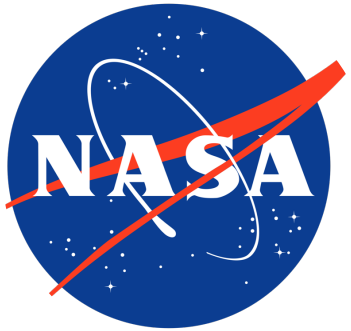
CTR | Stanford University
CENTER FOR TURBULENCE RESEARCH

Slip-wall-modeled large-eddy simulation for prediction of turbulent smooth-body separation

Michael P. Whitmore, Sanjeeb T. Bose[1,2] & Parviz Moin
[1]Cadence Design Systems, San Jose, California
[2]ICME, Stanford University

Advanced Modeling & Simulation (AMS) Seminar Series
NASA Ames Research Center, May 9th, 2024







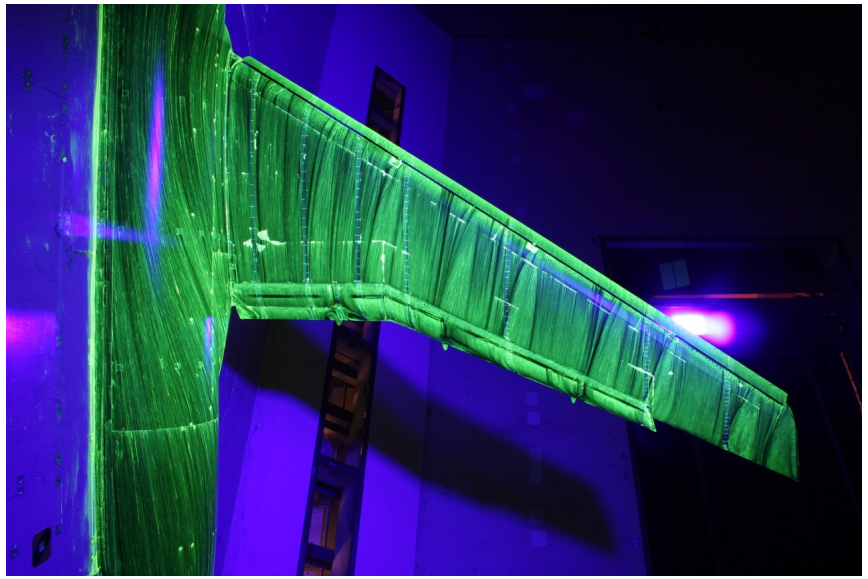


Smooth-body separation is important in many aerodynamic applications

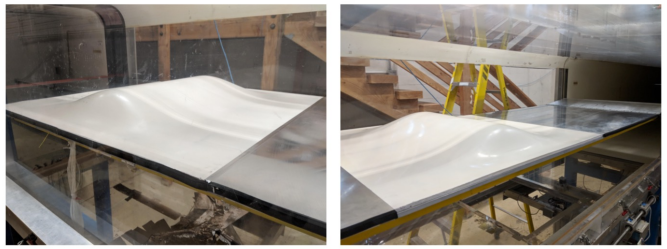
High Lift Aircraft Configurations



HLPW3 JAXA Standard Model



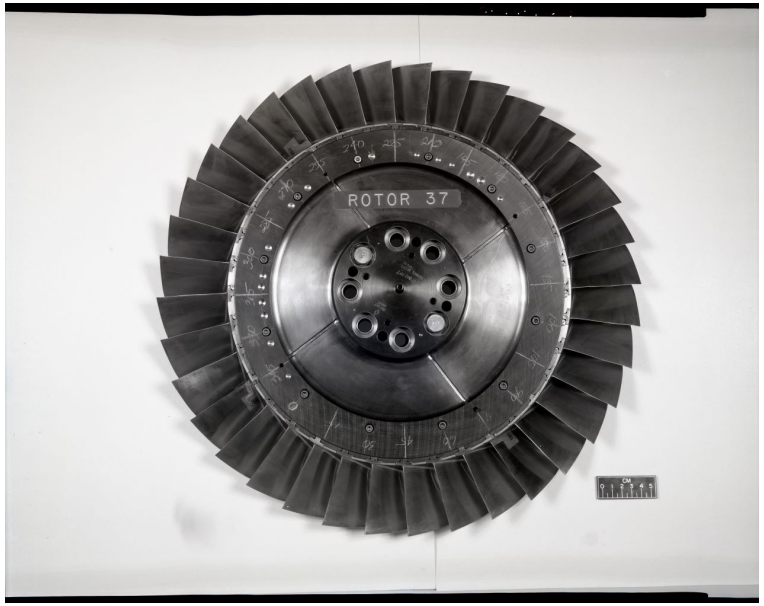
Yokokawa et al. 2008, AIAA 2008-350.



(a) (b)

Boeing speed bump, U. Washington tunnel

Turbomachinery



NASA Rotor 37, image from National Archives

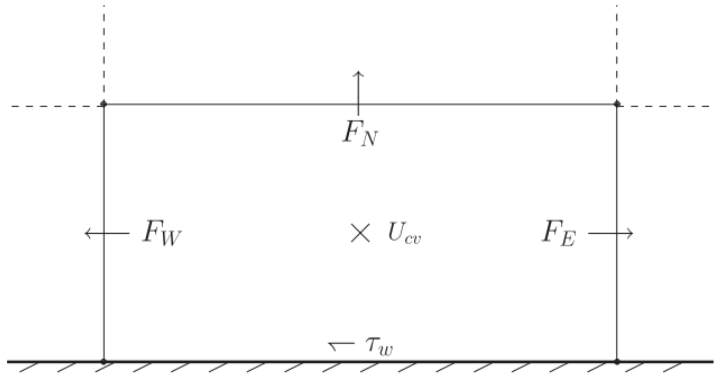
Wall-modeled large-eddy simulation

- WMLES:
  - Simulate wall-bounded turbulent flow w/out significant near-wall grid refinement
  - Model the unresolved flow near the wall



Bose & Park, Ann. Rev. Fluid Mech., 2018

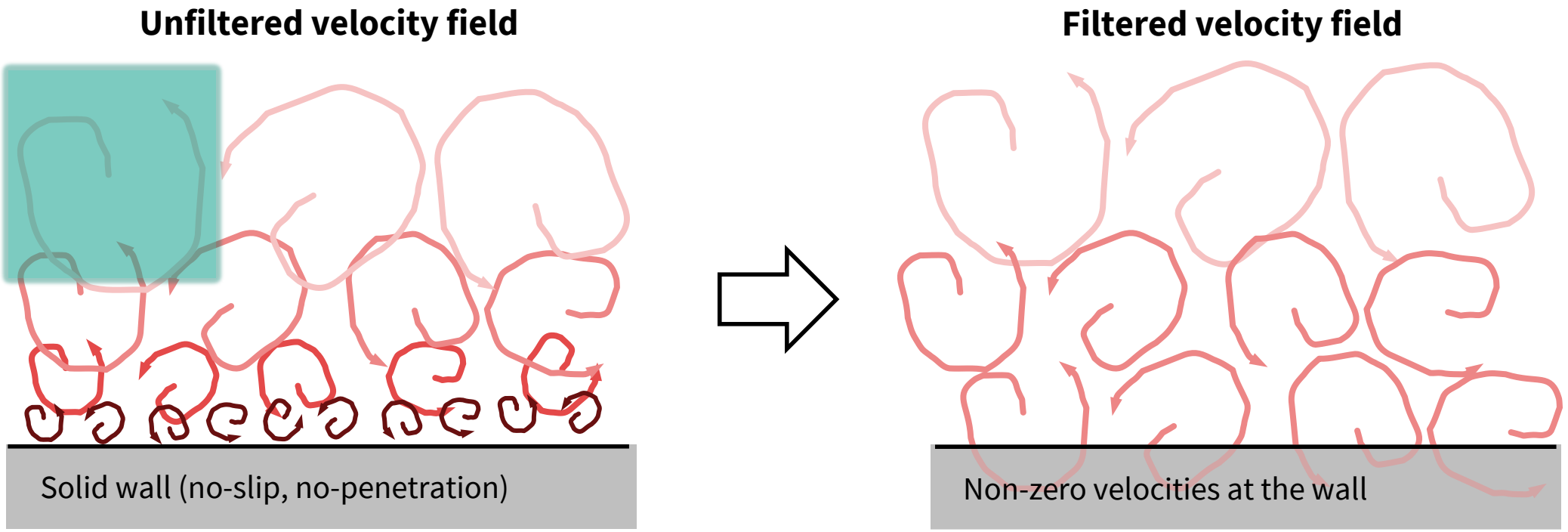
- Traditional wall-stress modeling
  - Suppose for finite-volume cell-averaged solution
  - Closure of LES equation requires wall shear stress τ_w
    - Typically, assume constant shear layer and "equilibrium" RANS eddy viscosity
    - Find τ_w by matching U_{cv} from LES to RANS solution
    - ➔**Equilibrium wall model (EQWM)**
  - Generally, no-penetration condition is preserved



Bose & Moin, Phys. Fluids, 2014

Fixed-width LES filter

- Convolve with fixed-width filter all the way to the wall
- Filtered velocity field permits non-zero velocities at the wall
  - Both tangential slip and transpiration velocities



Slip wall boundary conditions for LES

- Differential filter (elliptic PDE)

$$\bar{\phi} - \frac{\partial}{\partial x_j}\left(p \frac{\partial}{\partial x_j}\bar{\phi}\right) = \phi$$

Germano, Phys. Fluids, 1986.

Filtered quantity — Filter parameter — Unfiltered quantity

- Application of differential filter to Navier-Stokes leads to:
- Slip wall (Robin) BC:

$$\bar{u}_i\Big|_w = C_{slip}\Delta \frac{\partial \bar{u}_i}{\partial x_n}\Big|_w$$

Bose & Moin (2014). Phys. Fluids, 26.
Bae et al. (2019). J. Fluid Mech., 859.

- $C_{slip}\Delta$ is the slip length
  - Δ is the local cell-centered wall-distance

Slip wall boundary conditions for LES

- Slip wall (Robin) BC:

$$\bar{u}_i\Big|_w = C_{slip}\Delta \frac{\partial \bar{u}_i}{\partial x_n}\Big|_w$$

Bose & Moin (2014). Phys. Fluids, 26.
Bae et al. (2019). J. Fluid Mech., 859.

- The slip length $C_{slip}\Delta$ requires modeling
- Generate wall shear stress through resolved Reynolds shear stress

$$\langle \tau_{w,i} \rangle = \mu \left\langle \frac{\partial \bar{u}_i}{\partial x_n} \right\rangle\Big|_w - \rho \langle \bar{u}_i \bar{u}_n \rangle\Big|_w$$

Wall shear stress | Viscous stress | Reynolds shear stress

- Previous work has used static model

$$C_{slip}\Delta = \kappa\Delta \cdot \mathrm{D}(\mathrm{y}_1^+) \sim \ell_m$$

Whitmore et al. Ann. Res. Briefs, CTR, 2021.
Whitmore et al. Ann. Res. Briefs, CTR, 2022.

