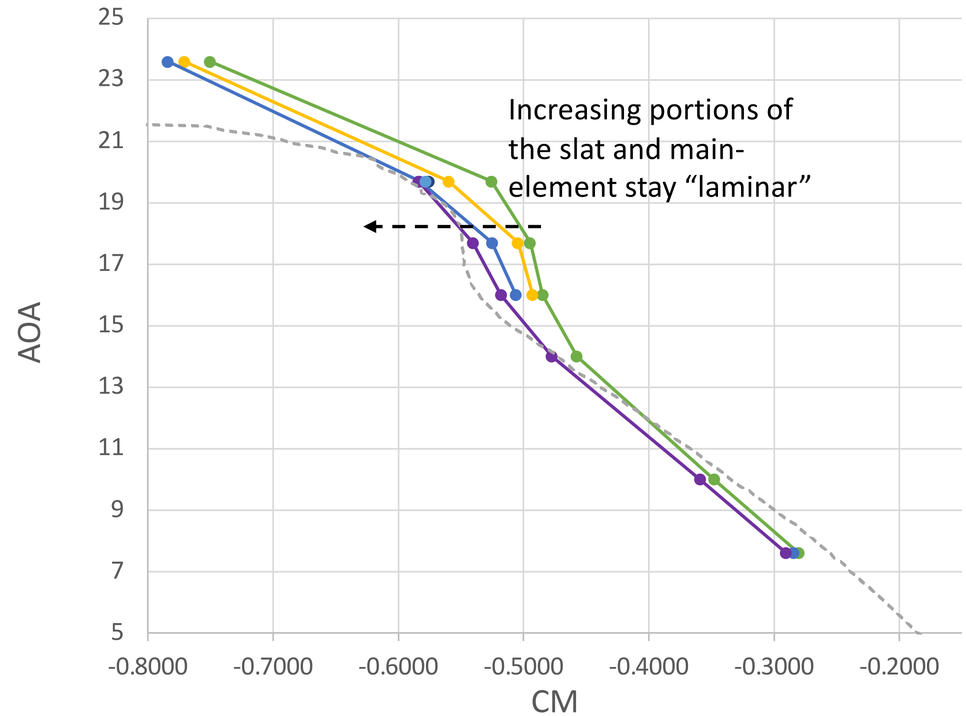


W-007 shows promising improvement based on a "transition sensor" to decide the switch between no-slip and WM boundary conditions

Arguments based on work by Bodart & Larrson (2012)

Transition Treatment: Tried by W-004 (Also Voronoi Grids)

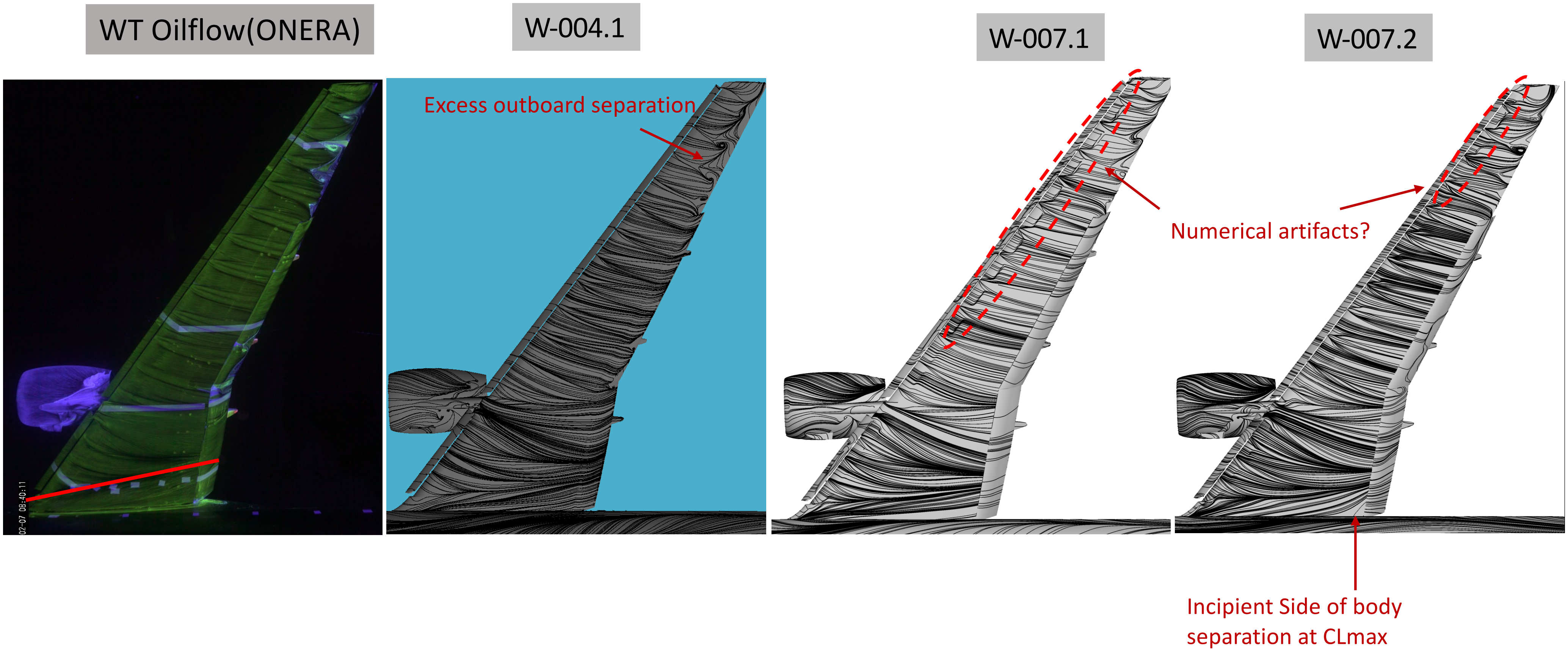




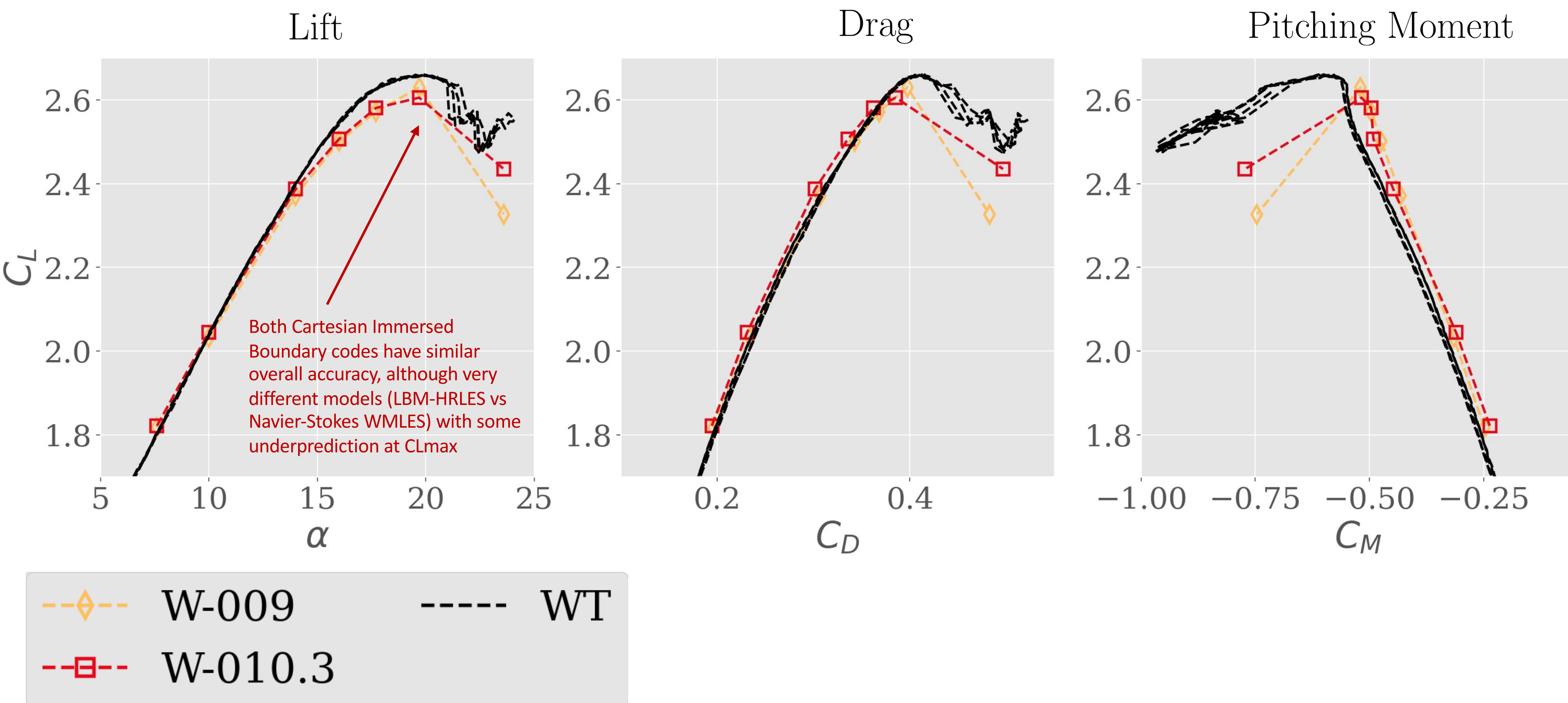
Bottom line:

- Clear that the state of the slat boundary layer has an influence of the maximum lift value predicted
- "Altering" the location of slat transition may provide a "change in the correct-direction"
- Unclear if this specific method can be made predictive; time will tell as more participants investigate ideas
- Expect lots of work on this topic to be presented at SciTech 2025

Case 2.4: Oilflow vs Streamlines α = 19.7° Explicit & Voronoi Grids

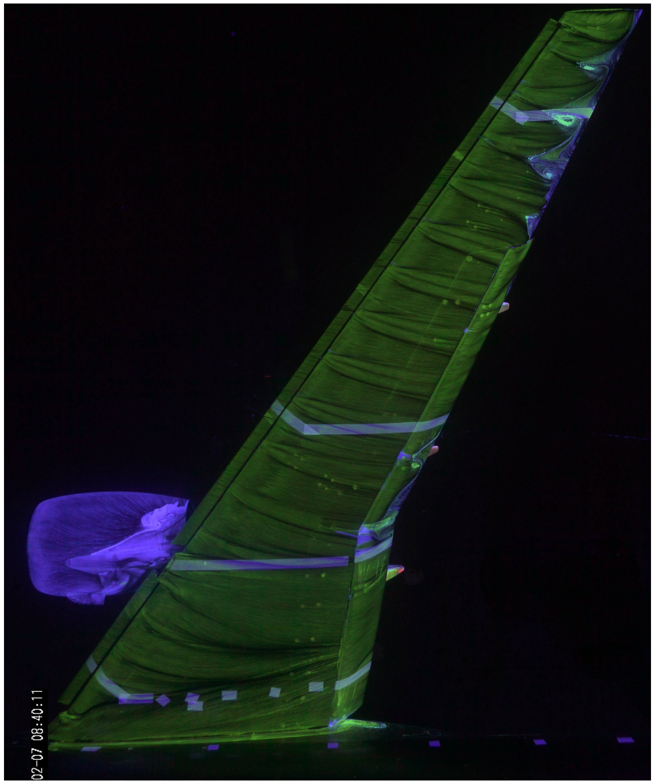


Submissions using Cartesian Octree grids (Explicit time-stepping)

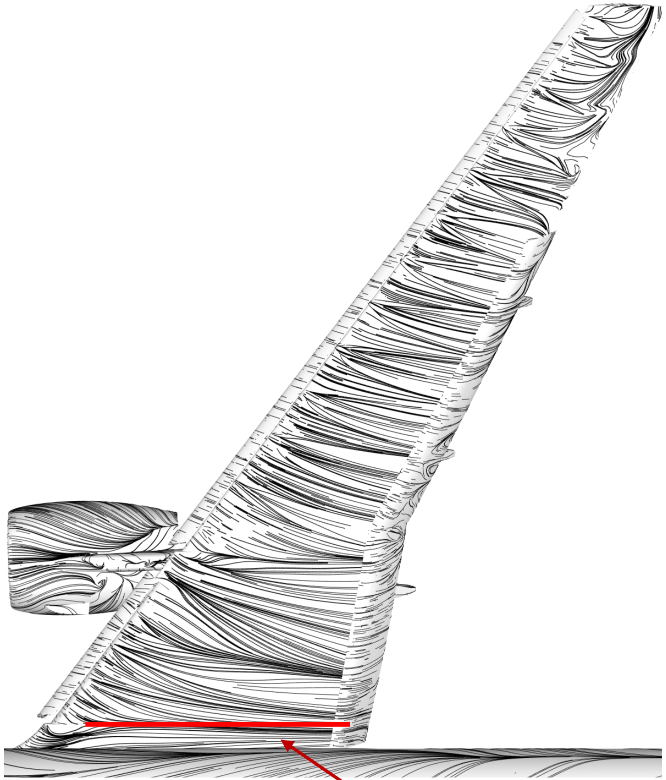


Case 2.4: Oilflow vs Streamlines α = 19.7° Explicit & Cartesian Grids

WT Oilflow(ONERA)