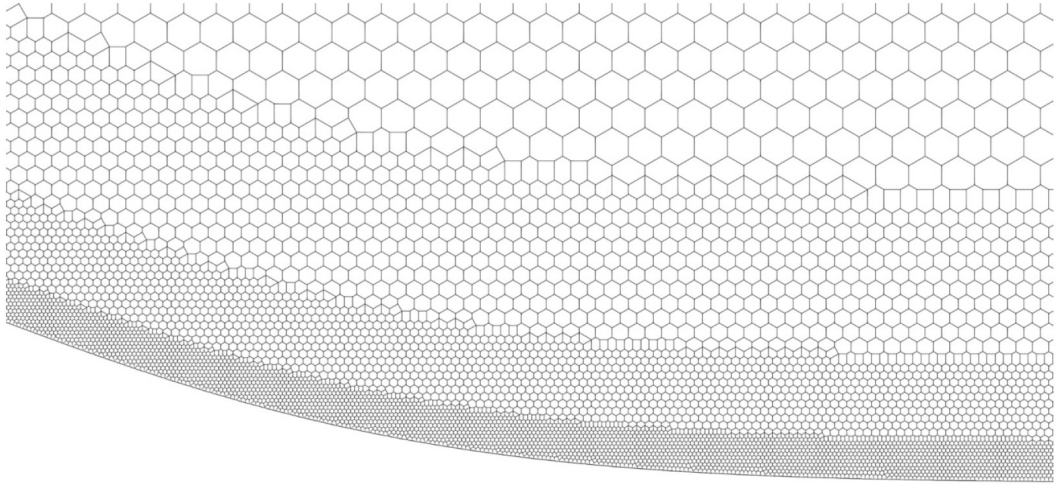
Motivation & objective

- Motivation: Simulate smooth body separation
  - Equilibrium wall model assumptions are violated in separated flow
  - Slip wall models for LES make no assumption about state of boundary layer and have potential for higher fidelity solution of flow separation

- Objective:
  - Evaluate slip wall models on canonical case of smooth body separation (Boeing speed bump)
  - Evaluate slip wall model performance on complex cases (high lift aircraft)
  - Identify ways to improve slip wall models

Computational details

- **charLES*** – compressible finite-volume solver with low-dissipation numerics
- Meshing based on Voronoi tessellations
  - Hexagonally close packed lattice point seeding
  - Layered refinement near walls



A cross-section of the Voronoi mesh generated for charLES simulation with refinement layers

*code from Cadence Design Systems

Subgrid-scale modeling

- ***Dynamic Smagorinsky*** SGS model used in this study
  - Germano et al. (1991). Phys. Fluids A, 3.
  - Moin et al. (1991). Phys. Fluids, 3.

- Focus of this work is on role of wall model in separation prediction
  - DSM is considered current best practice

- Work on non-linear SGS models suggests SGS model plays a role in separation predictions of WMLES
  - Agrawal, Whitmore, Griffin, Bose & Moin. (2022). Phys. Rev. Fluids, 7.
  - Zhou & Bae. (2024). J. Comp. Phys., 506.
  - Iyer & Malik. (2022). ICCFD11.

Outline

- Introduction
- **Canonical smooth body separation**
  - **Boeing speed bump**
- High lift aircraft simulations
  - JAXA Standard Model
  - NASA CRM-HL
- Fundamental improvements for slip wall models

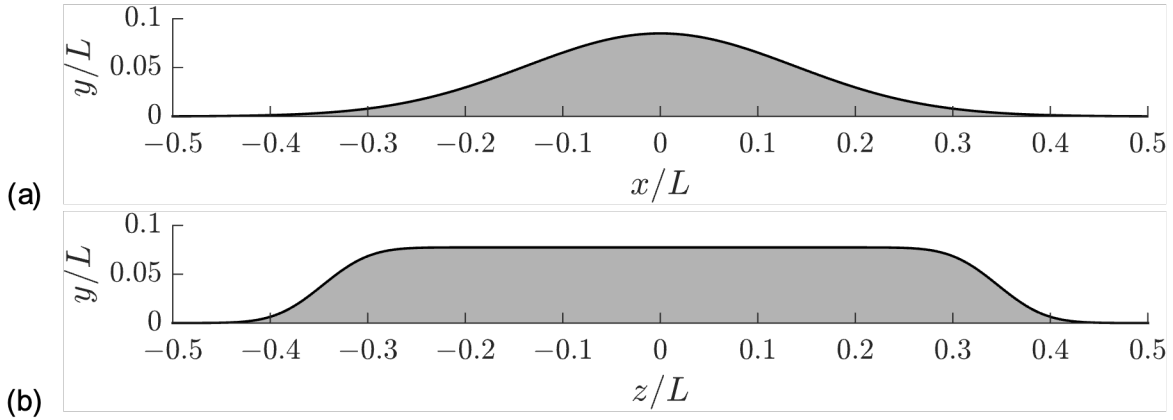
Boeing speed bump

- Boeing speed bump
  - $Re_L = 3.4\times10^6$
- Experiments
  - Williams et al., 2020. (C_p reference)
  - Gray et al., 2022. (C_f reference)



UW experimental setup

- More robust separation prediction with slip wall model, compared to EQWM
  - Whitmore et al., 2022, CTR Ann. Res. Briefs.

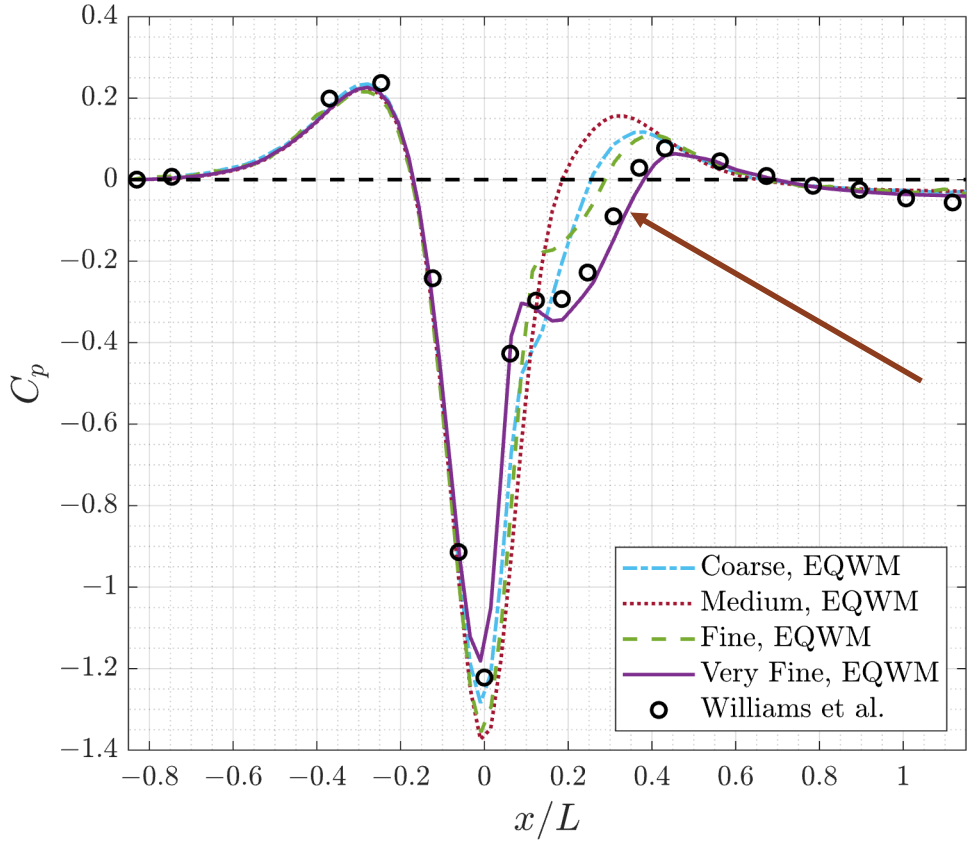


Boeing speed bump

More robust separation prediction with slip WM

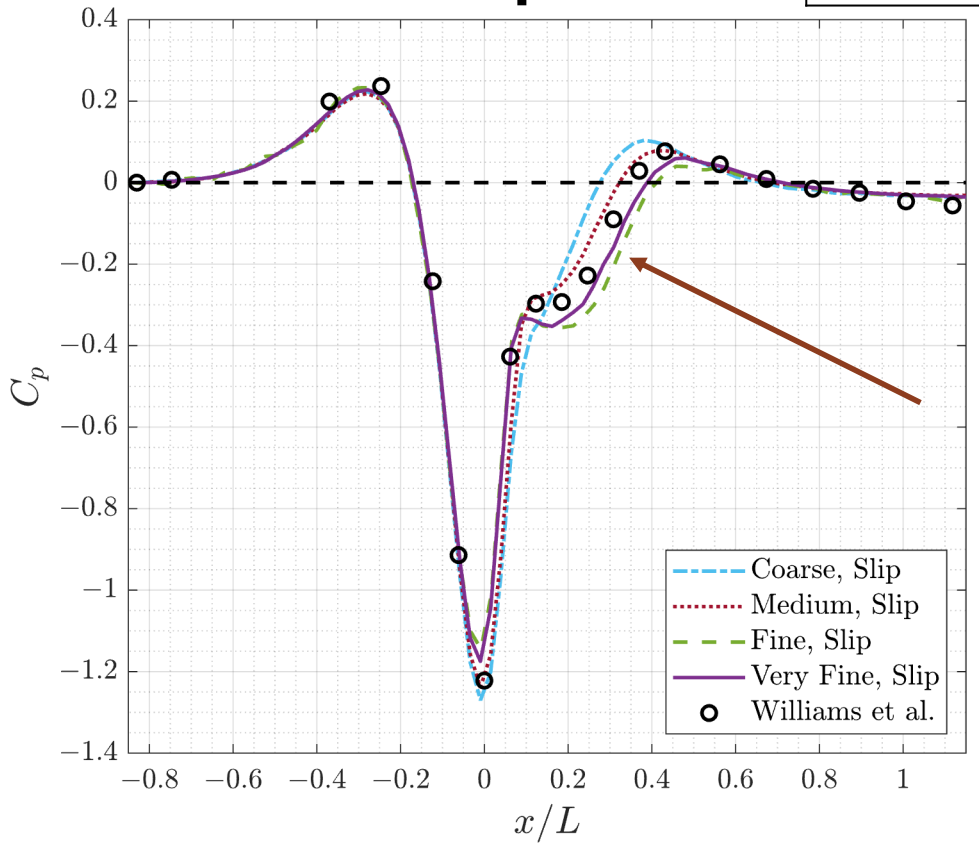
Mesh	Ncv (million)	$\min_{x<0} y_1^+$
Coarse	29.0	~60
Medium	77.6	~28
Fine	452	~14
Very Fine	1,830	~7