W-009

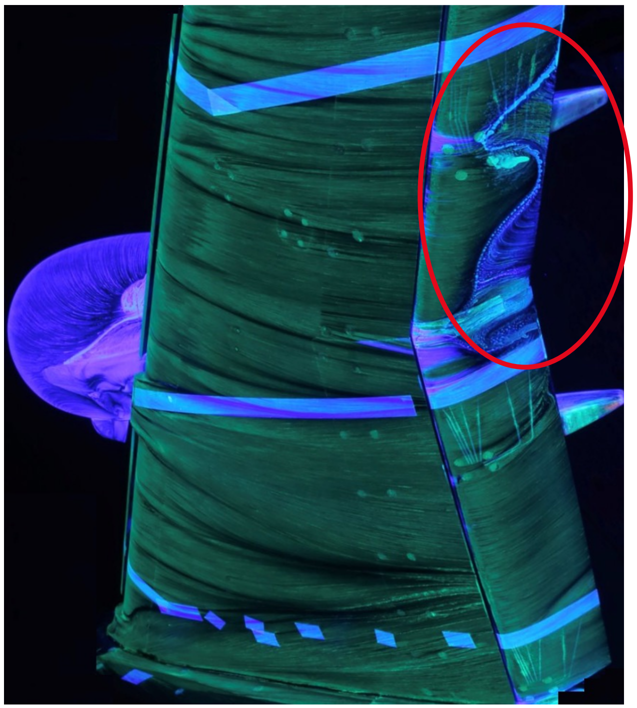


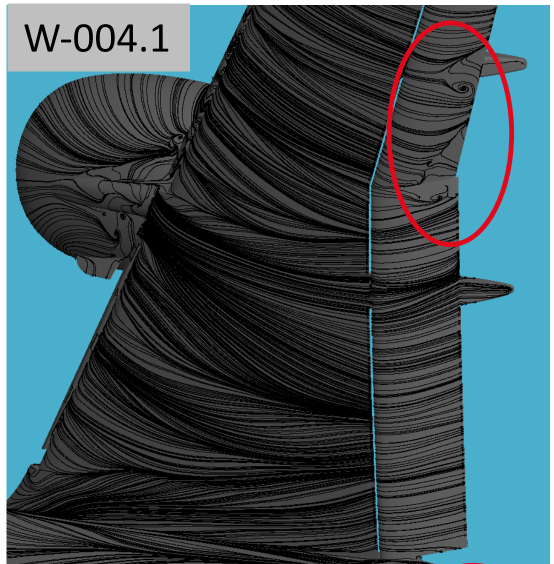
W-010.3

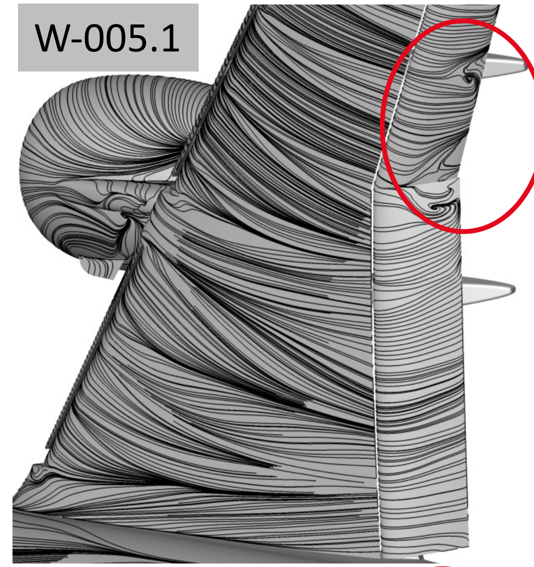
Straighter side-of-body streamlines

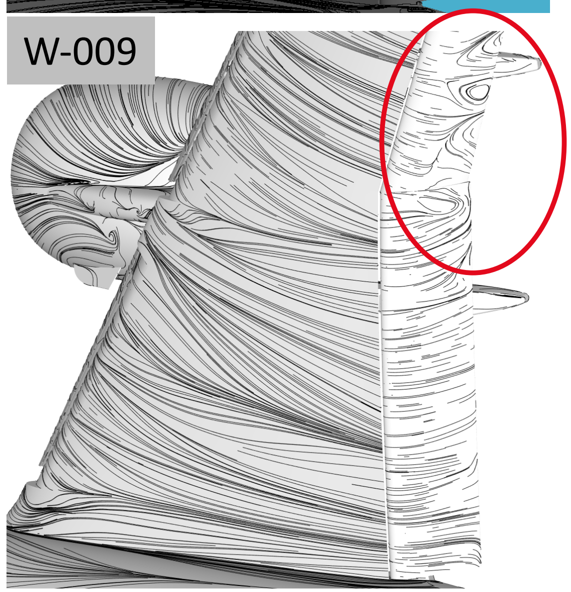
Case 2.4:
Oilflow vs Streamlines

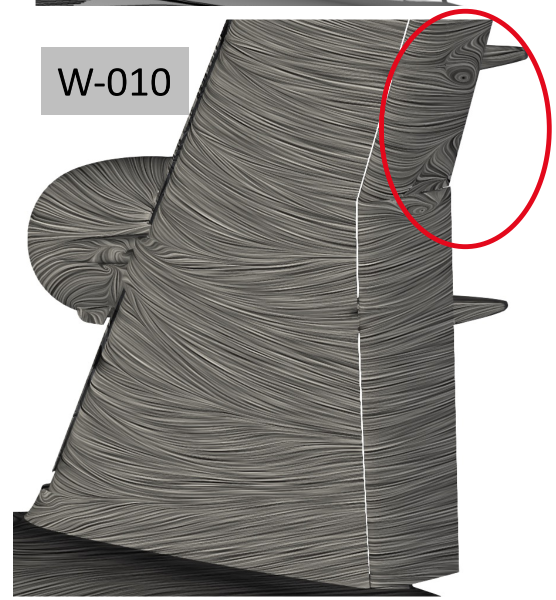
WT Oilflow (ONERA) α = 19.7º







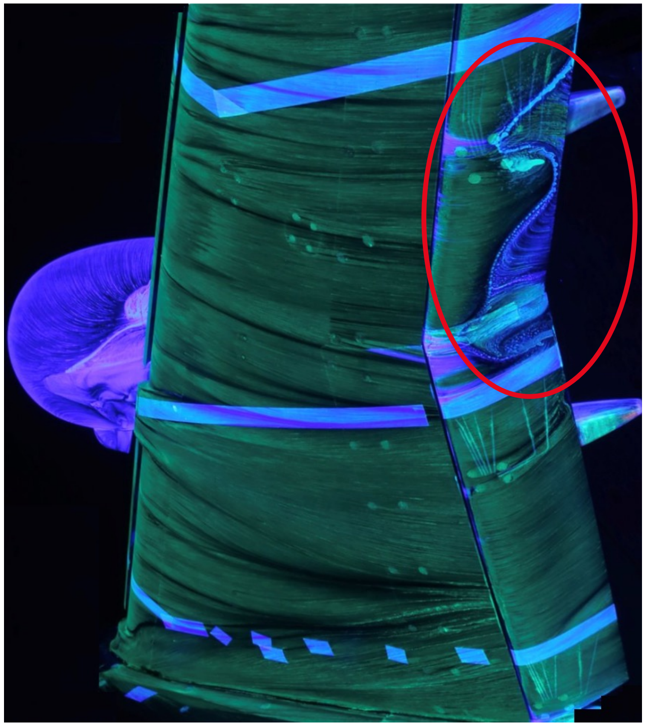




- Clmax for Case 2.3 does not show any flap separation; but Case 2.4 does show some flap separation near the flap-gap; **potentially influenced by nacelle-wake**

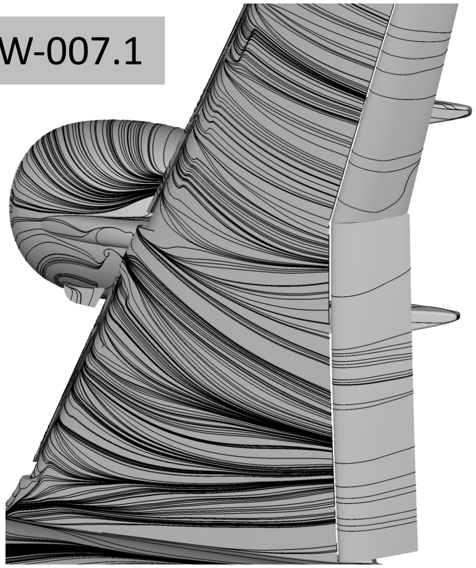
Case 2.4: Oilflow vs Streamlines

WT Oilflow (ONERA) $\alpha = 19.7^{o}$

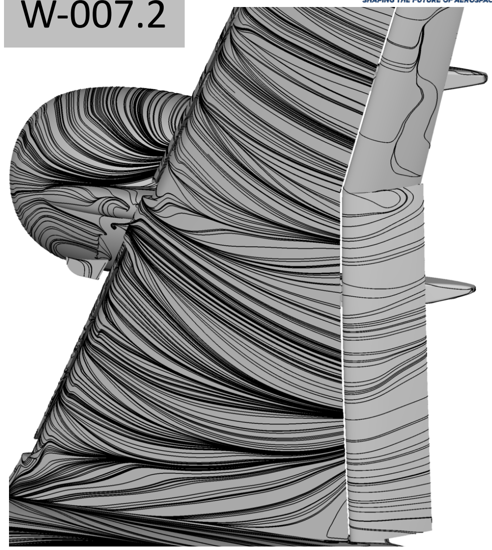


- Clmax for Case 2.3 does not show any flap separation; but Case 2.4 does show some flap separation near the flap-gap; **potentially influenced by nacelle-wake**

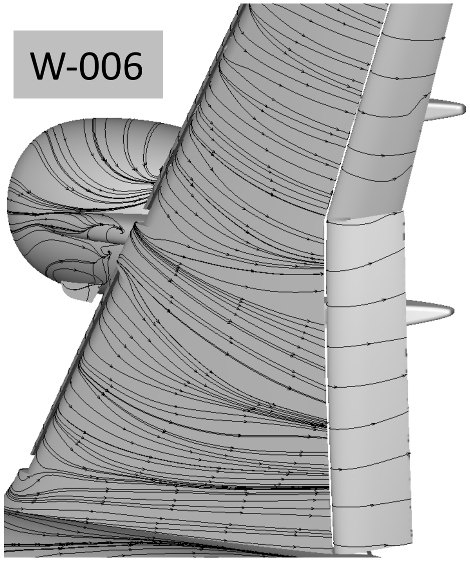
W-007.1



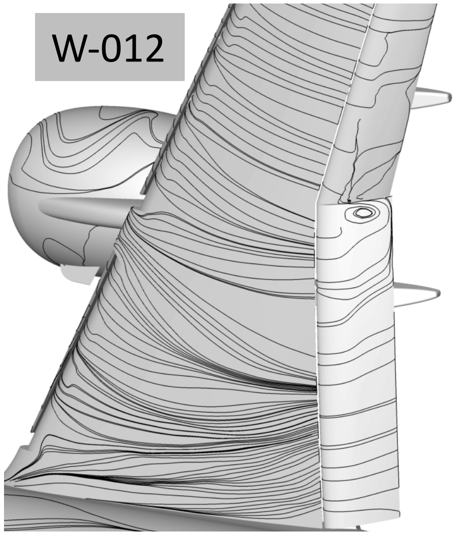
W-007.2



W-006



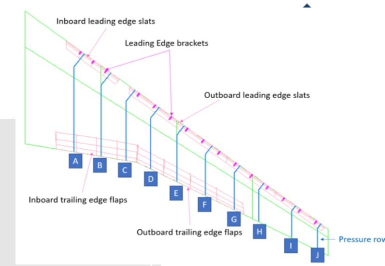
W-012

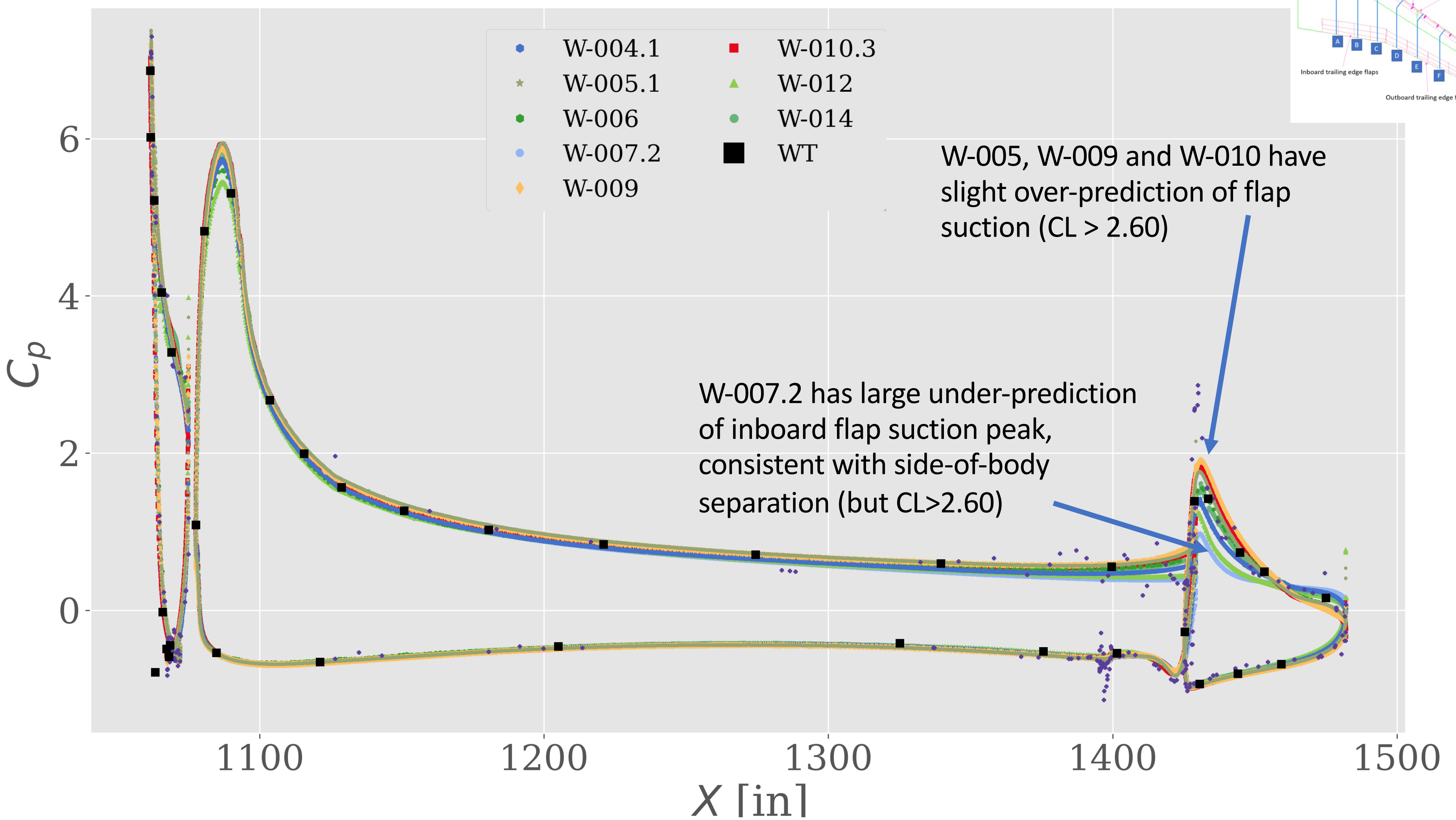


α = 19.7º

Case 2.4: Cp Cuts(in-board)