EQWM



- Non-monotonic prediction of separation bubble and slow convergence

Slip WM

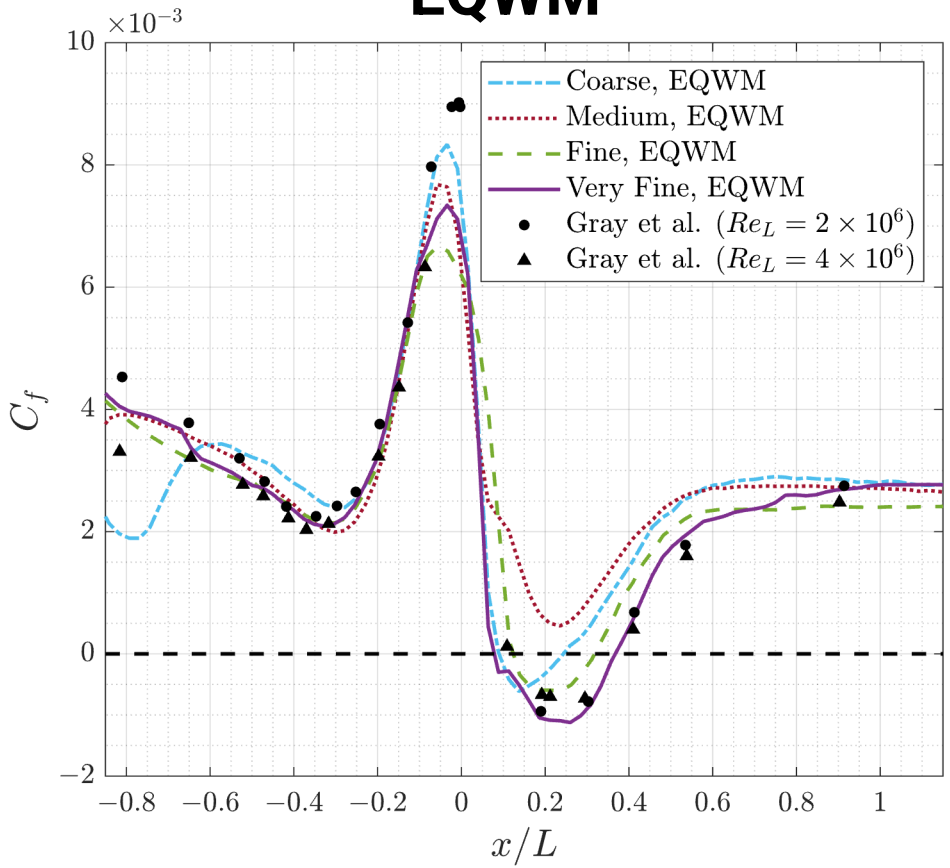


- Prediction of separation on all grids with fast convergence

Boeing speed bump

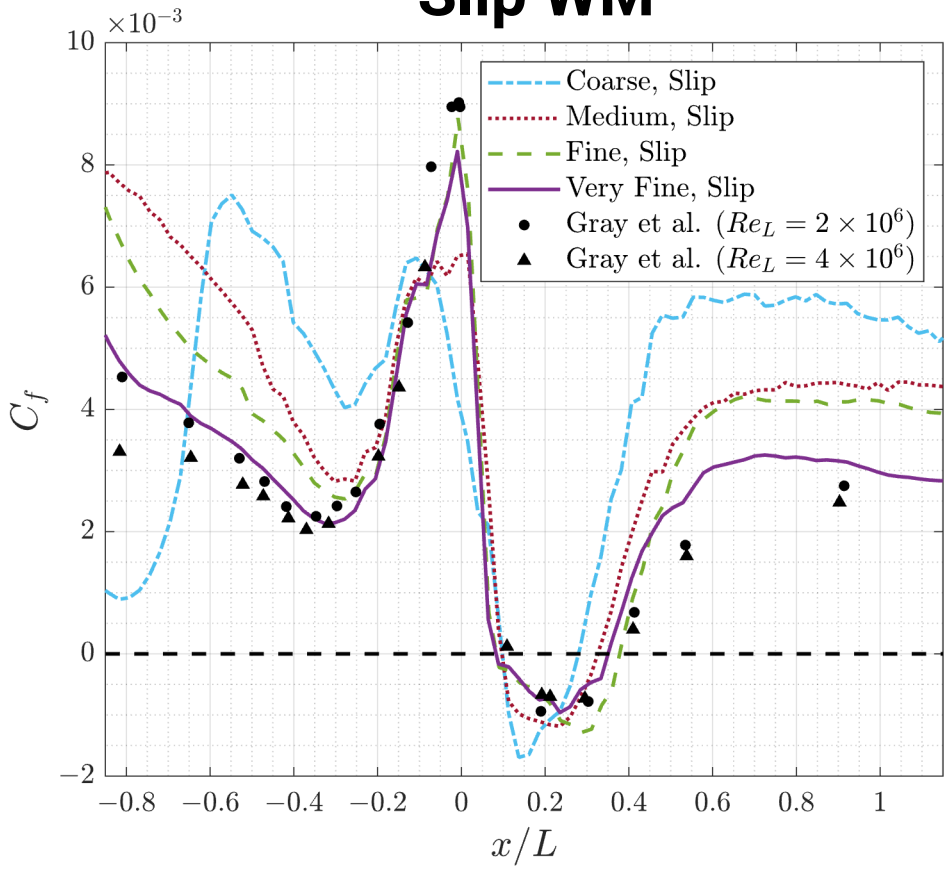
More robust separation prediction with slip WM (but slow ZPG C_f convergence)

EQWM



- Non-monotonic prediction of separation bubble
- Captures ZPG skin friction as expected

Slip WM

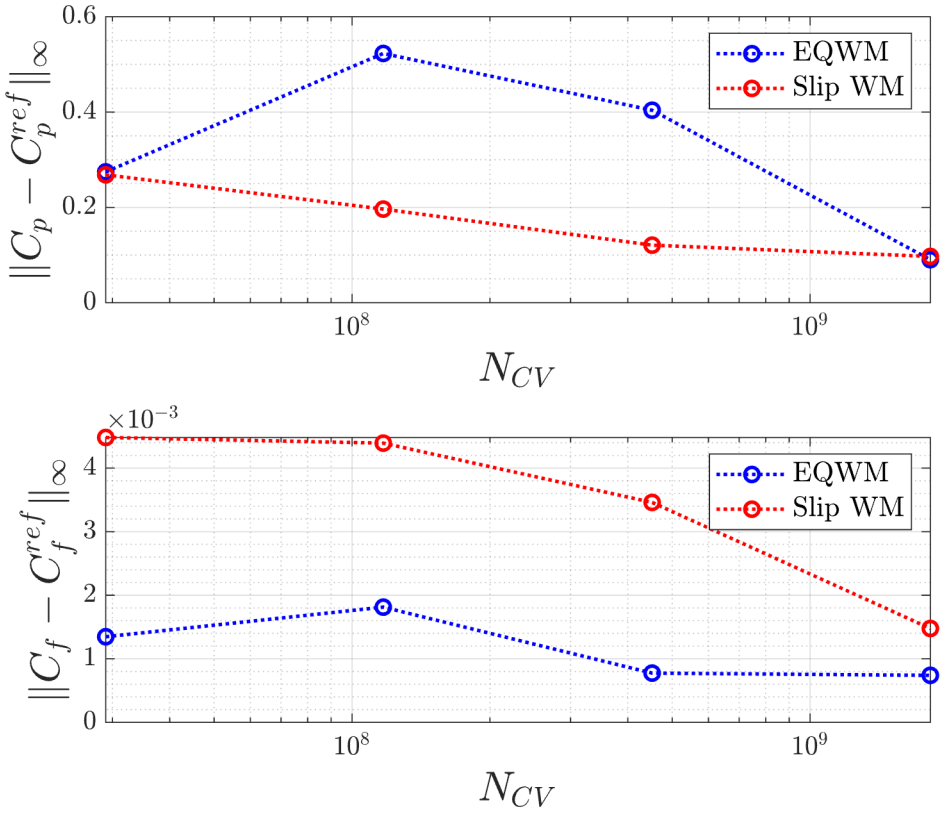


- Prediction of separation on all grids
- Needs a lot of grid refinement to capture correct skin friction

Boeing speed bump

More robust separation prediction with slip WM (but slow ZPG C_f convergence)

- Global error convergence in C_p and C_f via ∞-norm



- Slip WM monotonically converges in C_p
- More accurate overall

- Slip WM slower to converge in C_f
- Poor at coarse resolutions

Boeing speed bump: summary

- Slip wall model can capture separation bubble robustly across grids
  - Allows reasonably accurate prediction of pressure forces on this geometry

- Skin friction tends to be overpredicted by this slip length model ($\kappa \Delta D$)
  - Especially in **coarse, high-Re, attached** flows

Whitmore et al. Ann. Res. Briefs, CTR, 2021.
Whitmore et al. Ann. Res. Briefs, CTR, 2022.

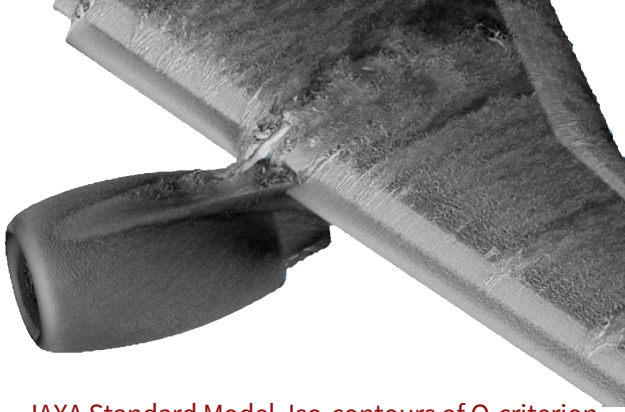
- Open question: How can the slip length be modeled to more accurately capture coarse, high-Re, attached flow?

Outline

- Introduction
- Canonical smooth body separation
  - Boeing speed bump
- **High lift aircraft simulations**
  - **JAXA Standard Model**
  - **NASA CRM-HL**
- Fundamental improvements for slip wall models

JAXA Standard Model

- Subject of 3rd High Lift Prediction Workshop
- $Re_{MAC} \approx 2{\times}10^6$, wind tunnel
- $\alpha = 4^\circ$ exhibits difficult to predict flap separation
  - Equilibrium wall model has diminished flap separation on grid refinement
  - Goc et al., Flow 1, 2021.



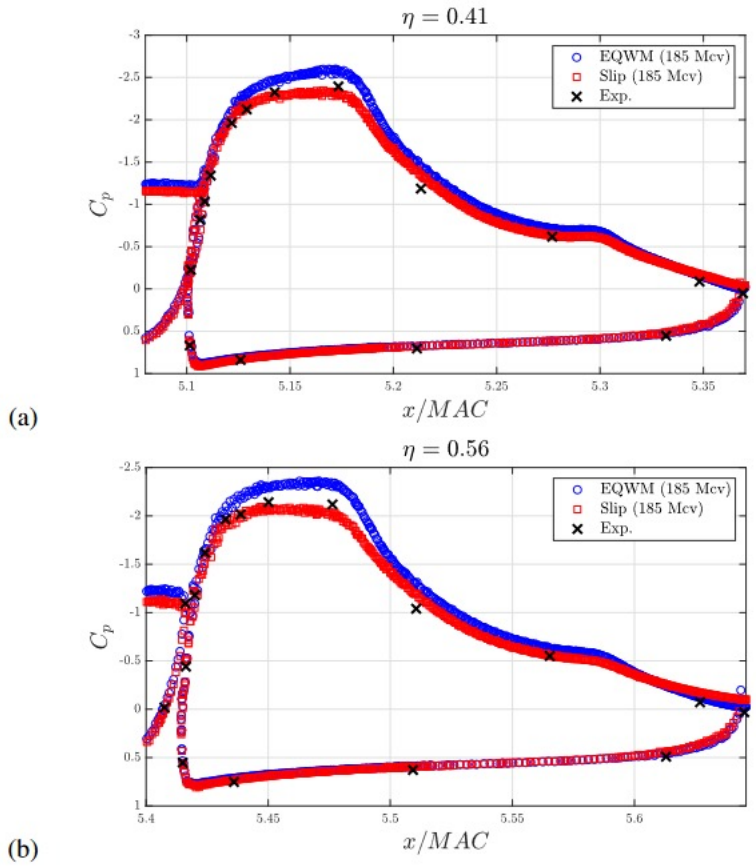
JAXA Standard Model, Iso-contours of Q-criterion
Goc et al. (2021). Flow 1.



HLPW3 – Half-span model wall mounted in JAXA tunnel

JAXA Standard Model

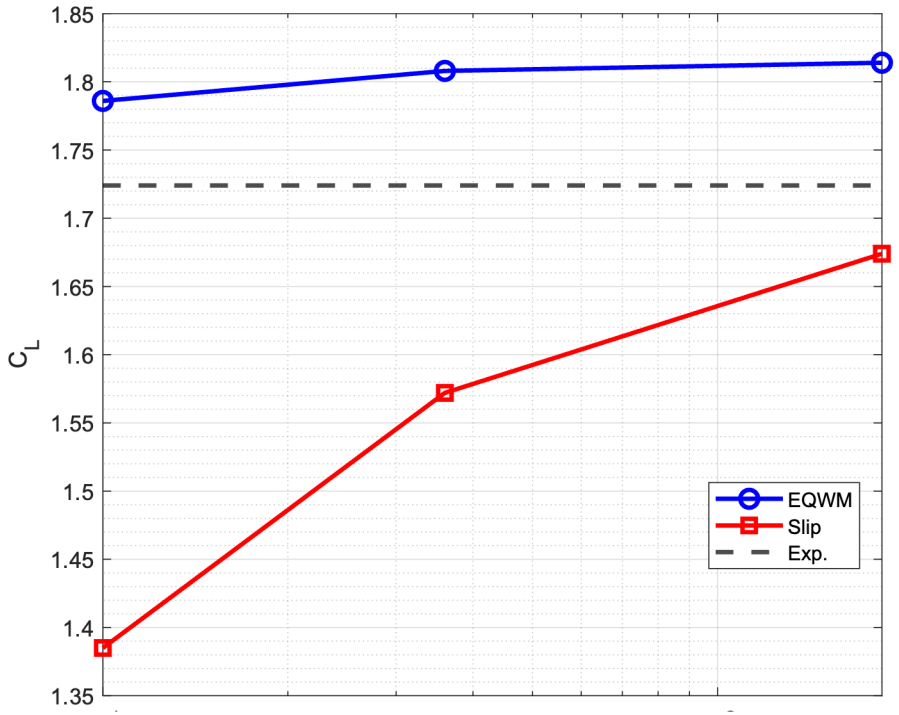
- $\alpha = 4°$ exhibits difficult to predict flap separation
  - Equilibrium wall model has diminished flap separation on grid refinement
  - Goc et al., Flow 1, 2021.
- Static slip WM improves flap separation prediction at 185 Mcv refined grid resolution



Midboard flap pressure belts

JAXA Standard Model

- $\alpha = 4°$ exhibits difficult to predict flap separation
  - Equilibrium wall model has diminished flap separation on grid refinement
  - Goc et al., Flow 1, 2021.
- Static slip WM converges slowly with grid resolution compared to EQWM
  - Tends to over-separate at coarser resolutions



Recall: Static slip WM overpredicts skin friction in coarse, high-Re, attached flow
Question: How can the slip length be modeled to more accurately capture coarse, high-Re, attached flow?