Row A

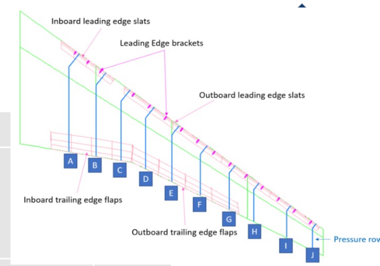


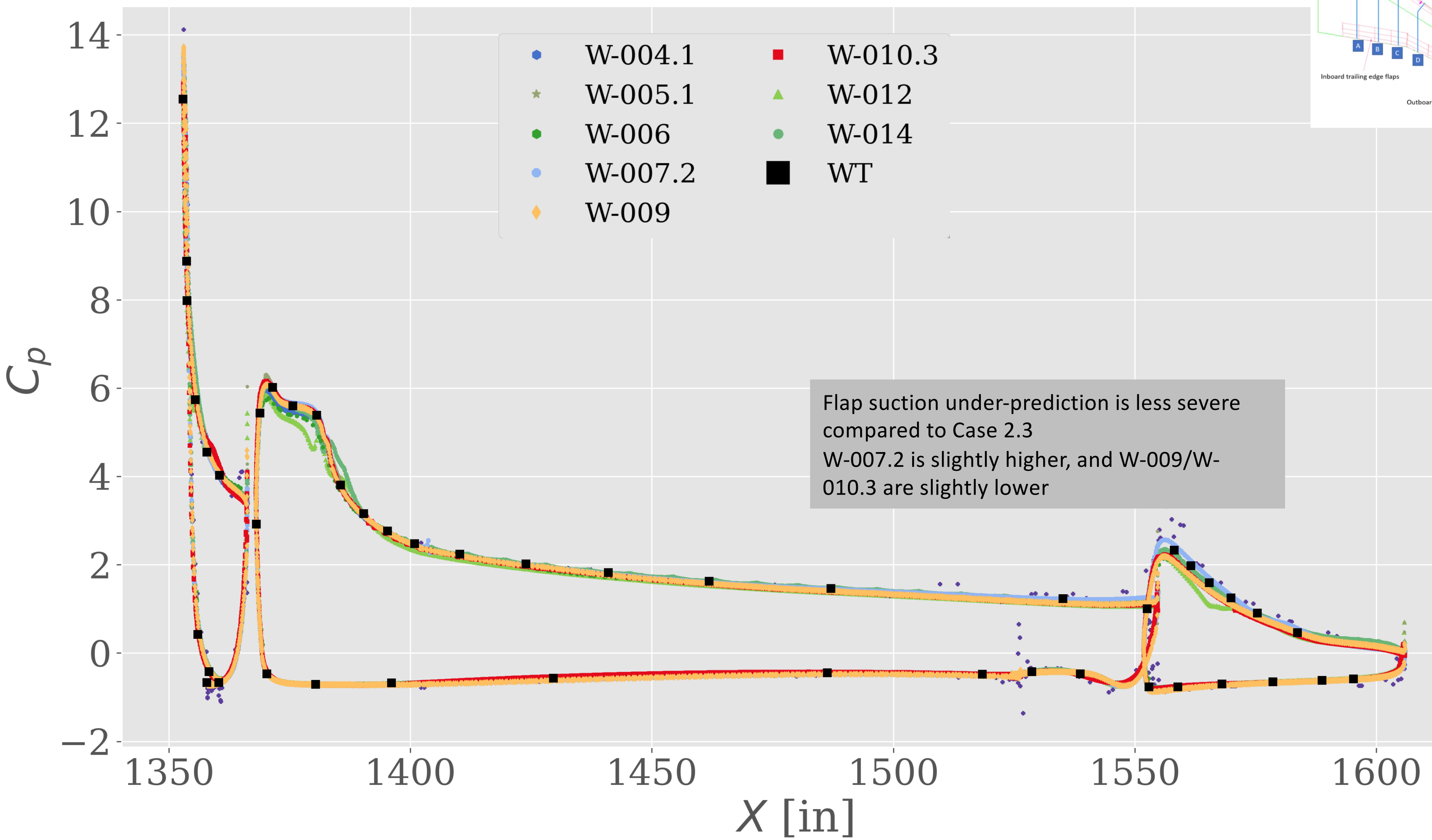


α = 19.7º

Case 2.4: Cp Cuts(mid-board)

Row E

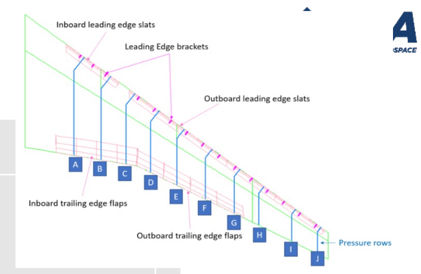


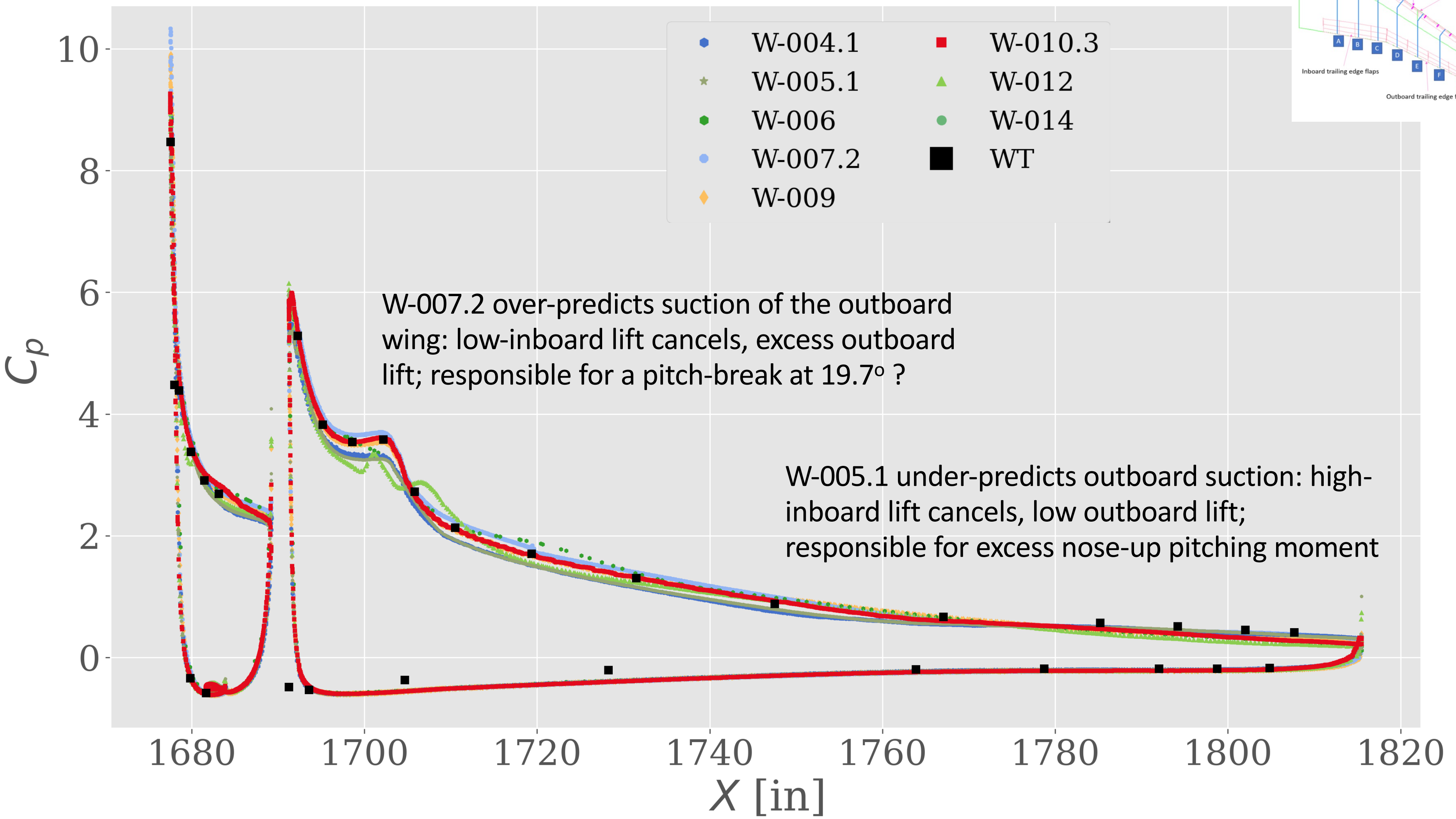


α = 19.7º

Case 2.4: Cp Cuts(out-board)

Row I

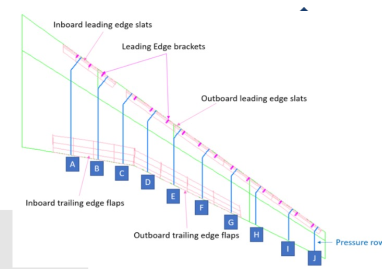




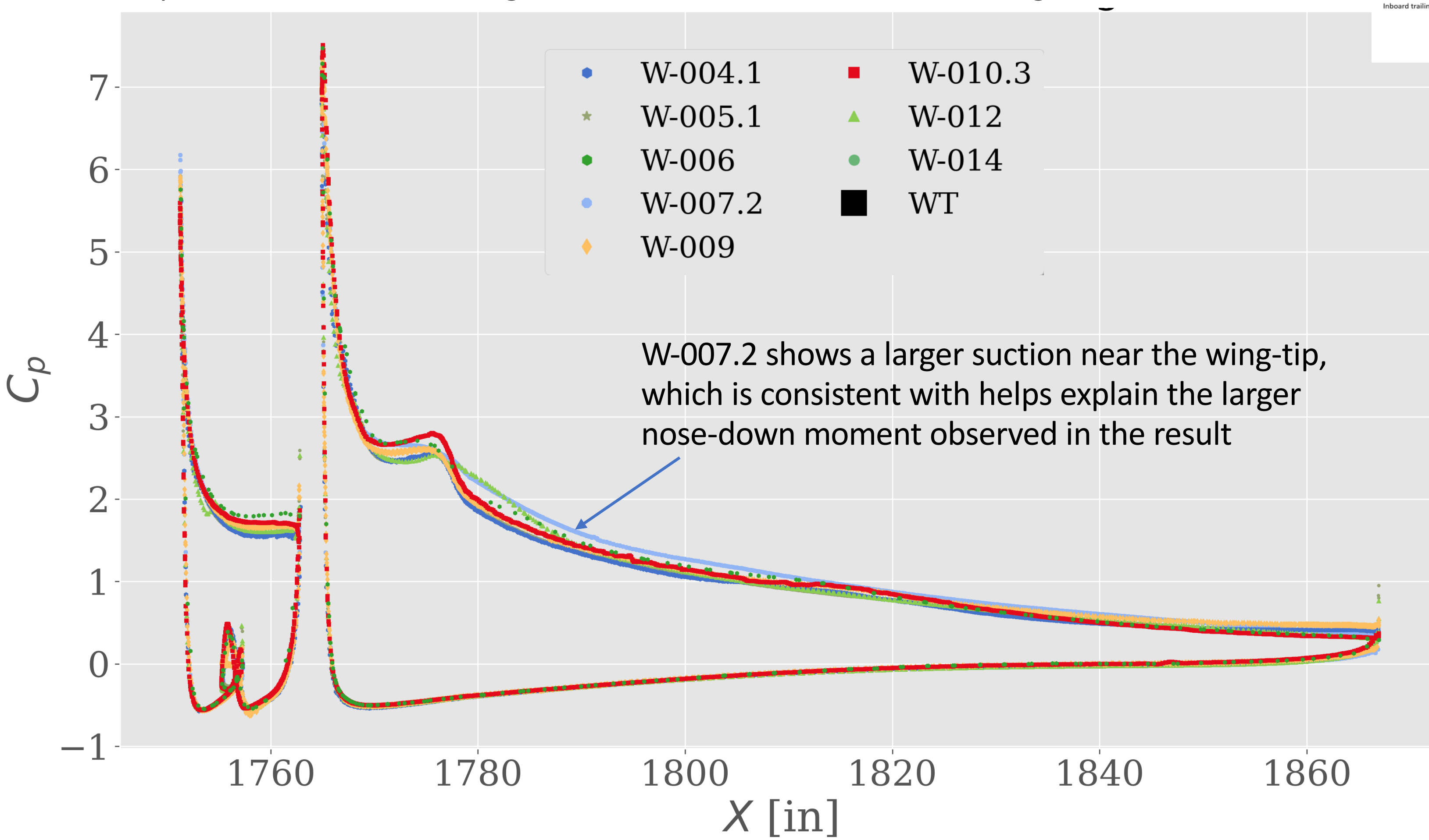
α = 19.7º

Case 2.4: Cp Cuts(out-board)

Row J

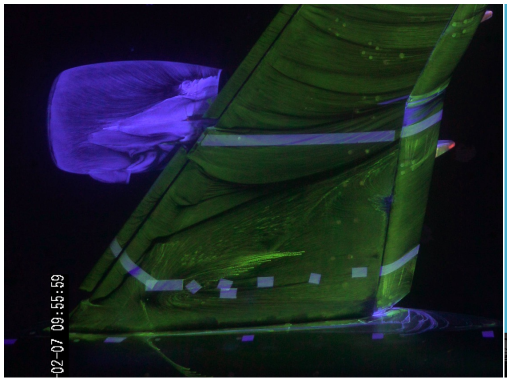


Experimental data is missing – however there are some interesting trends…

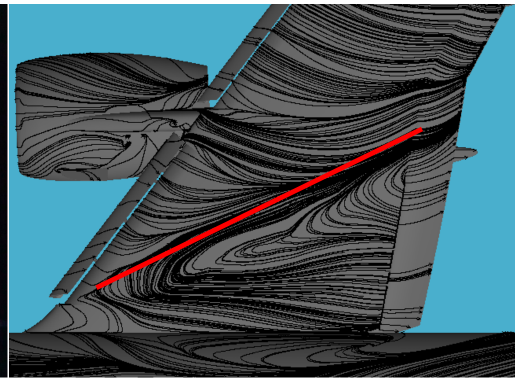


Case 2.4: Oilflow vs Streamlines $\alpha = 23.6^{\circ}$

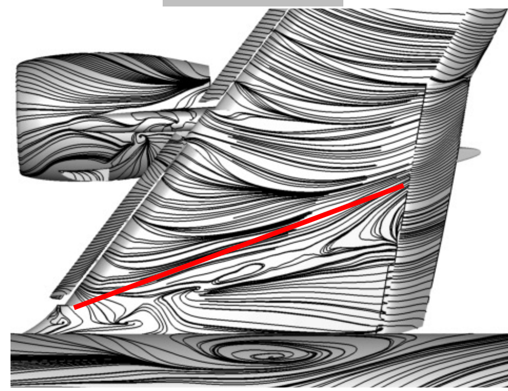
WT Oilflow(ONERA)



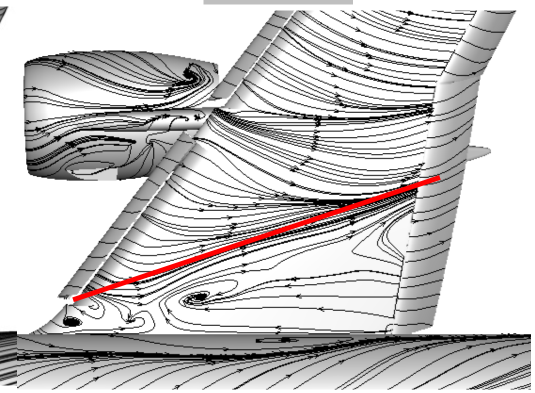
W-004.1



W-005.1

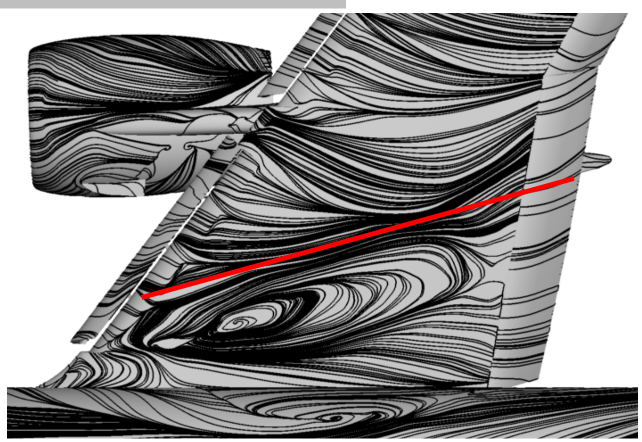


W-006

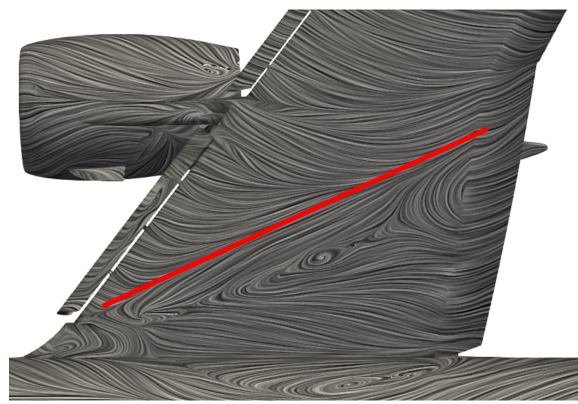


Submissions that showed attached flow on the nacelle

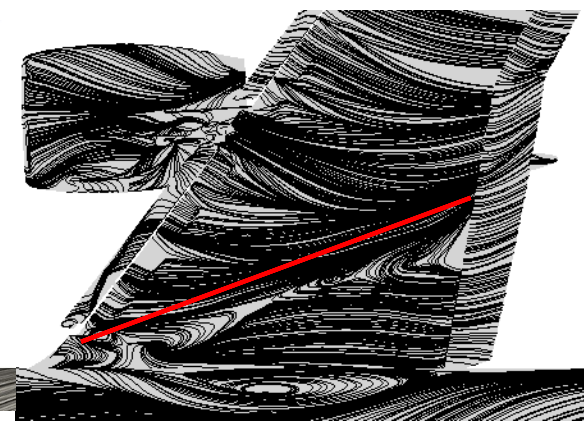
W-007.2



W-010.3

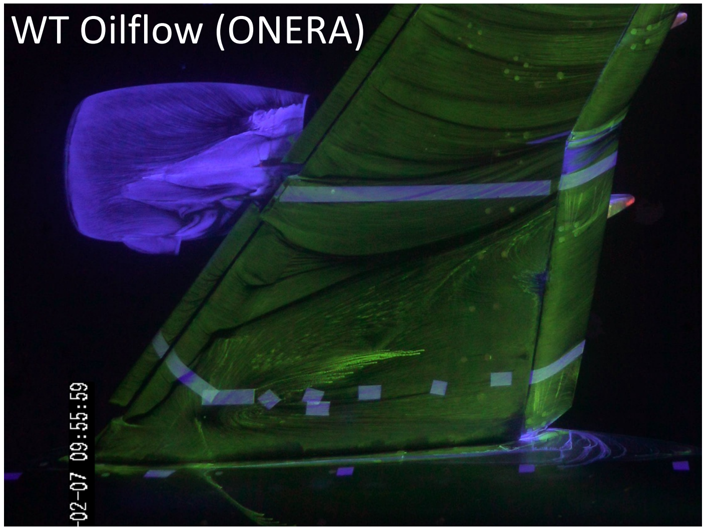


W-014



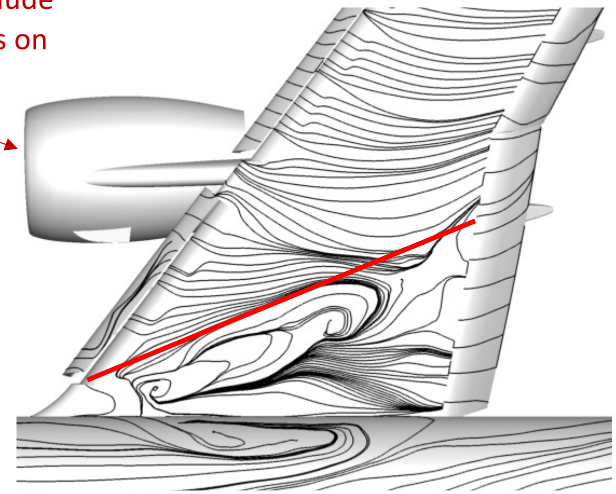
Case 2.4: Oilflow vs Streamlines $\alpha = 23.6^{o}$

WT Oilflow (ONERA)



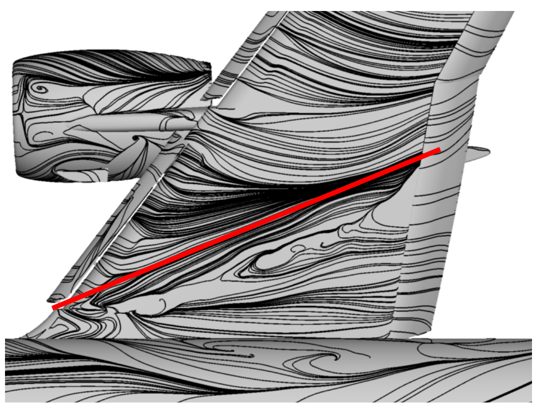
W-012

Did not include streamlines on nacelle

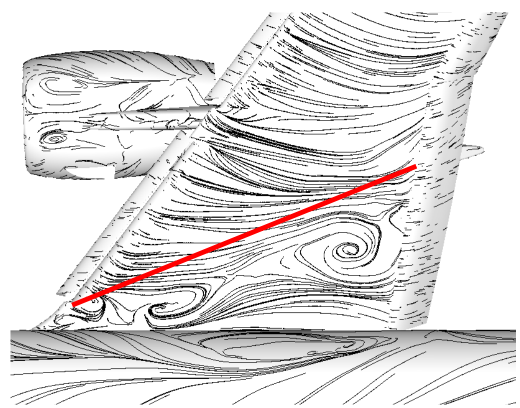


Submissions that showed separated flow on the nacelle

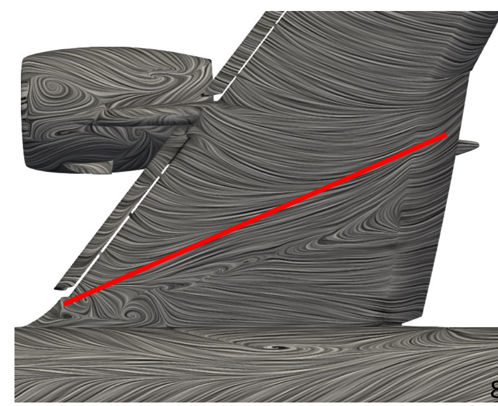
W-007.1



W-009



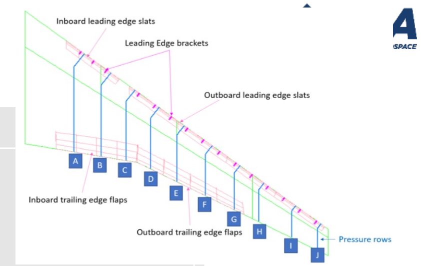
W-010.1 (Vreman)

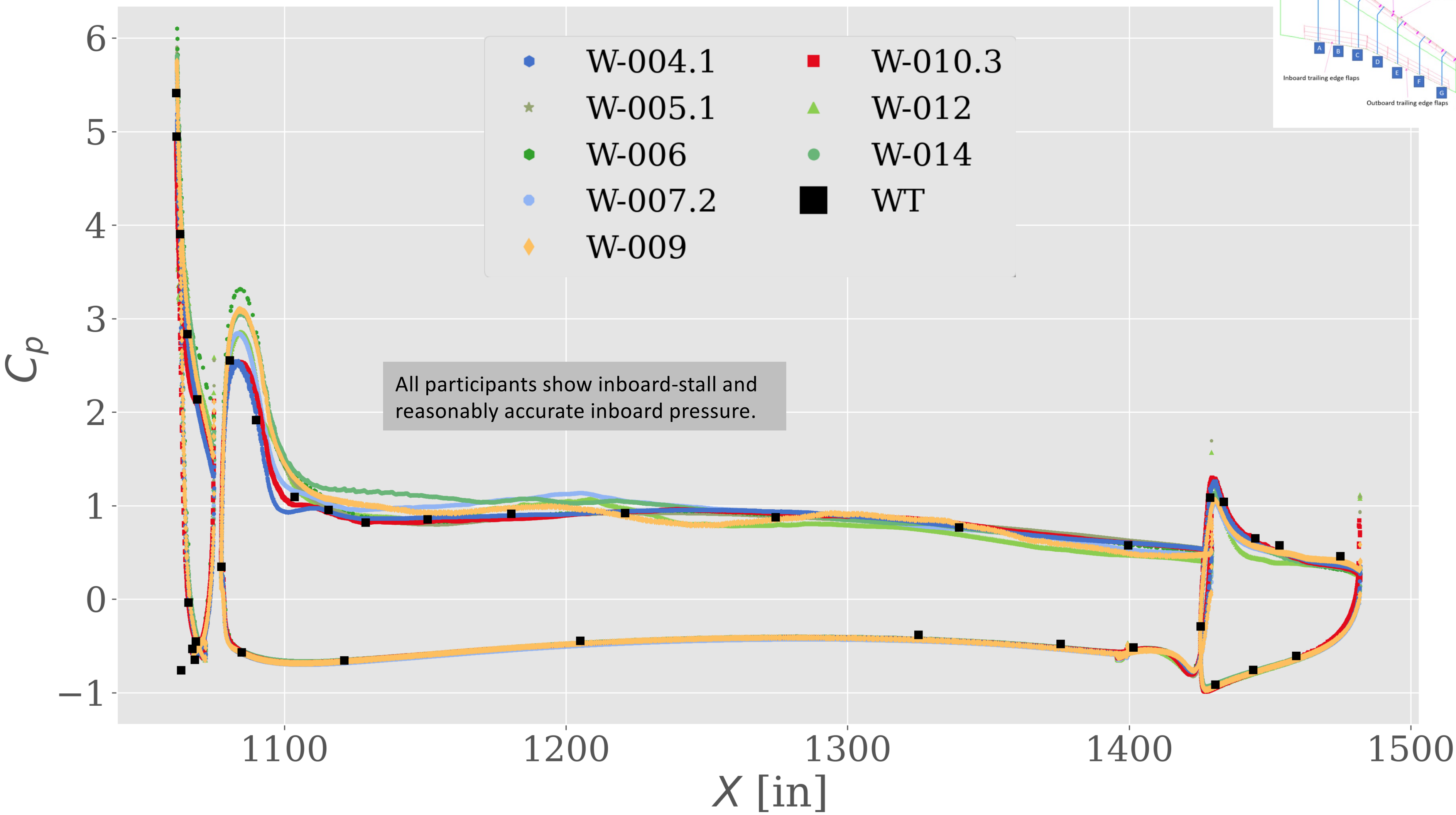


α = 23.6º

Case 2.4: Cp Cuts(in-board)