Optimal slip length approach: Turbulent channel

- Objective function: error in skin friction

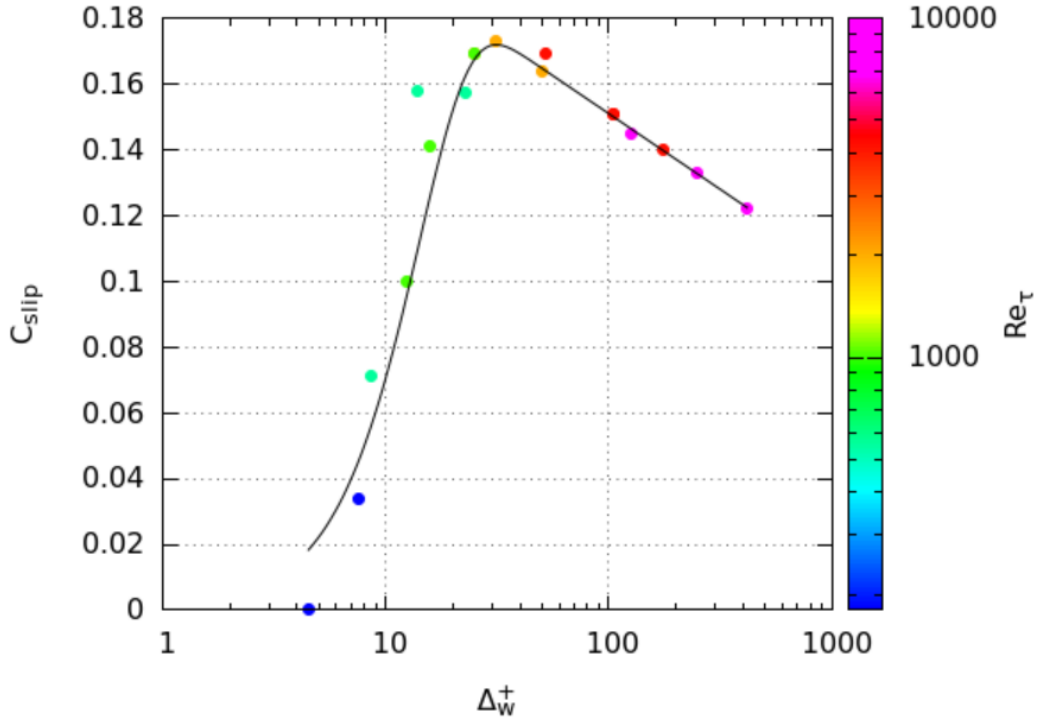
$$J(C_{slip}) = \frac{1}{2}\int \left[C_f(C_{slip}) - C_f^{ref}\right]^2 dA\,; \qquad \min_{C_{slip} \in \mathbb{R}_{\geq 0}} J(C_{slip})$$

- Allows optimization of slip coefficient via *a posteriori* simulation
- Turbulent channel: range of friction Reynolds numbers: $\boldsymbol{180 \leq Re_\tau \leq 10^4}$
  - Varied grid resolution: $\delta/\Delta_y \in \{12, 20, 32, 40\}$
  - $Re_\tau \in \{180, 395, 550, 10^3, 2000, 4200, 10^4\}$
- DNS statistics references:
  - Moser, Kim, & Mansour, Phys. Fluids 11, 1999.
  - Del Alamo & Jimenez, Phys. Fluids 15, 2003.
  - Lozano-Duran & Jimenez, Phys. Fluids 26, 2014.
  - Oberlack et al., Phys. Rev. Lett. 128, 2022.

Whitmore et al., CTR Ann. Res. Briefs, 2023.

Optimal slip results: channel

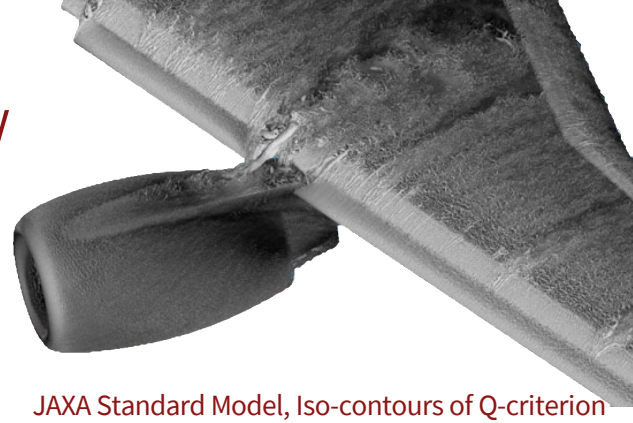
- Optimal slip length decays towards zero in limit $\Delta_w^+ \to 0$
  - Δ_w is an isotropic grid length scale
  - Consistent with no-slip BC in DNS limit
- At higher Re_τ slip length peaks around 0.17 and starts to decrease
- Result is unexpectedly smooth
  - Conducive to a data fit



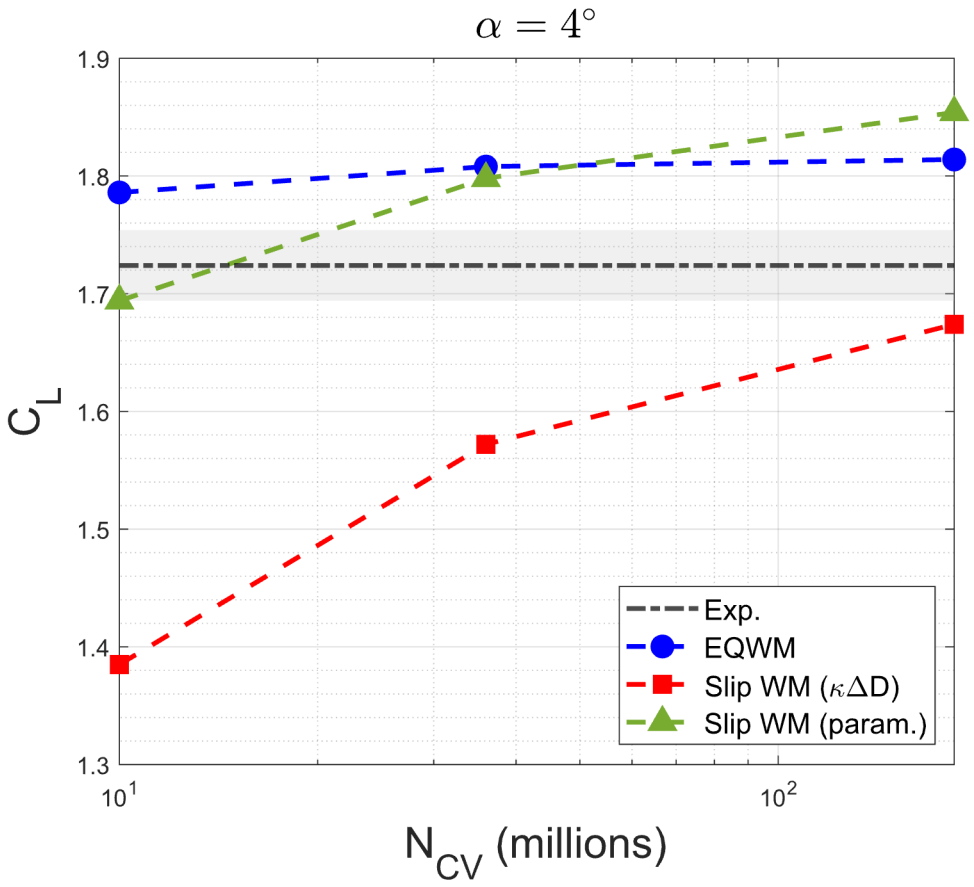
Whitmore et al., CTR Ann. Res. Briefs, 2023.

Applying parameterized slip to complex flow
JAXA Standard Model

- JAXA Standard Model
  - $Re_{MAC} \approx 2\times10^6$, wind tunnel
- $\alpha = 4°$ exhibits difficult to predict flap separation
  - Equilibrium wall model has diminished flap separation on grid refinement
  - Goc et al., Flow 1, 2021.
- Directly applying slip parameterization from channel effectively reproduces EQWM grid refinement behavior
  - → Slip length must also account for pressure gradient effects



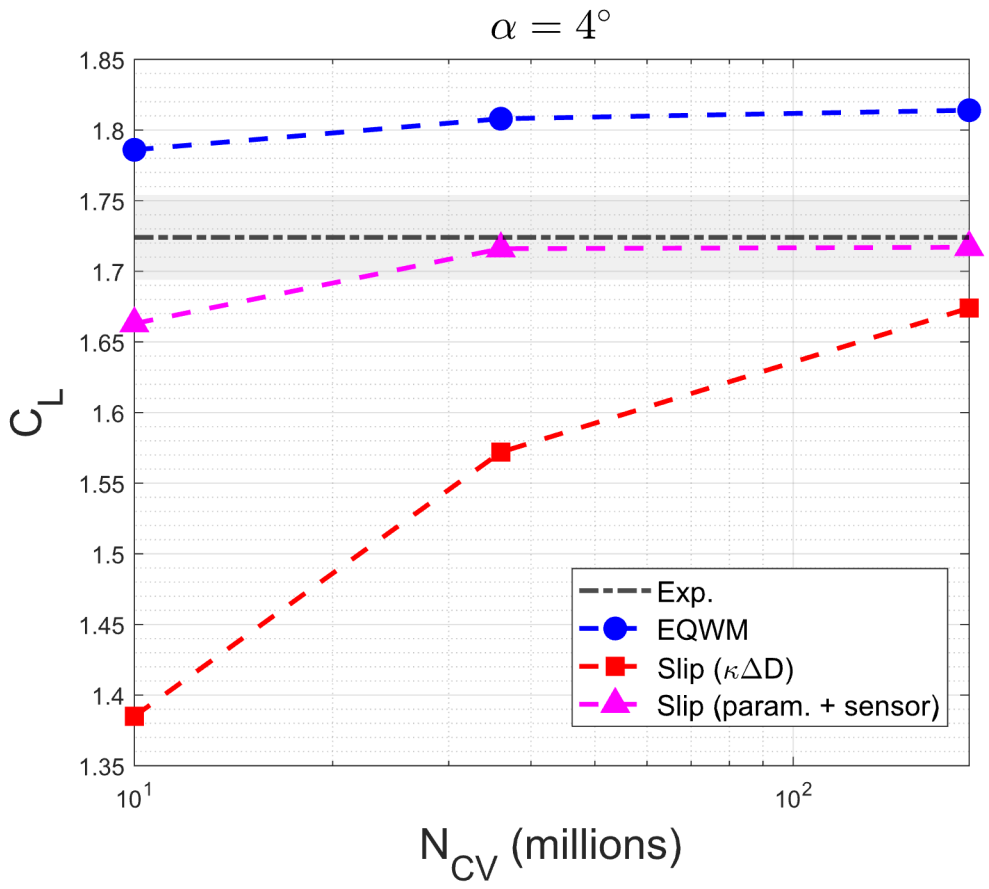
JAXA Standard Model, Iso-contours of Q-criterion
Goc et al. (2021). Flow 1.



Parameterized slip with pressure-gradient sensor
JAXA Standard Model

- We need to account for pressure gradients
  - $u_p = \left(\frac{\mu}{\rho^2}\left|\frac{\partial p}{\partial s}\right|\right)^{1/3}$; $\quad u_\tau = \left(\frac{\tau_w}{\rho}\right)^{1/2}$
- Sensor-based form:
  - If $u_p > u_\tau$:
    - use $C_{slip}\Delta = \kappa\Delta$
  - If $u_p \leq u_\tau$:
    - use the channel parameterization
  - Sensor reference:
    - Agrawal et al., CTR Ann. Res. Briefs, 2022.
- Slip parameterization with sensor recovers more accurate result on intermediate & refined grid!

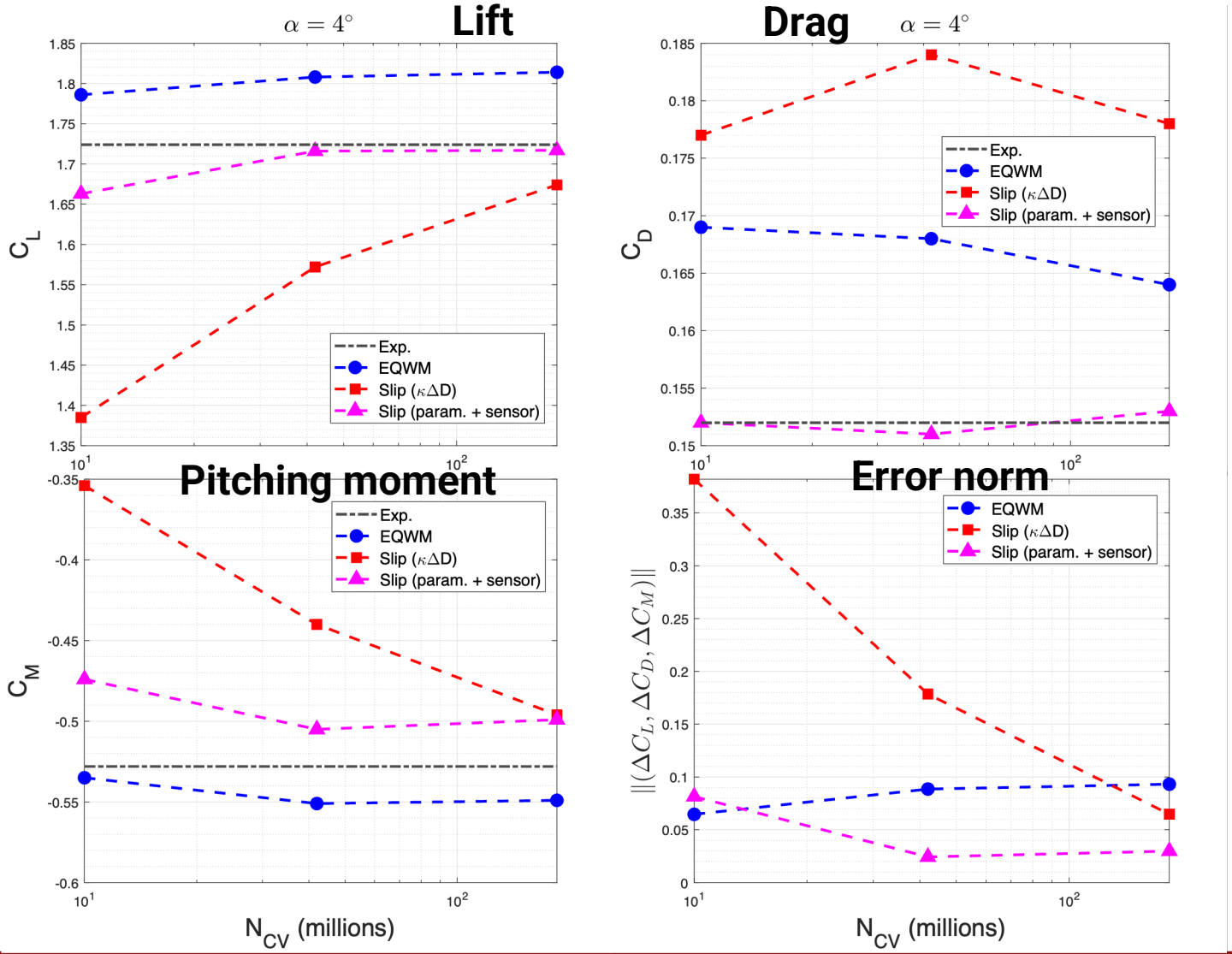
Whitmore et al., AIAA SciTech, 2024.



Parameterized slip with pressure-gradient sensor

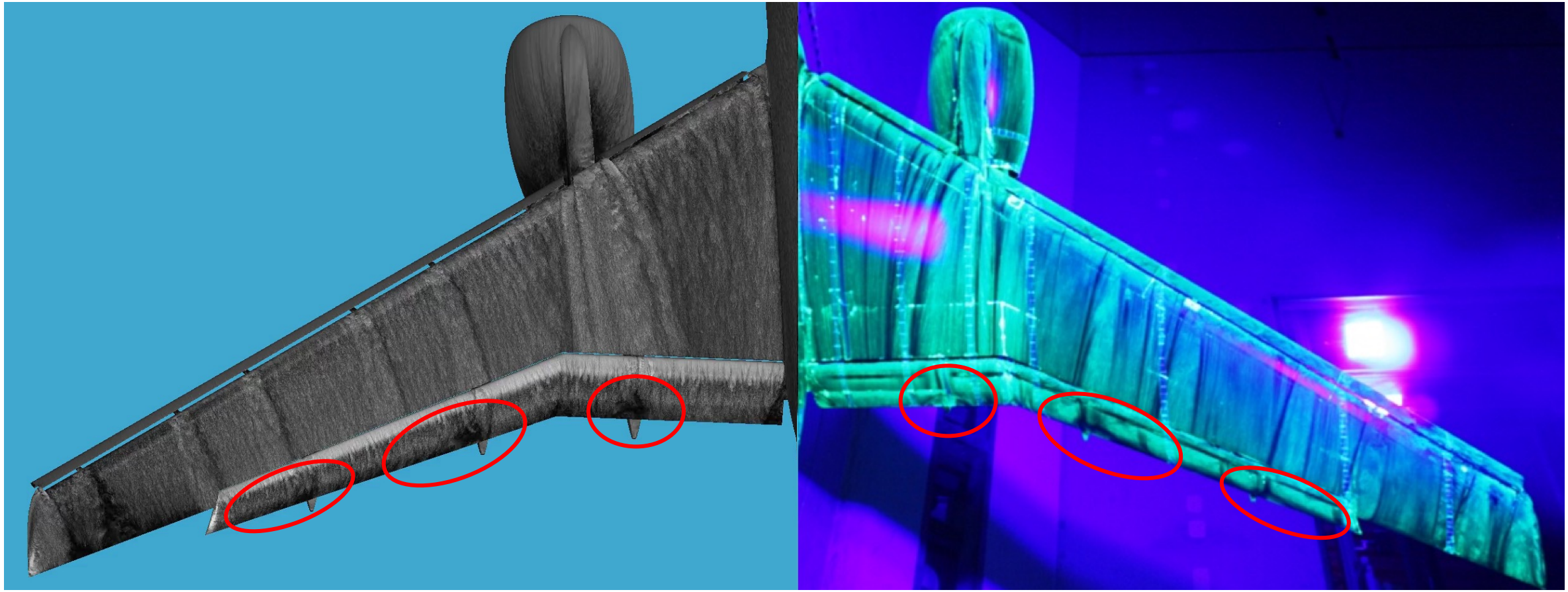
JSM: Lift, Drag, Pitching moment, Total error

- $\alpha = 4°$
- Sensor-based slip converges most quickly in lift, drag
  - Pitching moment comparable to EQWM
- Overall error norm shows sensor-based slip performing best
  - $\|(\Delta C_L, \Delta C_D, \Delta C_M)\|_2$



Instantaneous projected near-wall velocity, JSM $\alpha = 4°$

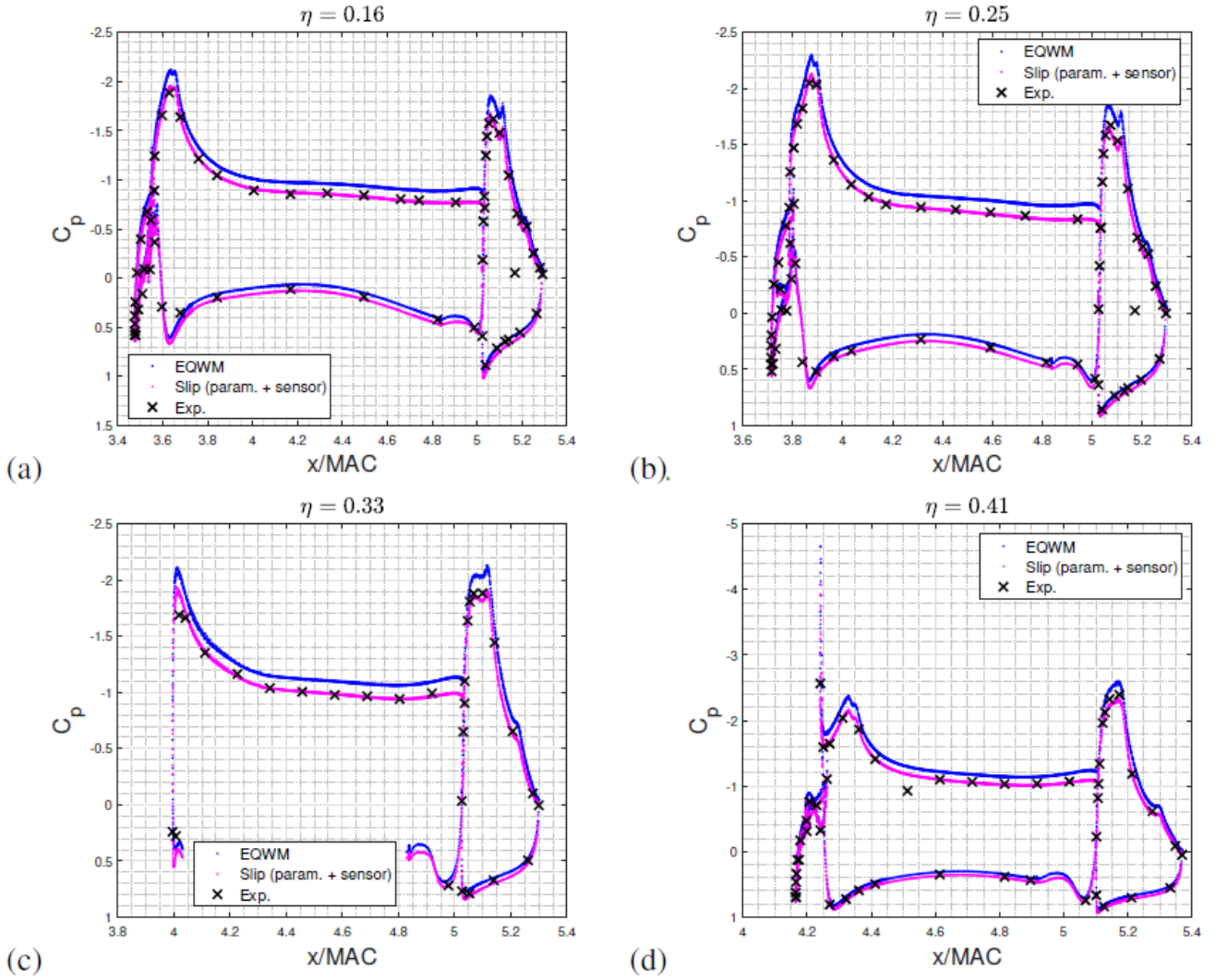
Sensor-based slip result



Yokokawa et al. 2008, AIAA 2008-350.