Row A

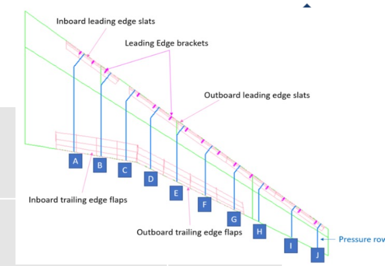


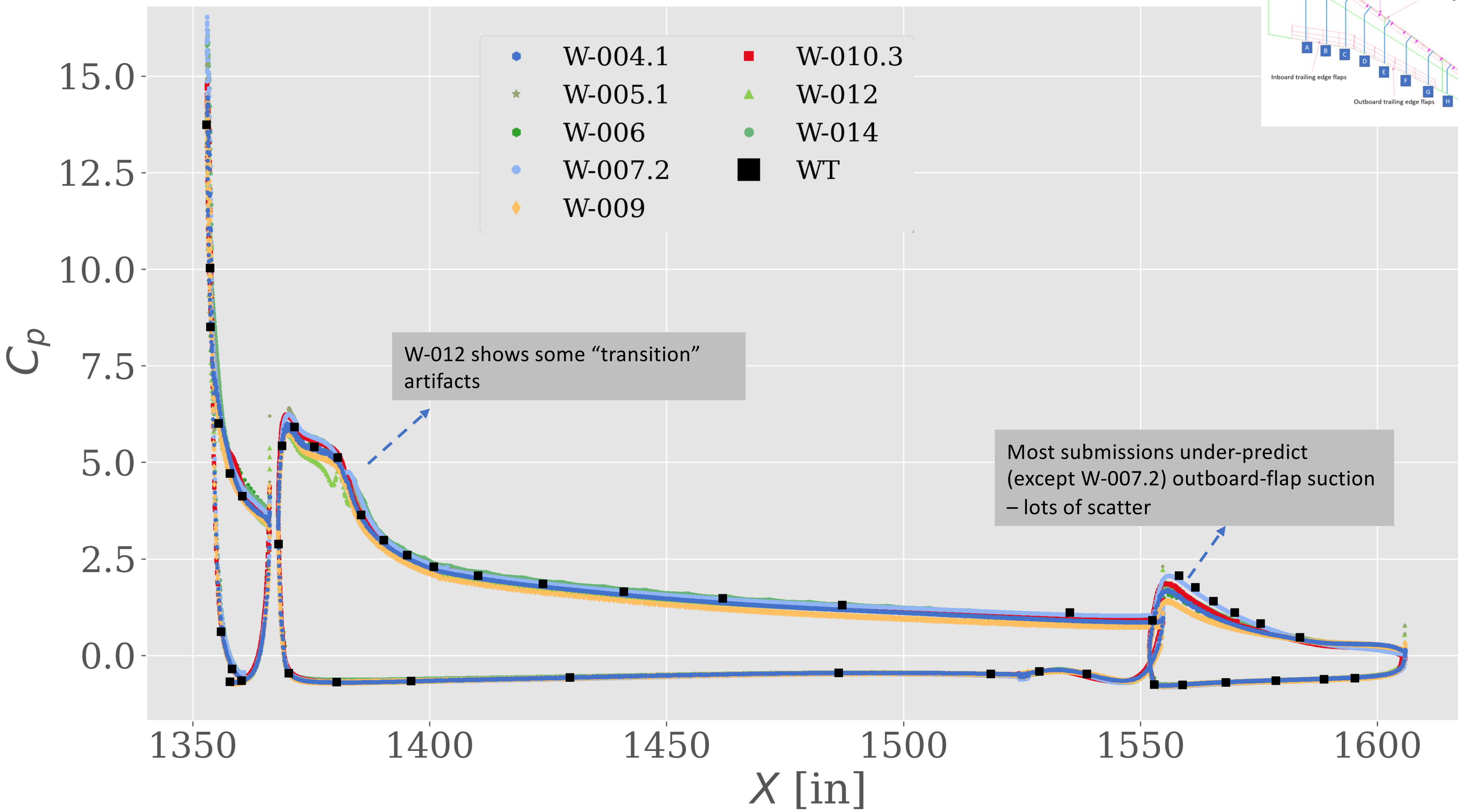


α = 23.6º

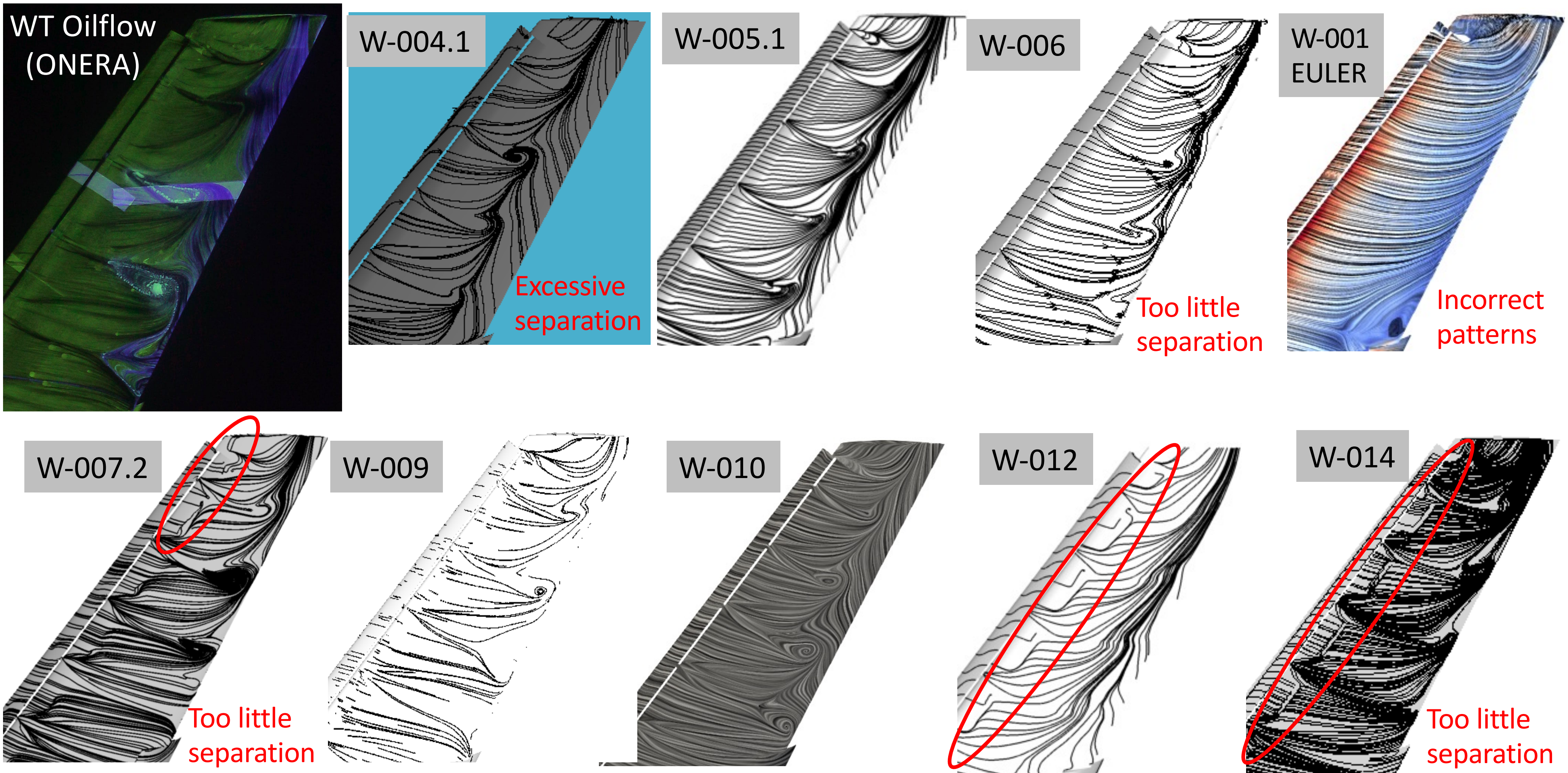
Case 2.4: Cp Cuts(mid-board)

Row E





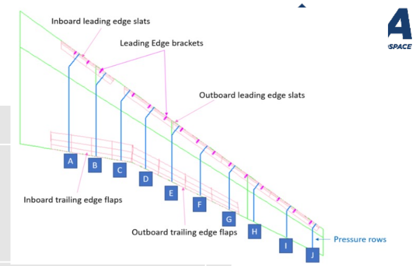
Case 2.4: Oilflow vs Streamlines α = 23.6°

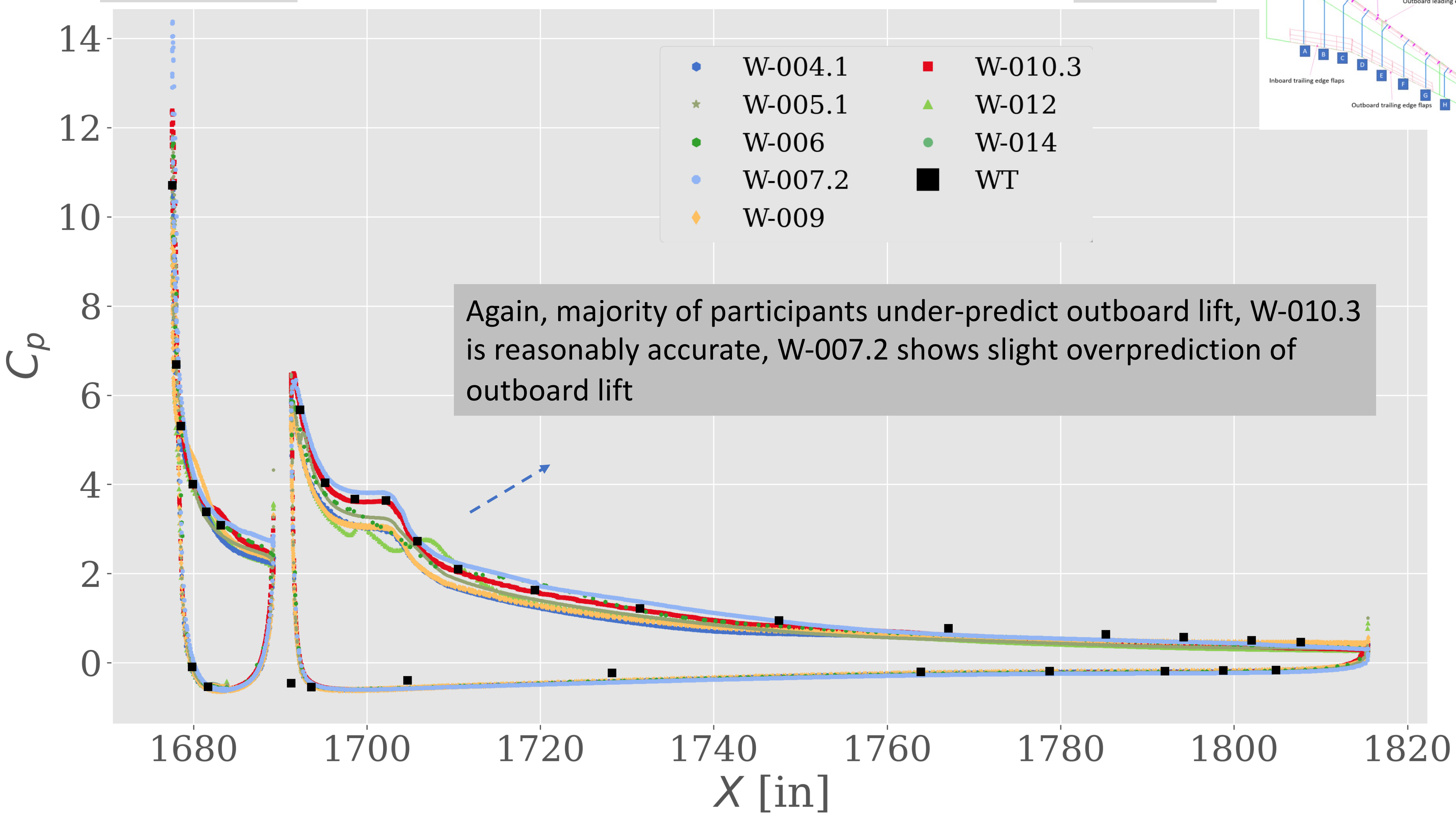


α = 23.6º

Case 2.4: Cp Cuts(out-board)

Row I

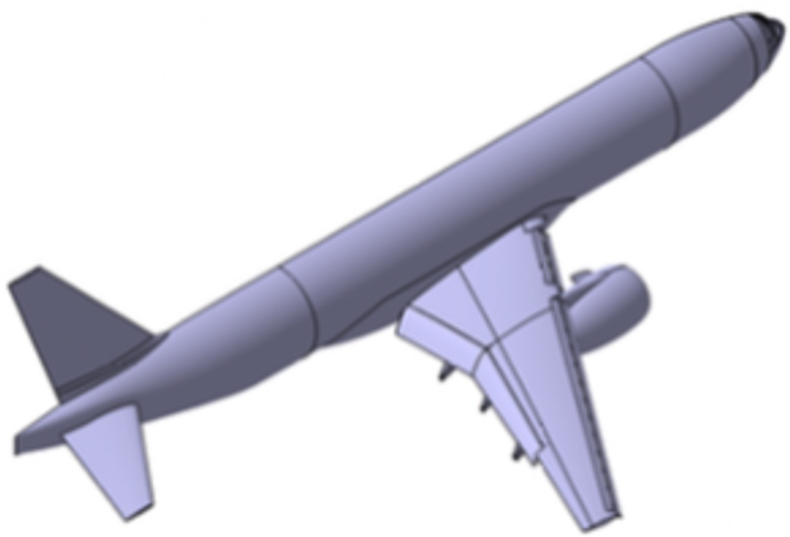




Case 2.4 – Observations

- 9 submissions – only 3 within 2% CL error at CLmax:
  - The 3 submissions still show some evidence of inboard/outboard error-cancellation: over-predict inboard flap CL and under-predict outboard flap CL
  - Only 2 of those 3 submissions also predict the correct CL at lower angles
  - Most other participants under-predicted CLmax because of lower lift mid-board and out-board
- Flap-related challenges mostly consistent with those from Case 2.3; some submissions under-predict outboard flap flow-separation leading to much higher lift, others show some error cancellation
- All submissions predict the correct stall-onset mechanism (inboard stall)
  - Majority of participants did not show inboard separation at 19.7^o; only 1 participant showed incipient separation
  - All participants showed well-formed inboard separation at 23.6^o
  - Virtually all participants predicted the correct qualitative wedge-shaped flow-separation patterns on the outboard wing even on coarse grids
- W-001 (Euler) submissions has reasonable CLmax value but inaccurate flow (based surface and Cp): lots of error cancellation