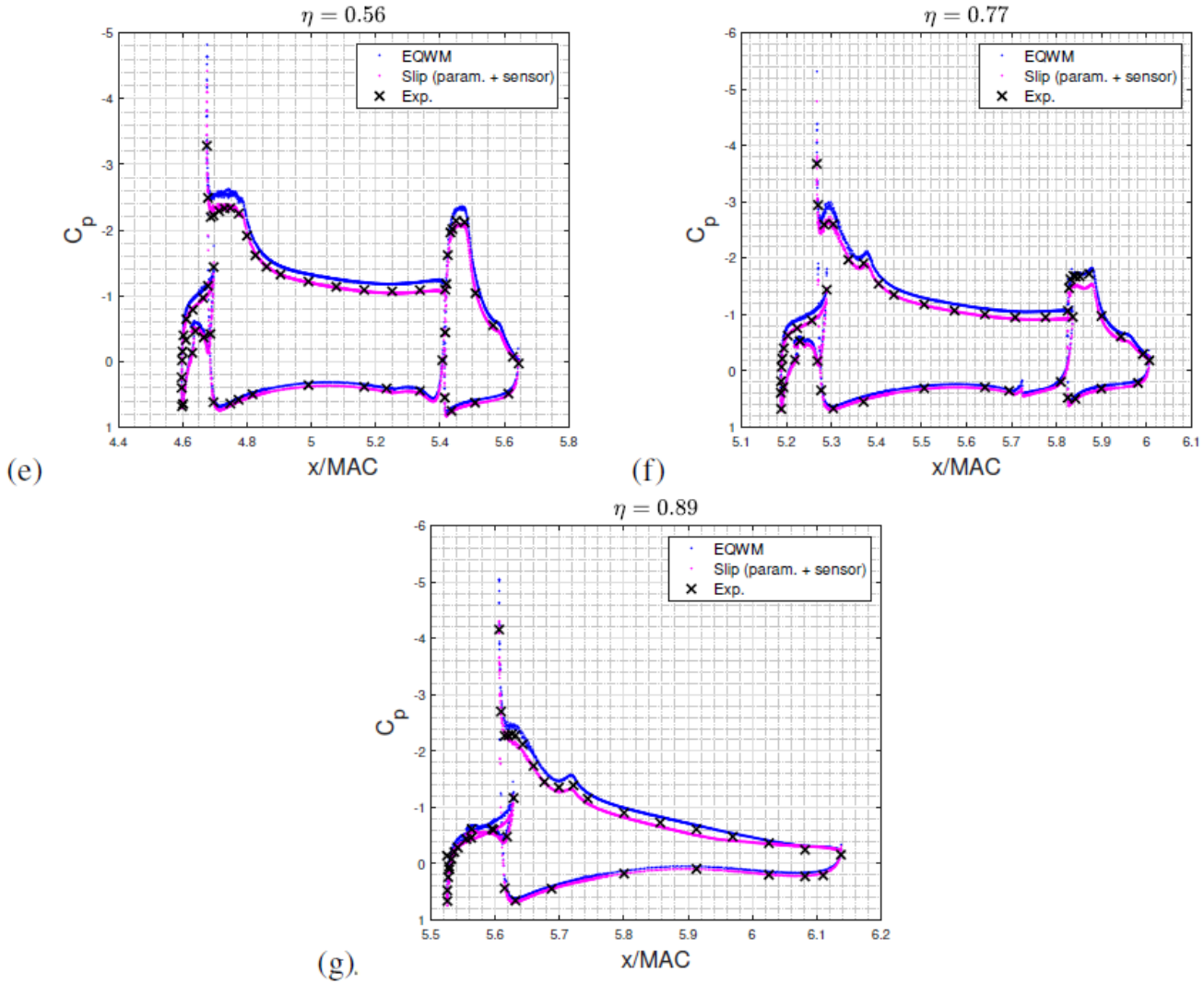
Pressure belts (JSM $\alpha = 4°$)

- Inboard stations show good agreement using Slip WM



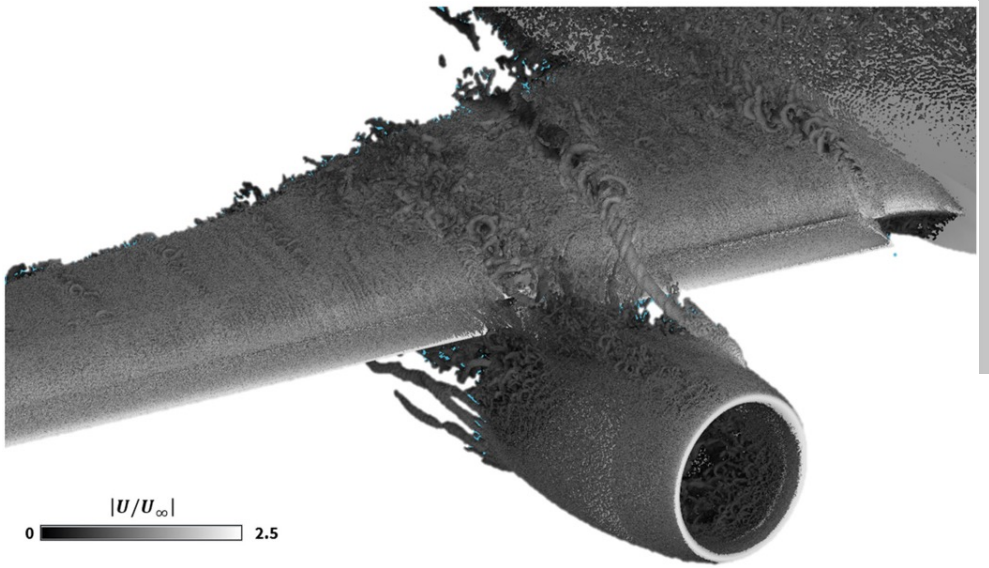
Pressure belts (JSM $\alpha = 4°$)

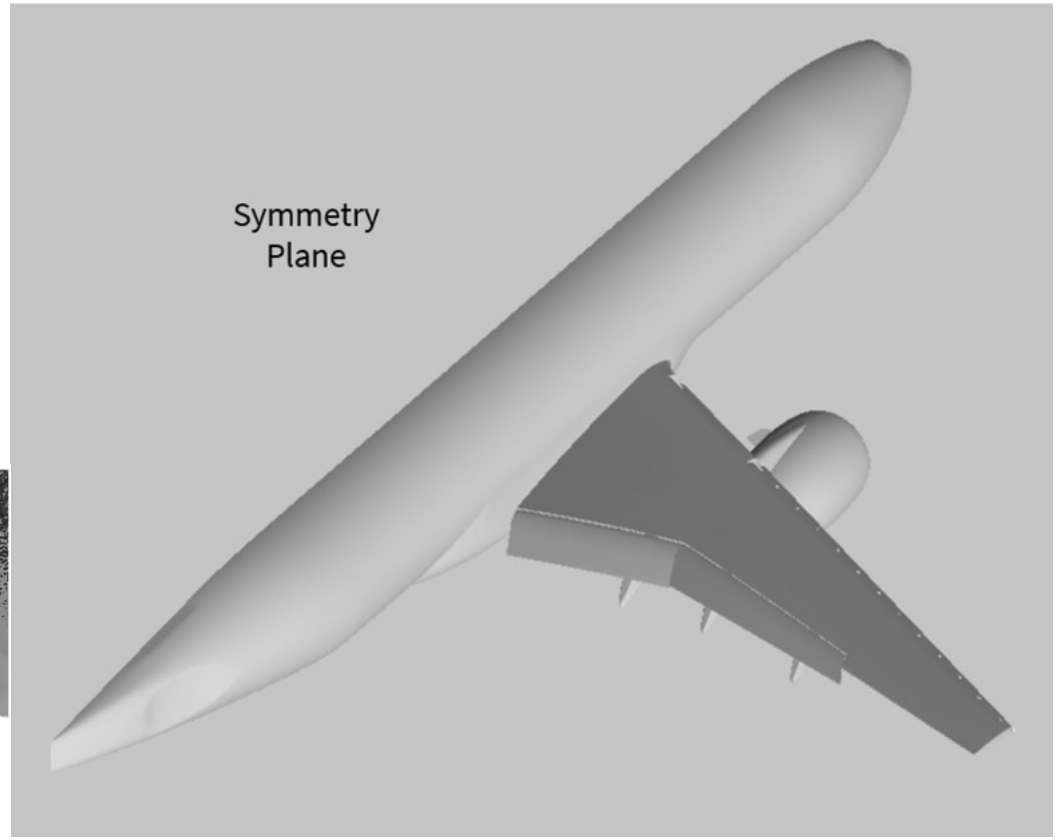
- Outboard stations show generally good agreement using Slip WM
- Some discrepancy near the wing tip and on outboard flap



NASA CRM-HL (QinetiQ geometry)

- CRM-HL
  - $\alpha = 7.05°$
  - $Re_{MAC} = 5.49 \times 10^6$
  - Free air
    - Setup matches Goc et al. (2023)
  - Showed flap separation issue like JSM



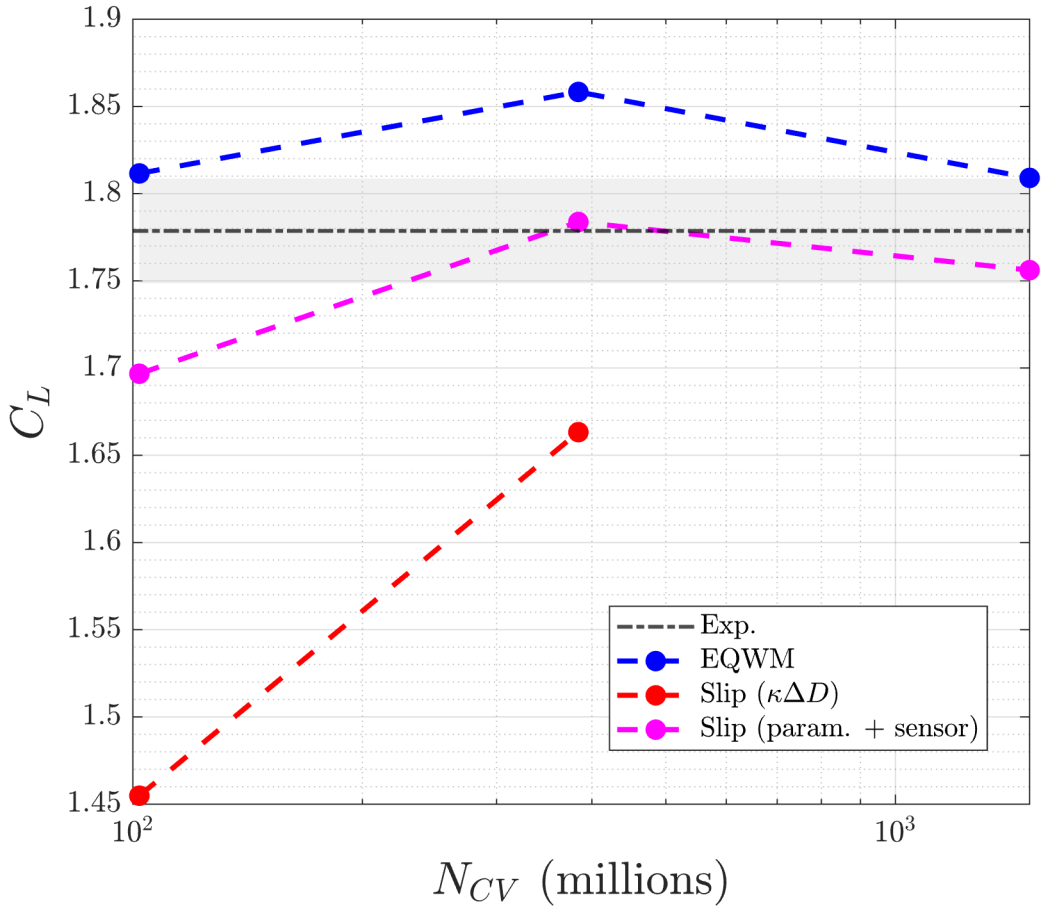


Goc et al. (2023). J. Aircraft, 61.

Parameterized slip with pressure-gradient sensor
NASA CRM-HL

- CRM-HL
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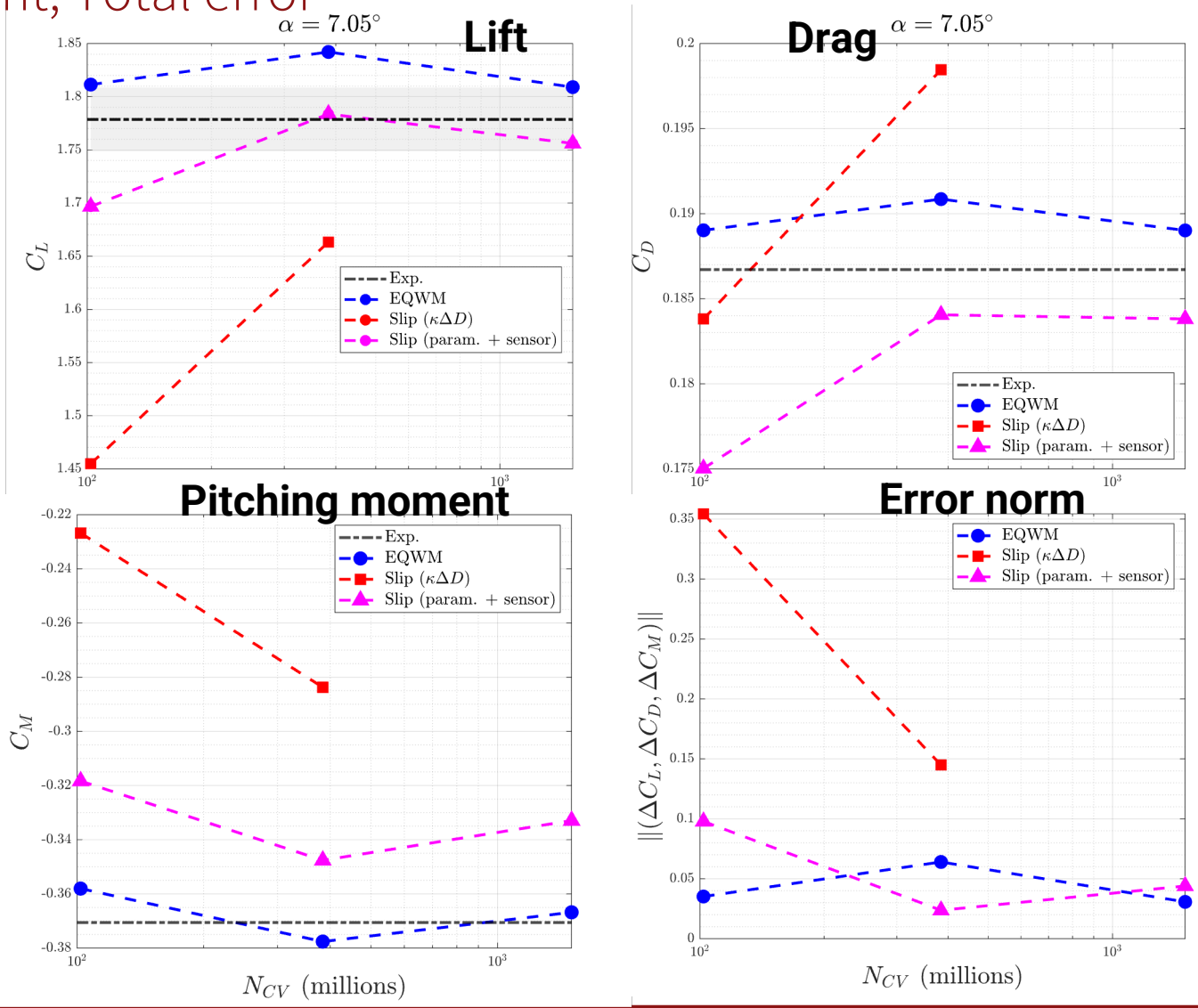
- Sensor-based slip is within ± 0.03 of experimental C_L on intermediate and refined grids (385 Mcv and 1.5 Bcv)
  - Similar improvement over EQWM at higher Reynolds number than JSM



Parameterized slip with pressure-gradient sensor

CRM-HL: Lift, Drag, Pitching moment, Total error

- $\alpha = 7.05°$
- Sensor-based slip converges most quickly in lift, drag
  - Pitching moment slightly worse predicted than EQWM
- Overall error norm shows sensor-based slip performing better or about as well as EQWM
  - $\|(\Delta C_L, \Delta C_D, \Delta C_M)\|_2$



Conclusions: High-lift aircraft

- Optimal slip length approach in turbulent channel led to parameterized slip length in inner units Δ^+
  - Combined with sensor to account for pressure gradient effects
- Sensor-based slip lengths to account for pressure gradient effects show improved results on JAXA high-lift aircraft
- Similarly, sensor-based slip length model improves lift prediction of CRM-HL at low angle-of-attack

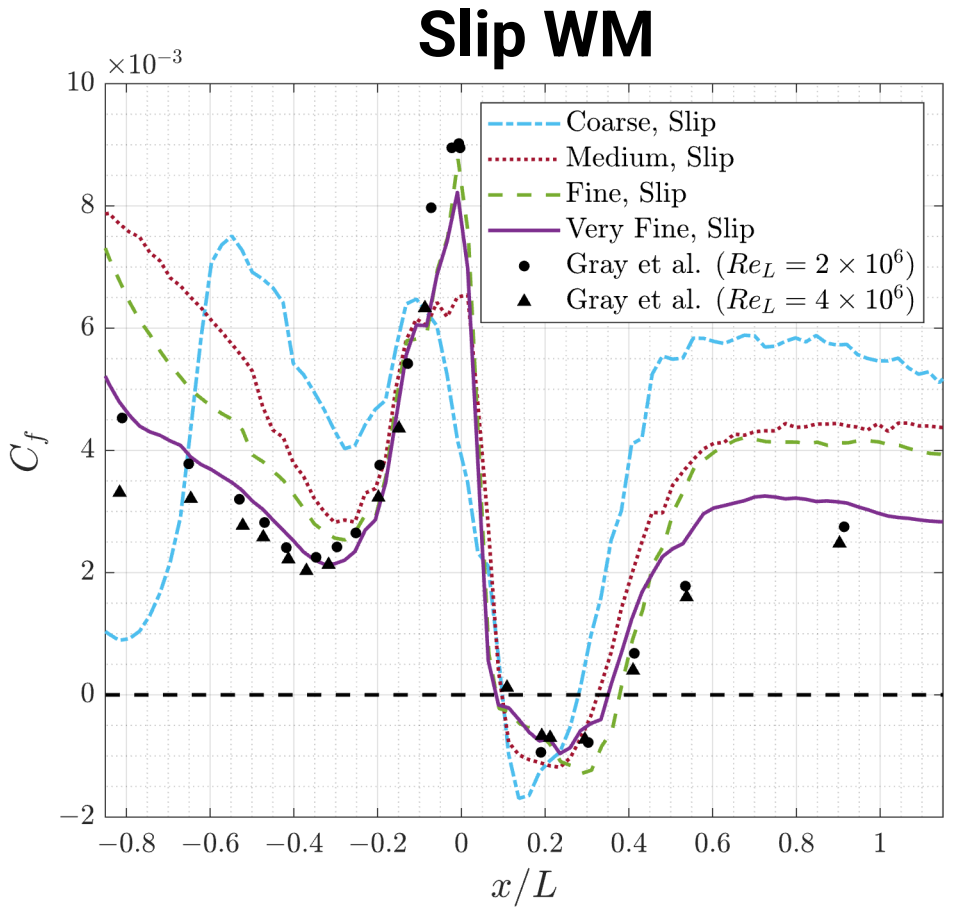
Outline

- Introduction
- Canonical smooth body separation
  - Boeing speed bump
- High lift aircraft simulations
  - JAXA Standard Model
  - NASA CRM-HL
- **Fundamental improvements for slip wall models**

Recall: Boeing speed bump

- Good prediction of separation bubble across grids
- Poor prediction of skin friction in coarsely-resolved, high-Re, attached flow

- Sensor-based slip length model helps improve skin friction issue
  - Let's apply it here

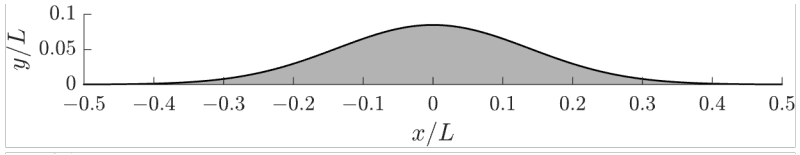


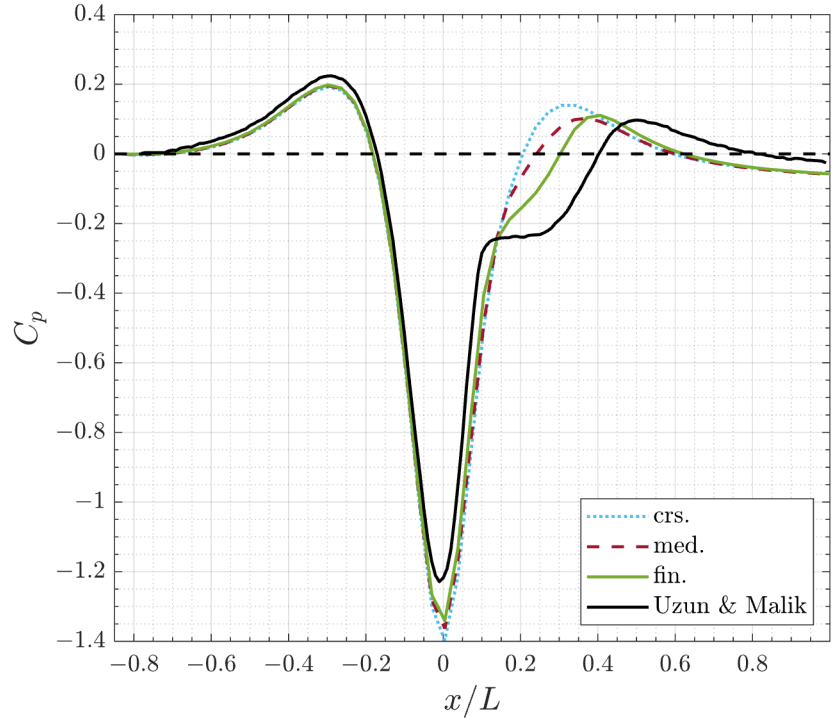
- Prediction of separation on all grids
- Needs a lot of grid refinement to capture correct skin friction

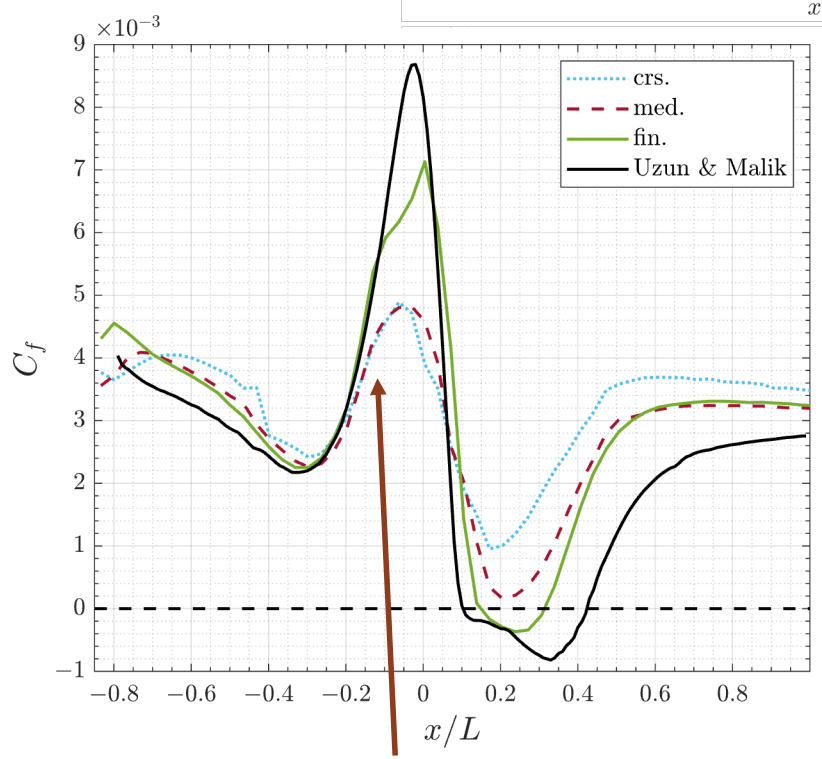
Sensor-based slip formulation can't capture FPG region on Boeing speed bump

Spanwise-periodic speed bump

$Re_L = 2\times10^6$







Mesh	Mcv	$\min_{x<0} y_1^+$
Crs.	3.3	~30
Med.	13	~15
Fin.	50	~8

Insufficient rise in C_f in FPG region

Explanation: FPG region shrinks the boundary layer, forcing more of the turbulence to be subgrid scale. The slip BC relies on resolved scales to generate stress. Therefore, a subgrid-scale model is needed to capture skin friction rise in FPG region.