Case 3



Participant ID	Solver	Grids Used			
W-001	Adaptive Euler	164K*			
W-003	BCFD	470*	569*		
W-005.1	FUN3D (FV)	460M	460M* 476M*		
W-006	hpMusic	83M (DOF)	145M*	232M	
W-004.1	CharLES (DSM)	103M	384M*	1.49B*	5.89B
W-007.2	LAVA	110M	193M	431M*	
W-009	PowerFLOW	65M 98M 125M	167M/ 240M 325M	457M* 627M* 826M*	1.37B
W-010.3	Volcano ScaLES (DSM)	256M	562M	1.08B*	1.25B
W-011	FFVHC-ACE	640M	2.56B	11.6B*	

Angle of Attack (AoA) for each Re Number
Case 3: 6º , 10º , 14º , 16º , 18º , 19º , 20º , 22º

Case 3.1: Re= 1.05 Million
Case 3.2: Re= 5.49 Million
Case 3.3: Re= 16 Million
Case 3.4: Re= 30 Million

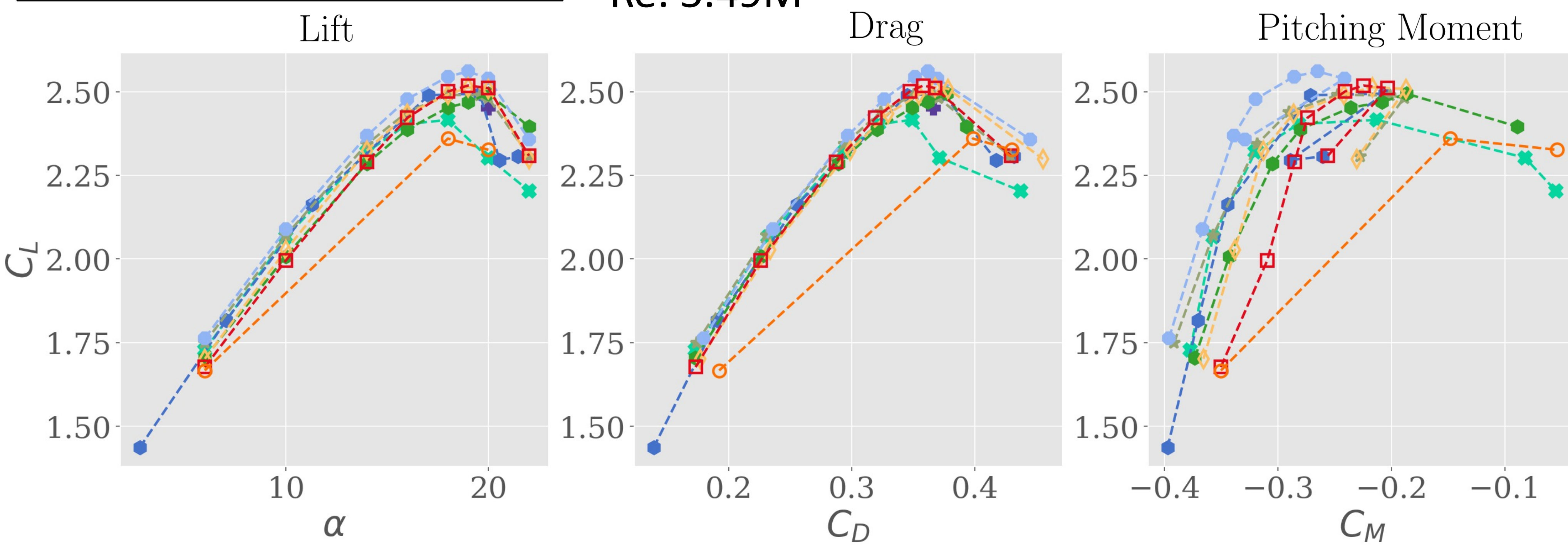
**Nominal grid used by participants in Cases 3.1, 3.2, 3.3, 3.4*

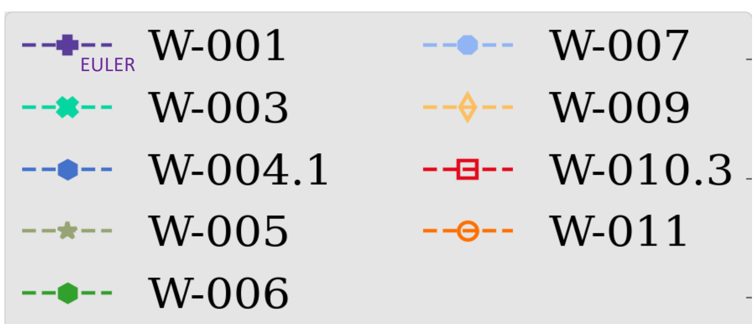
WMLES TFG Objectives for Case 3

- Can WMLES predict the first order effect the Reynolds number?
  - Observation: most submissions largely agree in qualitatively in terms of Re sensitivity
- Can we achieve grid-converged loads for the high-Reynolds number cases?
  - Observation: Maybe, but substantially higher resolution simulations are needed for confirmation; initial submissions look promising.
- Are some of the low-Re issues identified in Case 1 and 2 mitigated when large Re simulations are performed?
  - Observation: Unclear at this time, since high resolution simulations are needed to assess this rigorously.

Case 3.2 Integrated F&M

Re: 5.49M



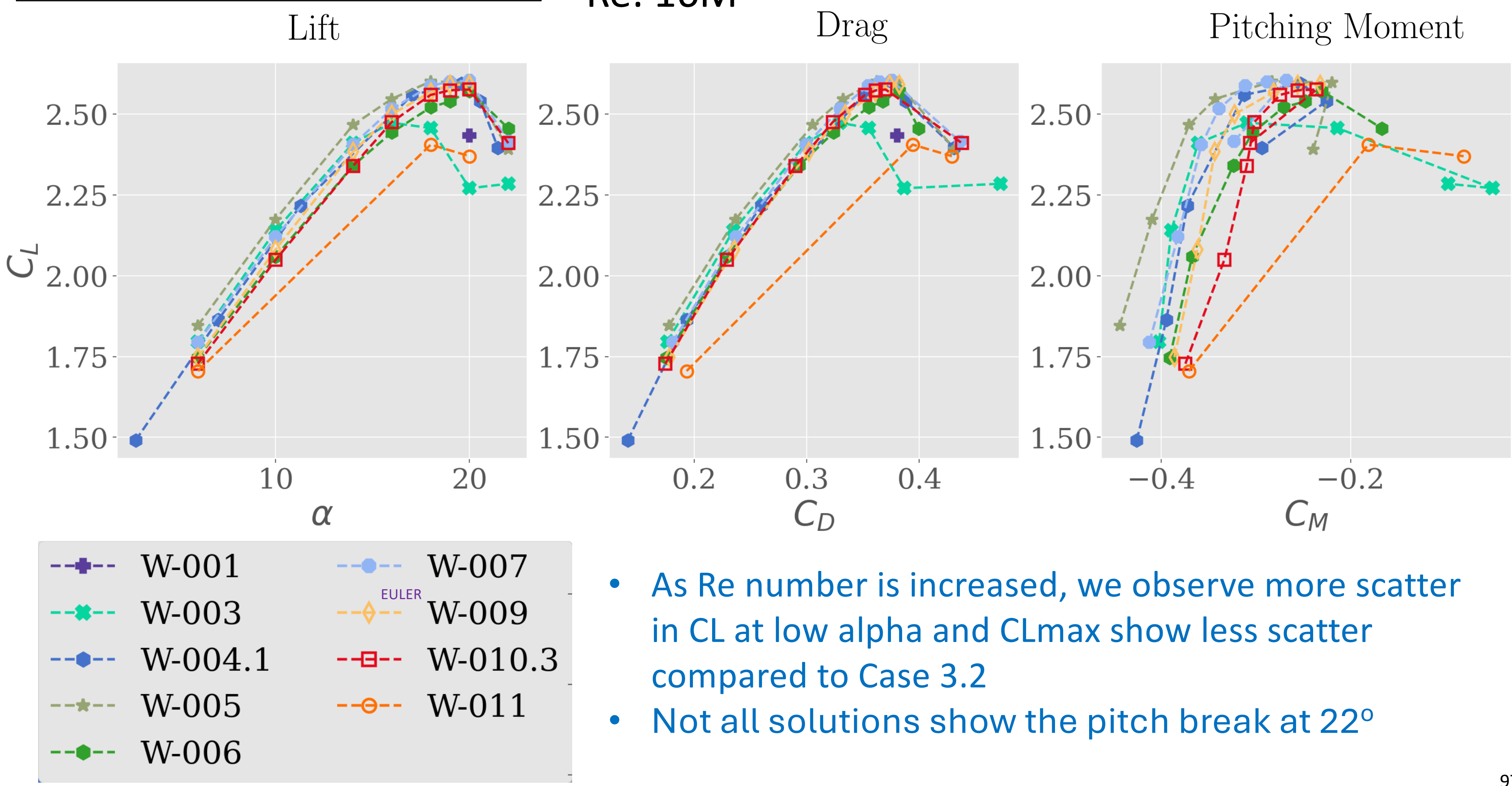


All participants predict a pitch break in Free air at 22°; this is in stark contrast to HLPW4 where it was unclear whether pitch break would occur in free-air (probably due to minor geometry change and AoA differences)

More scatter in CL at high-alpha, some scatter in low-alpha

Case 3.3 Integrated F&M

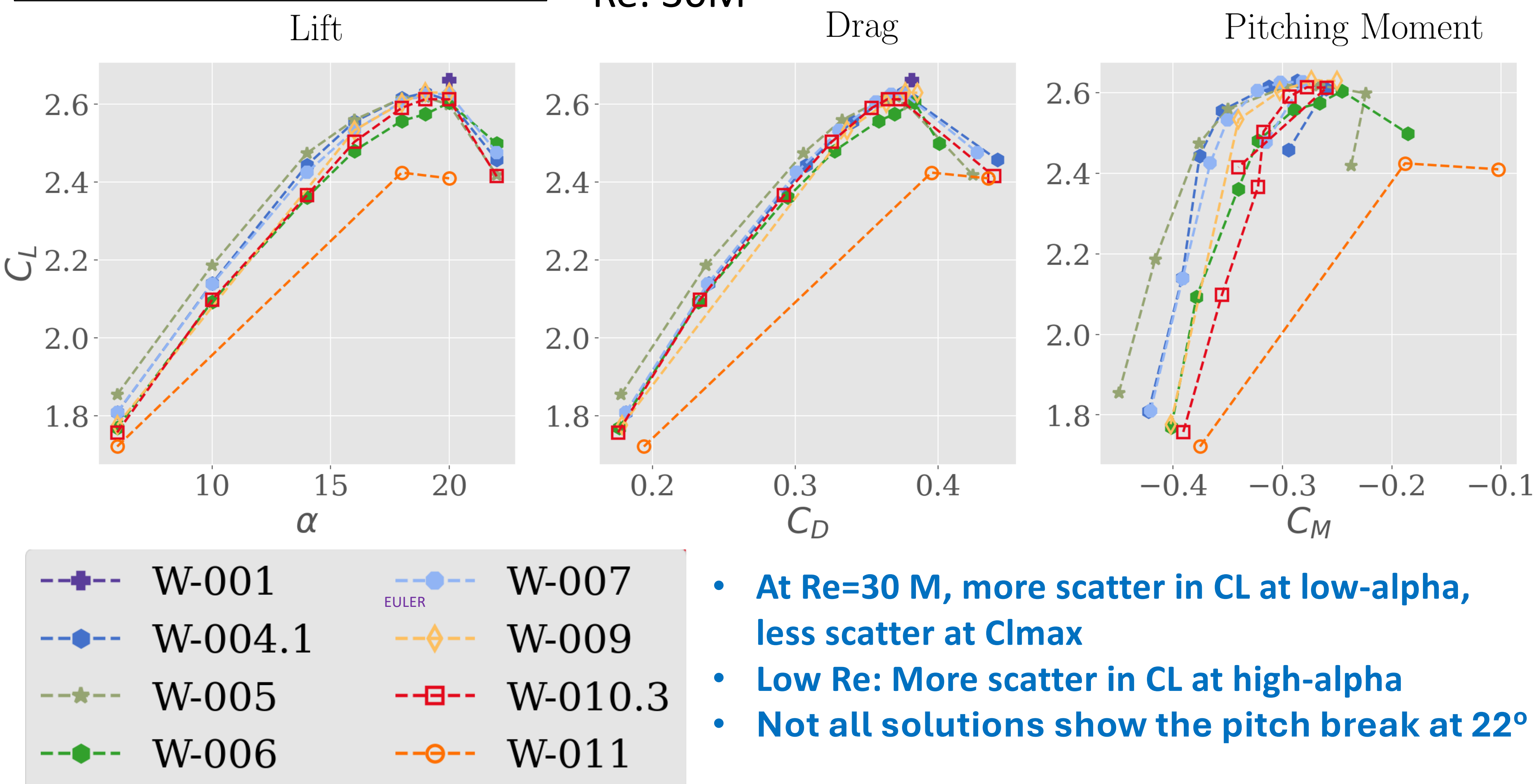
Re: 16M



- As Re number is increased, we observe more scatter in CL at low alpha and CLmax show less scatter compared to Case 3.2
- Not all solutions show the pitch break at 22°