Consistent boundary condition for the subgrid-scale stress

- Slip BC derived from application of differential filter to velocity field
  - Similarly use differential filter to develop BC for SGS stress

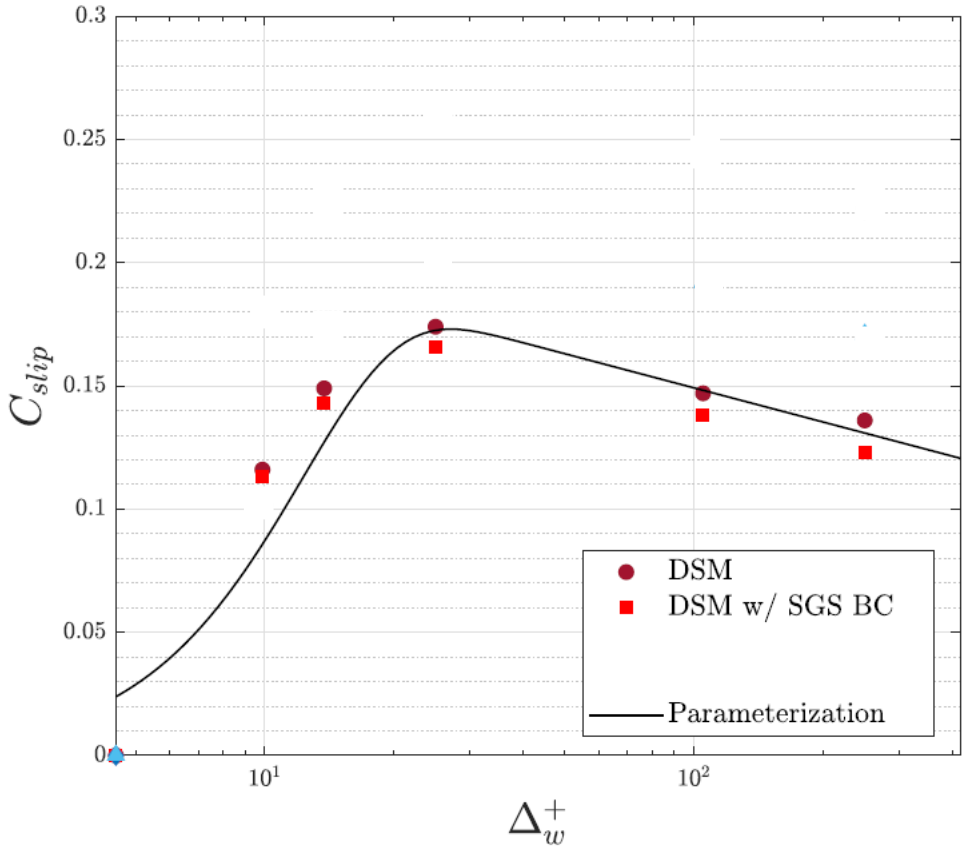
$$\tau_{ij}|_w - (C_{\text{slip}}\Delta_w)\left.\frac{\partial \tau_{ij}}{\partial n}\right|_w = \overline{u}_i\overline{u}_j|_w \,,$$

- Solve in a least-squares sense to get eddy viscosity BC

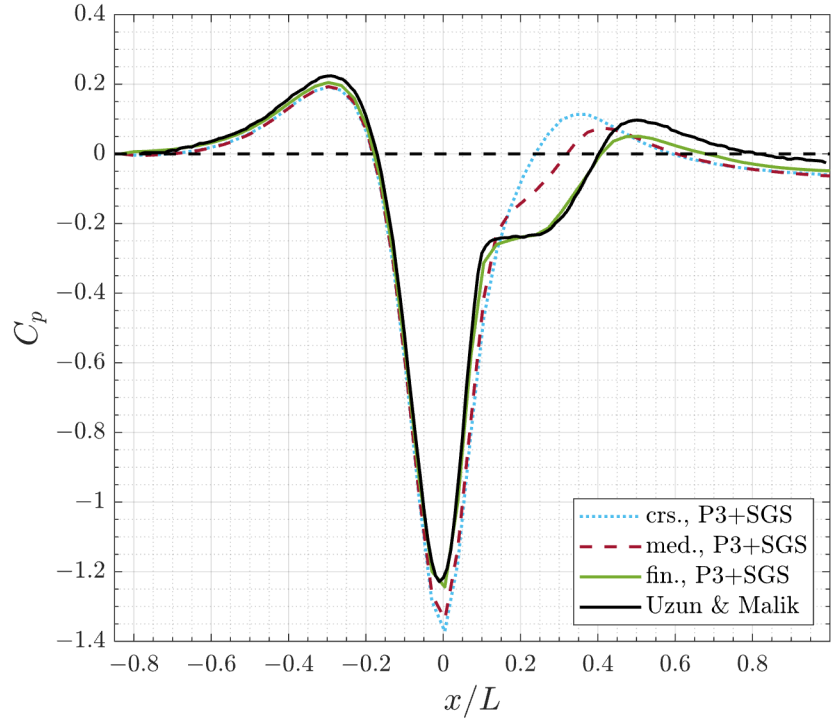
$$\nu_t|_w - C_{\nu_t}\Delta_w \left.\frac{\partial \nu_t}{\partial n}\right|_w = f_{\nu_t}|_w \,,$$

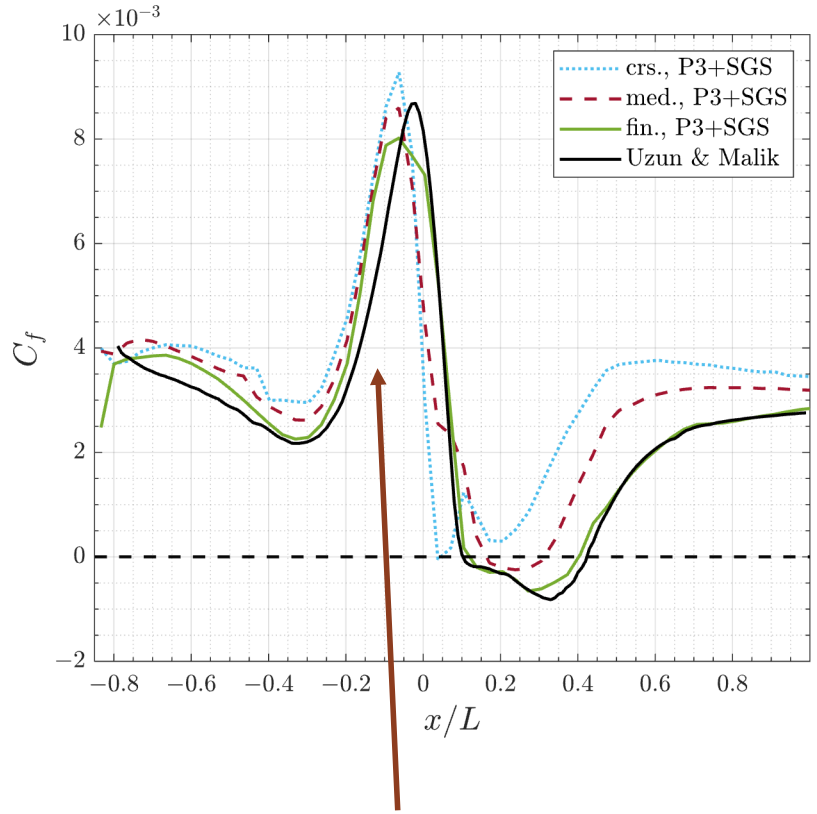
$$C_{\nu_t} = C_{\text{slip}}\frac{\beta_{ij}\overline{S}_{ij}}{\beta_{kl}\beta_{kl}}; \qquad f_{\nu_t} = \frac{-\overline{u}_i\overline{u}_j\beta_{ij}}{2\beta_{kl}\beta_{kl}},$$

Optimal slip length parameterization is consistent when using DSM with or without SGS BC



Subgrid-scale stress boundary condition improves behavior in FPG region





Mesh	Mcv	$\min_{x<0} y_1^+$
Crs.	3.3	~30
Med.	13	~15
Fin.	50	~8

SGS stress BC captures the skin friction rise in FPG region
Monotonic prediction of separation on grid refinement

Conclusions and future directions

- Developed subgrid-scale boundary condition consistent with Slip WM
- SGS BC is important in capturing effects of FPG on skin friction
  - Using DSM, optimal slip lengths do not depend on SGS BC, suggesting a level of consistency of the dynamic model with Slip BC
- Room for improvement in slip length models
  - More accurate models at coarse grid resolutions
  - Improved sensors and models for effect of pressure gradients
  - Dynamic slip length models are a possible avenue that could avoid physical modeling

Dynamic slip wall modeling

- Dynamically evaluate a slip length through mathematical identities
- Assuming invariance of total Reynolds stress to test filtering:

$\overline{(\cdot)}$ = grid filter, $\widehat{(\cdot)}$ = test filter

$$\rho\widehat{\overline{u}_i\overline{u}_j} = \rho\widehat{\overline{u}_i}\widehat{\overline{u}_j} + \hat{\tau}_{ij} = \rho\hat{\bar{u}}_i\hat{\bar{u}}_j + T_{ij}$$

- Introduce slip BC and manipulate

$$\rho\widehat{\overline{u}_i\overline{u}_j} - \rho\bar{u}_i\bar{u}_j + \hat{\tau}_{ij} - T_{ij} = \rho\left(C\widehat{\Delta}\right)^2 \frac{\partial\hat{\bar{u}}_i}{\partial x_n}\frac{\partial\hat{\bar{u}}_j}{\partial x_n} + \rho(C\overline{\Delta})^2 \frac{\partial\bar{u}_i}{\partial x_n}\frac{\partial\bar{u}_j}{\partial x_n}$$

- Linear system of 6 equations, can solve for slip length(s)
  - Various modeling choices are possible

Bose & Moin (2014). Phys. Fluids, 26.
Bae et al. (2019). J. Fluid Mech., 859.

Summary

- Slip WM showed improved separation prediction capability over EQWM for a canonical case of smooth-body separation (Boeing speed bump)
- Sensor-based slip length formulation allowed for more accurate predictions of high-lift aircraft (JSM, CRM-HL)
  - At low angle-of-attack with difficult to predict flap separation
- Consistent subgrid-scale boundary condition developed for slip WM
  - Improves slip WM performance in favorable pressure gradient boundary layers
- Dynamic modeling offers future avenue for improvement of slip wall models

Thank you!

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