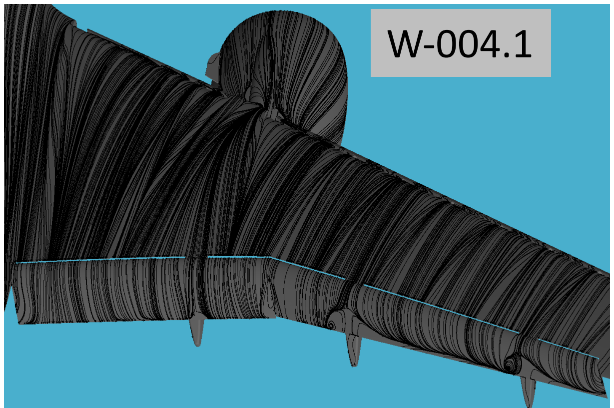
Case 3.4 Integrated F&M

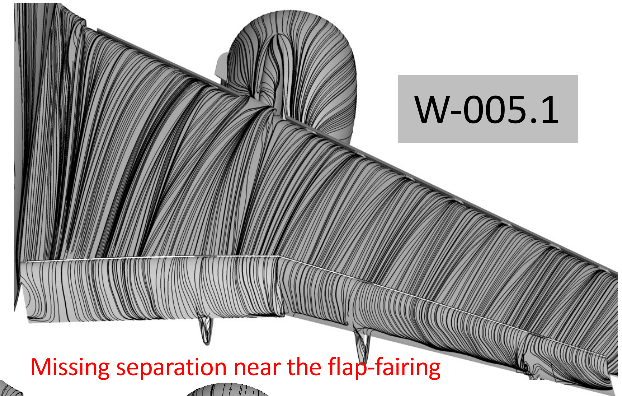
Re: 30M



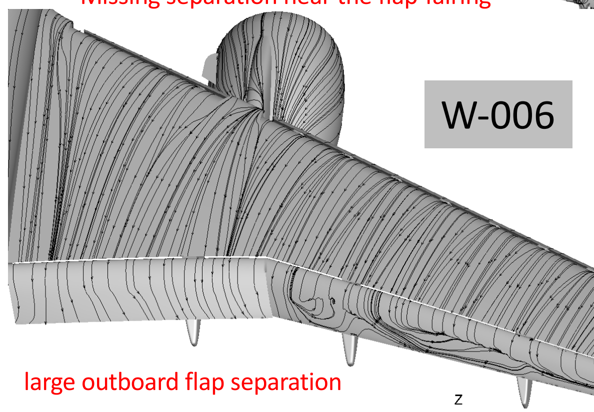
- **At Re=30 M, more scatter in CL at low-alpha, less scatter at Clmax**
- **Low Re: More scatter in CL at high-alpha**
- **Not all solutions show the pitch break at 22º**

Case 3.4: Streamlines $\alpha = 6.0^{o}$

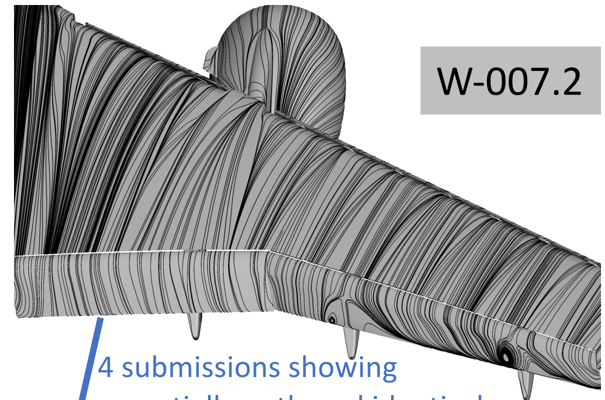




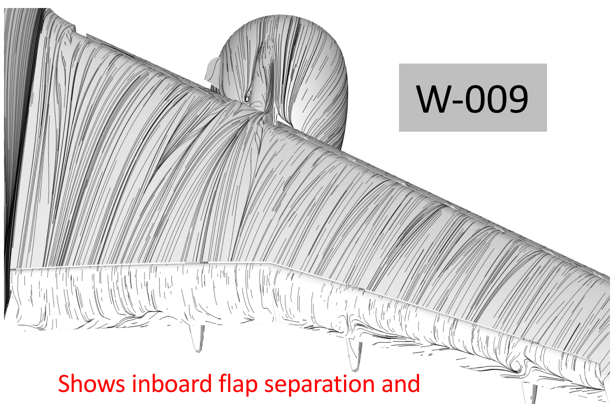
Missing separation near the flap-fairing



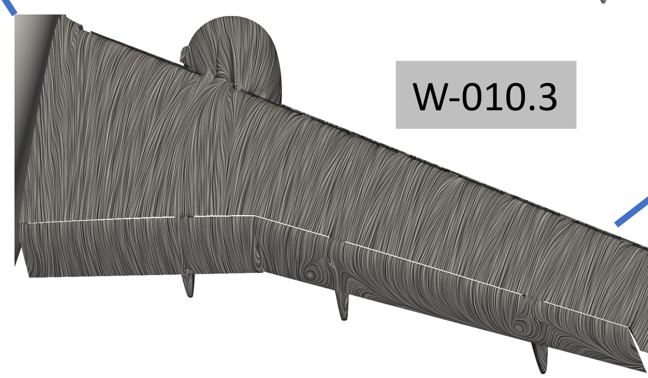
large outboard flap separation

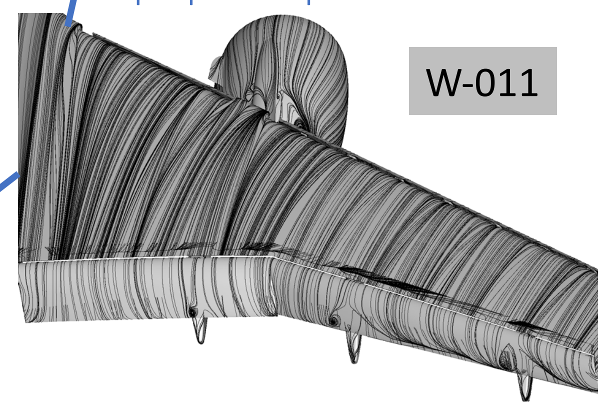


4 submissions showing essentially outboard identical flap separation pattern



Shows inboard flap separation and large outboard flap separation

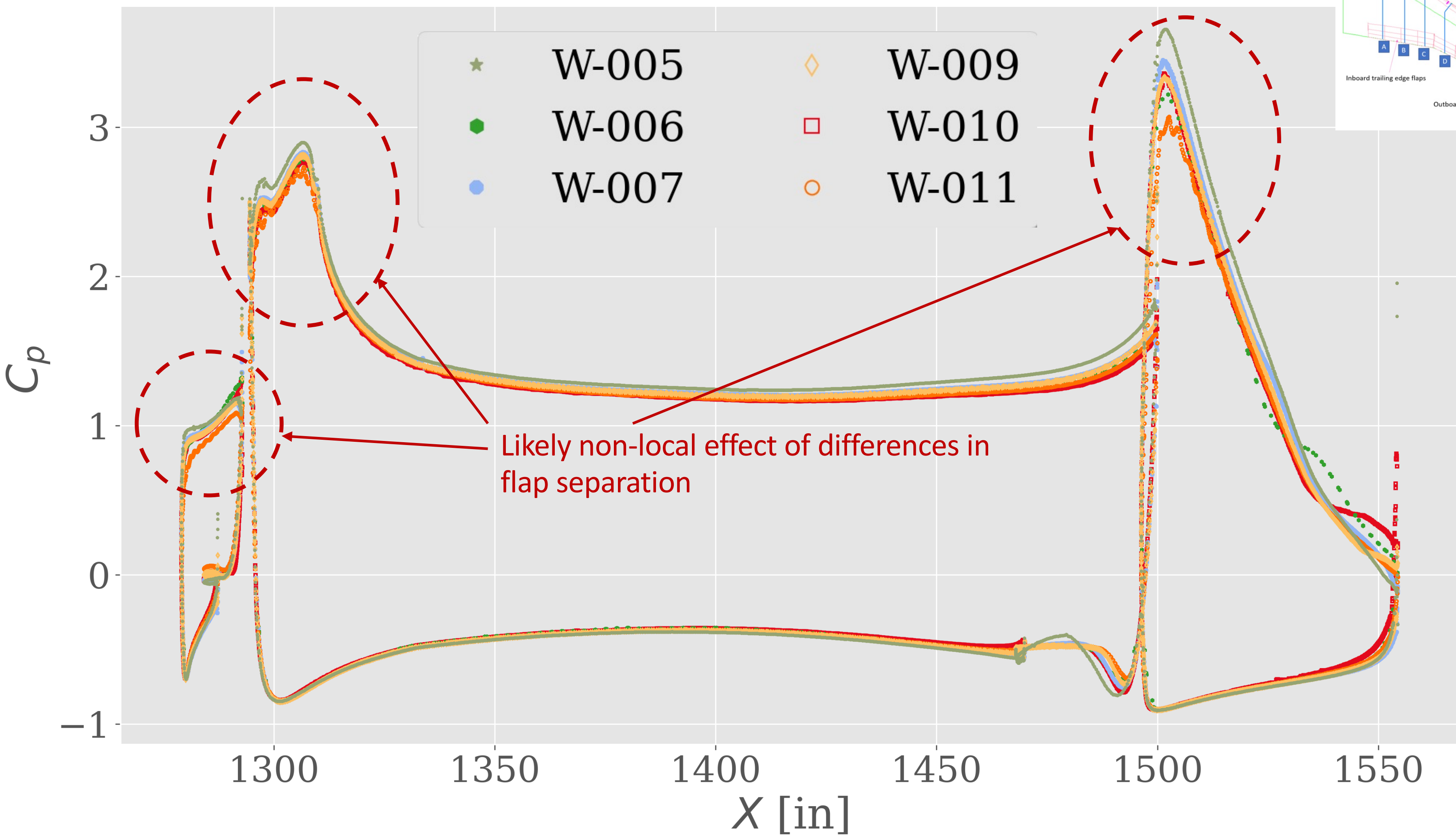


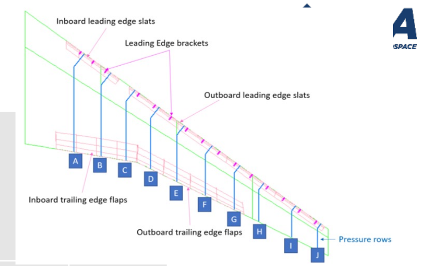


α = 6.0°

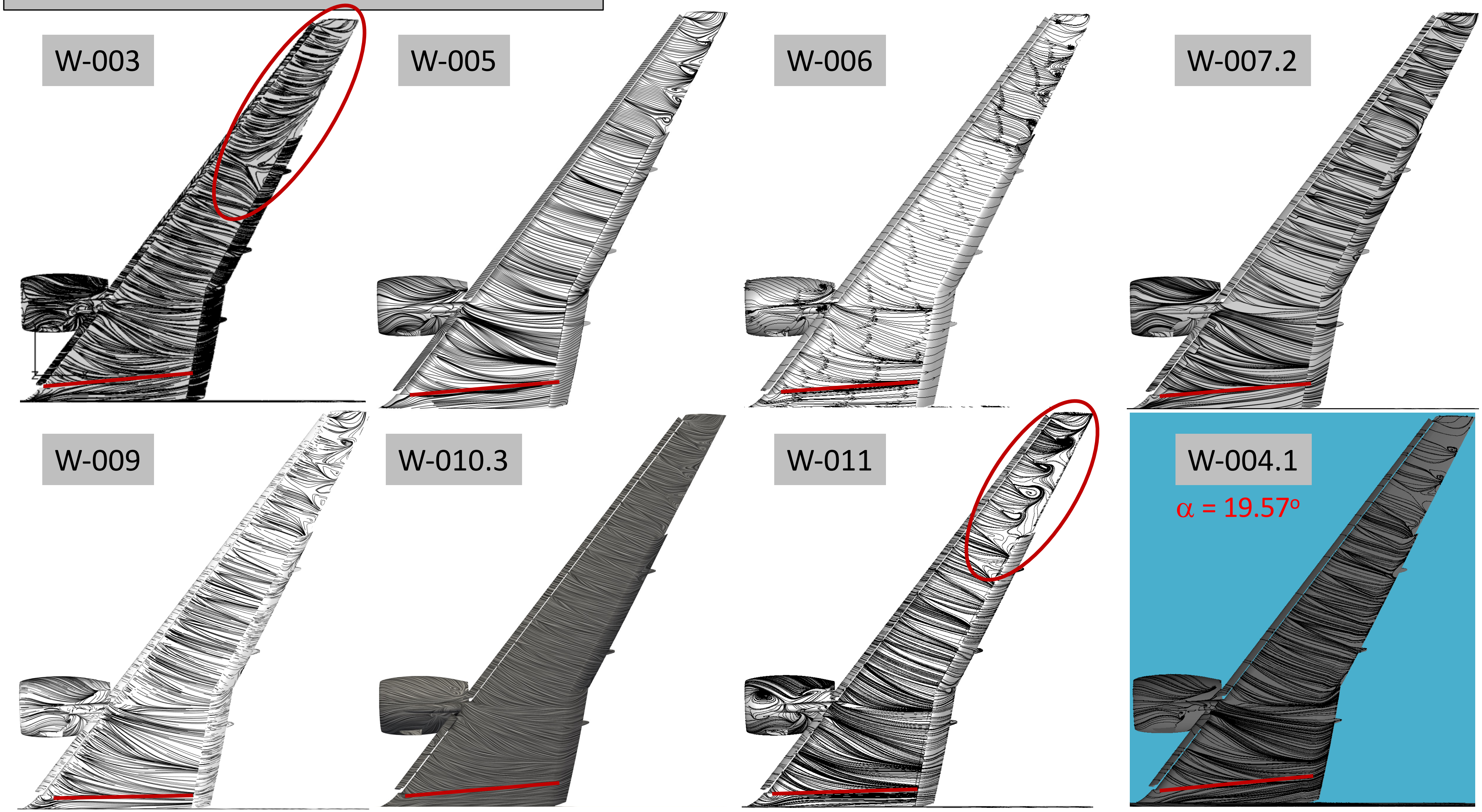
Case 3.4: Cp Cuts(mid-board)

Row D





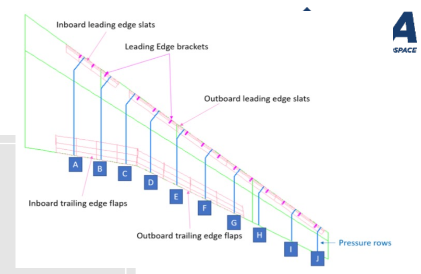
Case 3.4: Streamlines $\alpha = 20.0^{o}$

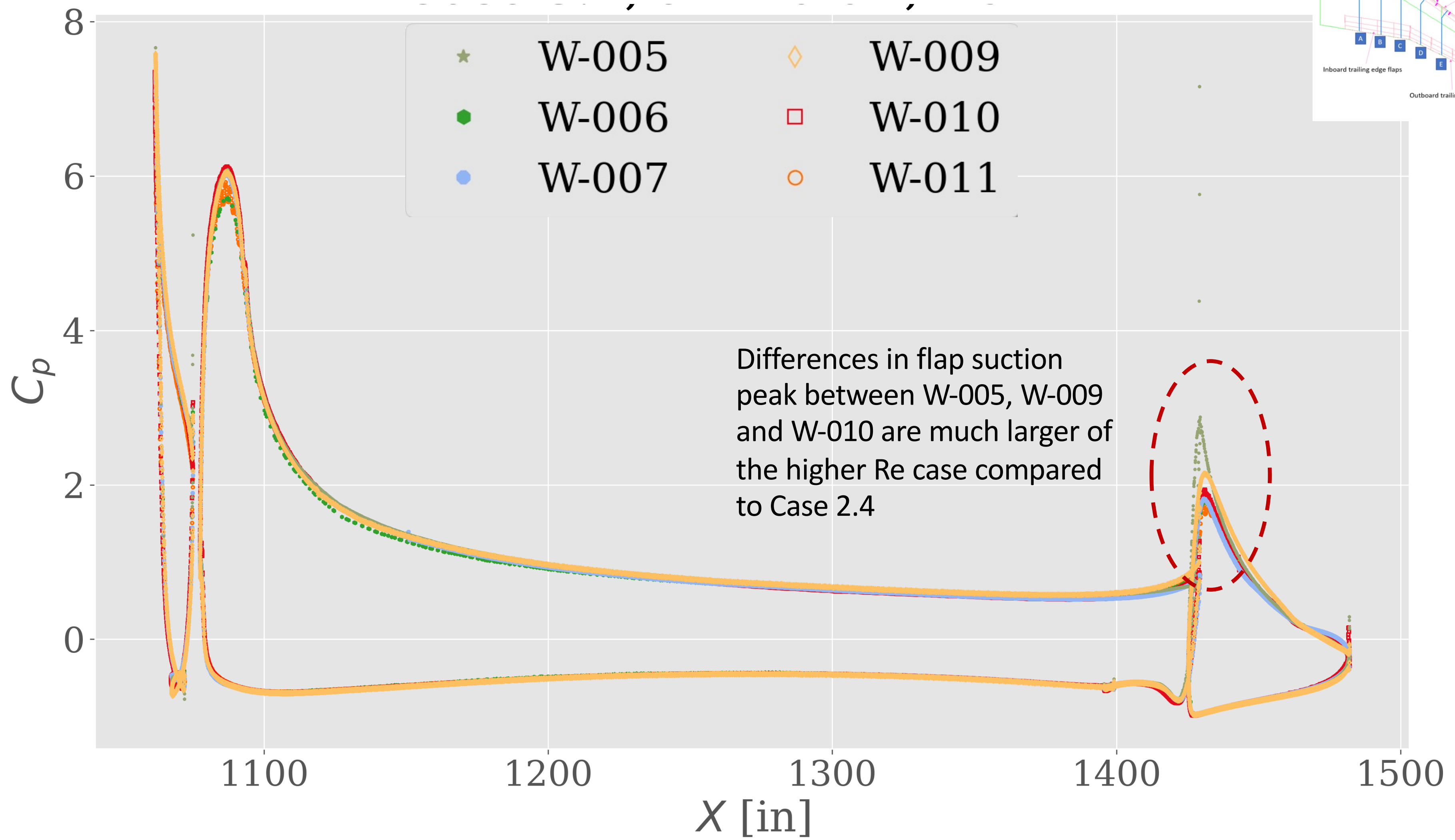


α = 20.0º

Case 3.4: Cp Cuts(in-board)

Row A

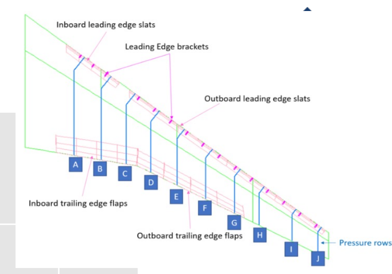


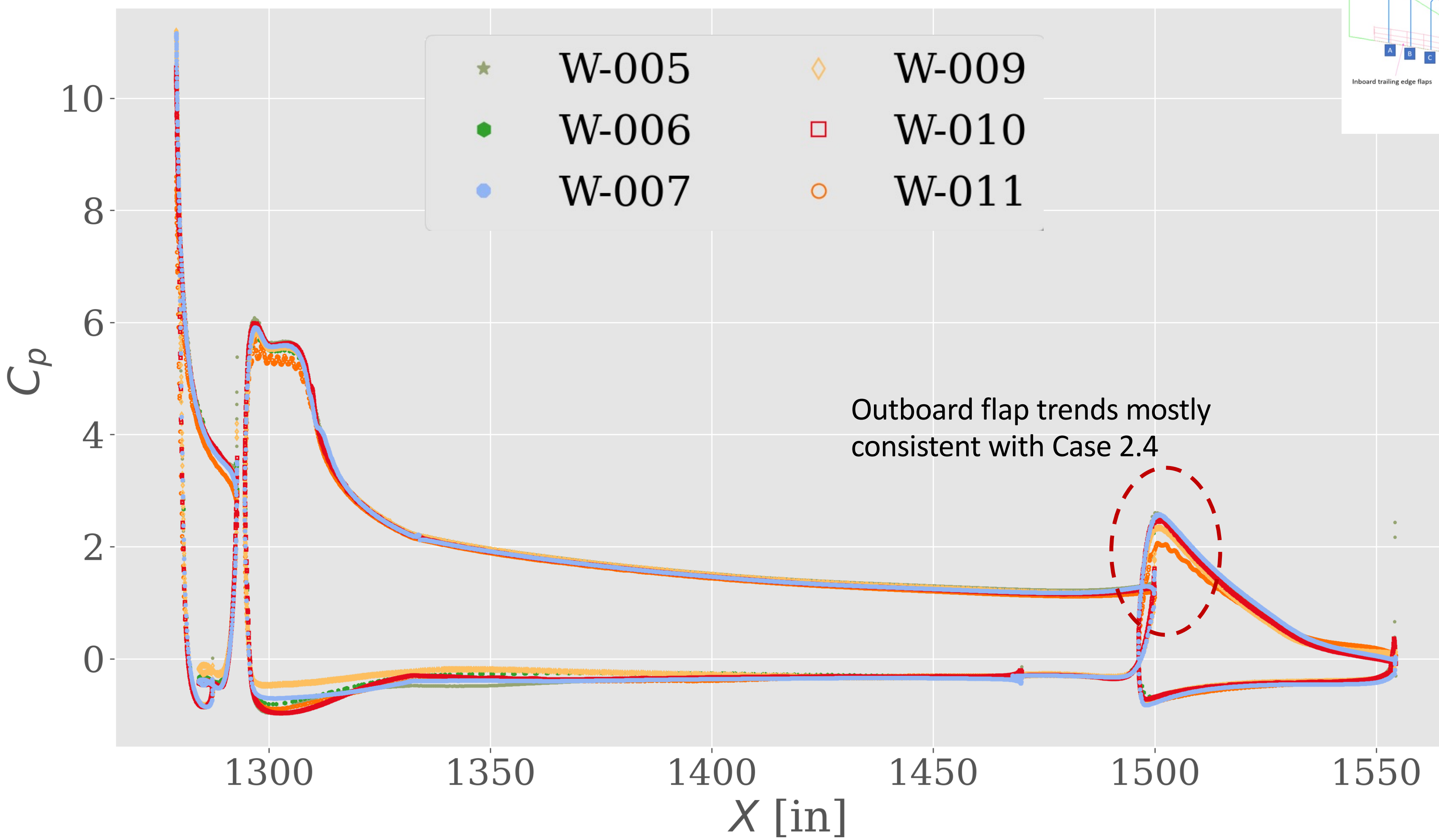


α = 20.0º

Case 3.4: Cp Cuts(mid-board)

Row D

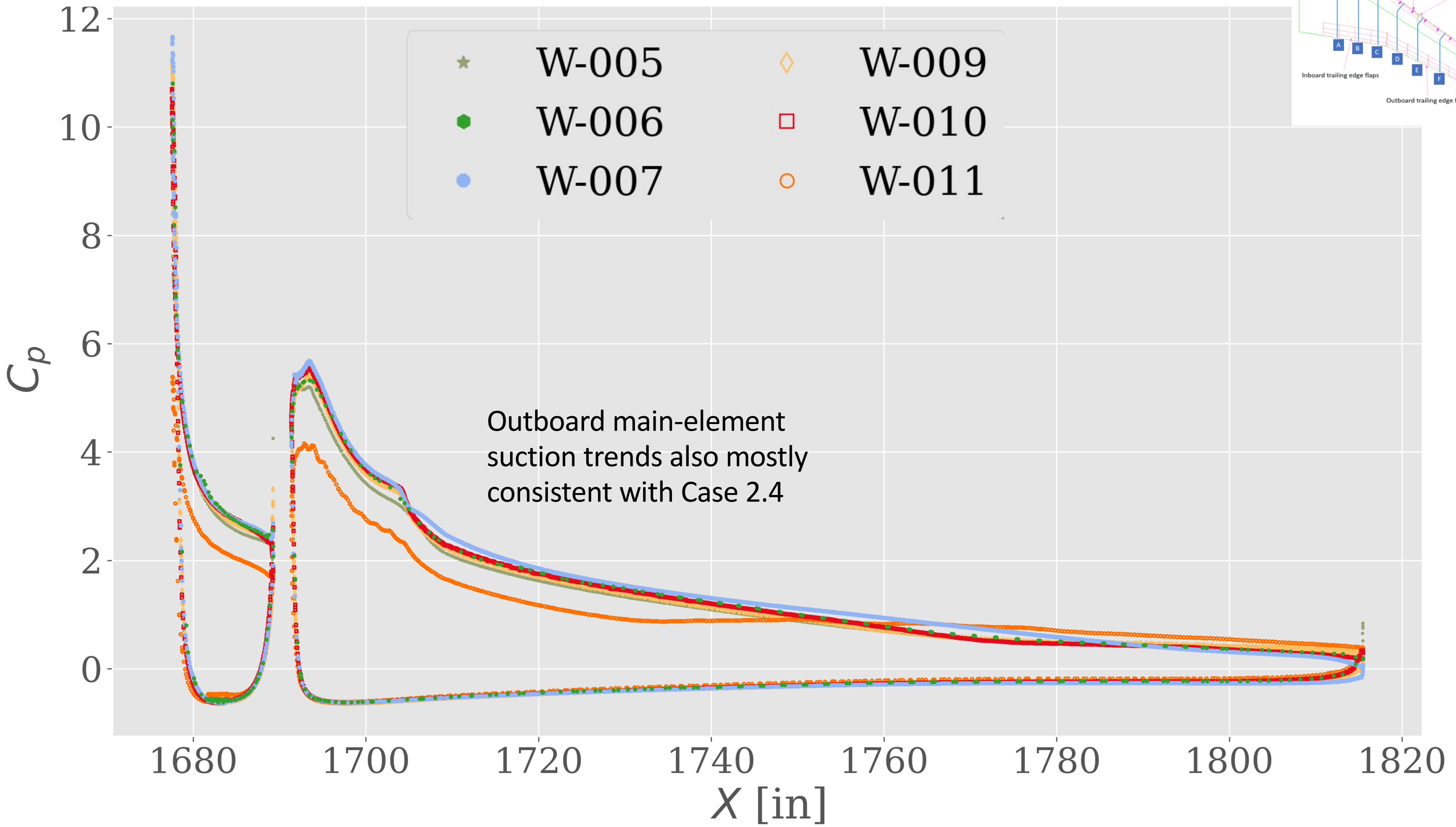




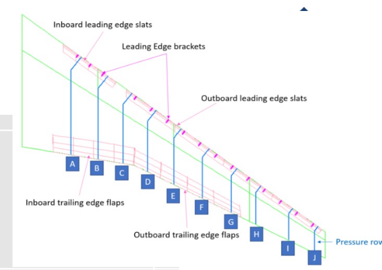
α = 20.0º

Case 3.4: Cp Cuts(out-board)

Row I



Outboard main-element suction trends also mostly consistent with Case 2.4



Conclusions and Outlook

- Participants submitted 500+ simulation results with grid points ranging 120 Million through 11.6 Billion.
- Majority of results for Case 2 are from blind simulations.

- Extensive grid resolution studies were performed.
- Best practice grid results were relatively good agreement with the ONERA WT data (Cases 2.2, 2.3, and 2.4)
  - Flap-separation dominates the low-alpha integrated loads (Cases 2.3, and 2.4)
  - Some submissions under-predict outboard flap flow-separation leading to much higher lift
  - Majority of submissions predict the correct stall-onset mechanism (inboard stall)
  - Most participants predicted the correct qualitative wedge-shaped flow-separation patterns on the outboard wing
  - Coarse grid results suffer predicting Clmax and flow patterns accurately
  - (Euler) submissions has reasonable CLmax value but inaccurate flow (based surface and Cp): lots of error cancellation

- Case 3 submissions showed scatter due to flap suction peak. Finer resolution may be required in these regions even low Re cases (2.4 and 3.2)

- Transition treatment improved CLmax for one participant's results for Case 2.4. Further sensitivity studies are is necessary along with WT data.
- Clean wing WT data will be extremely helpful (Case 1 and/or Case 2.1). WMLES simulations should be carried out exactly how the transition is treated in the experiment.