

# DES Prediction of a 3-Element High-lift airfoil with a Blown Flap

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- Accurate prediction of high-lift device (HLD) flow physics and performance is important; otherwise it is difficult to mitigate against design shortcomings.
  - RANS methods (industrial standard) lose accuracy when dealing with complex separated flows; commonly seen around high-lift devices at high angles of attack.
  - Interest in higher-fidelity simulations such as DNS or wall-resolved LES is growing, but the computational cost is extremely expensive for complex flows at large  $Re$ . Therefore, an optimal compromise between accuracy and computational cost is required to support the study of HLDs.
  - DES based models (based on LES/RANS hybrid approach) are generally better at modelling separated flows, but they require more computational resources and are more grid sensitive than RANS (less than pure LES, however).
  - Assess capabilities of high fidelity, DES-based numerical methods applied to HLD with/without flow control.
  
- Flow control may sometimes complicate the flow field around an airfoil
  - Current RANS capability is further challenged if flow control is present. How about DES based methods?
  - The motivation to use active flow control is based on the assumption that active methods can improve aerodynamic performance beyond the limits of an optimised (passive) geometric shape.

➤ DES (Spalart et al., 1997) is a hybrid technique combining RANS (near the wall region) and LES (away from the wall):

- A number of turbulence models (e.g. SST, SA) may be used with DES
- Can specify a grid length scale to switch between RANS and LES
- Can explicitly designate specific regions as either RANS or LES
- Can use different differencing schemes for RANS (e.g. forward) and LES (e.g. central) regions

➤ Historical developments of DES:

- Started with DES97, followed by Delayed DES (DDES, Spalart et al., 2006) which improves the switching and solves some induced separation problems caused by LES
- IDDES (Improves Delayed DES) and improvement of DDES, allowing implementation of specific unsteady boundary conditions
- SDES (Delayed and Shielded DES): Maintains BL flow under
- SBES (Stress Blended Eddy simulation), based on SDES, adds function to switch between different LES models in the LES zone

# Research Objectives

- HLDs generate unsteady flow fields with interesting flow physics e.g. flow separation, vortex shedding, merging of shear layers, airframe noise, etc that is worth studying
- To benchmark the post stall lift prediction performance of high fidelity DES based methods (and compare against RANS) on a baseline 30P30N 3-element airfoil (a simplified, unswept configuration) in its high lift configuration.
- To design steady and unsteady active blowing configurations based on 30P30N airfoil.
- Can we extend the maximum achievable lift coefficient and useful angle-of-attack range?
- Produce suggestive guidelines for computation of similar flow-controlled airfoils using high fidelity, DES based methods (long term).

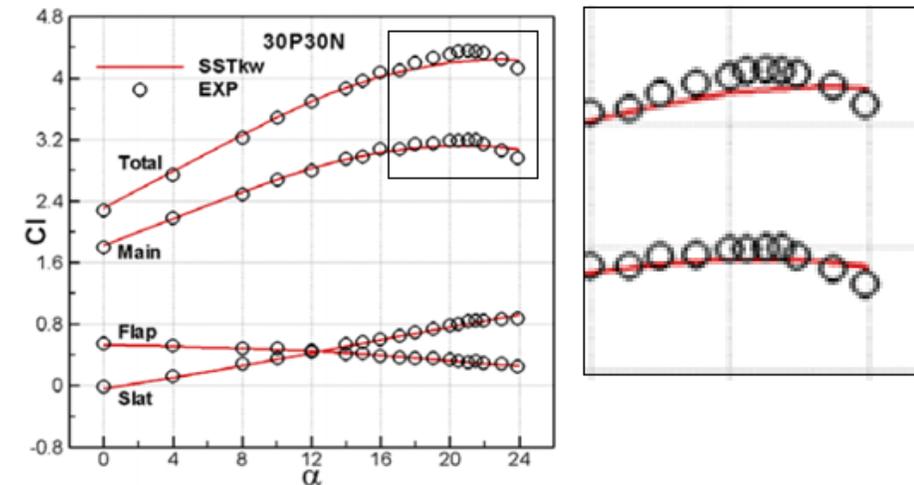
# Case Description

Baseline airfoil: NASA's 30P30N 3-element high-lift configuration, was extensively tested in NASA wind tunnel during 1990s-2000s.

- Free stream  $Re_c = 5$  million,  $M = 0.2$ , slat & flap deflection =  $30^\circ$ .
- Model was designed to provide a test case under common take-off/landing configurations.
- Previously, accuracy of RANS modelling for lift worsens when  $\alpha \geq 19^\circ$  (near  $C_{Lmax}$ )
- Dominant flow physics will be those due to flow reversal in the main element wake, and upper surface separation over flap trailing edge
- Tests were conducted with free transition. Deployed chord  $c = 1.2m$ .



**Fig. 1** The 30P30N three-element airfoil (Klausmeyer, 1994)

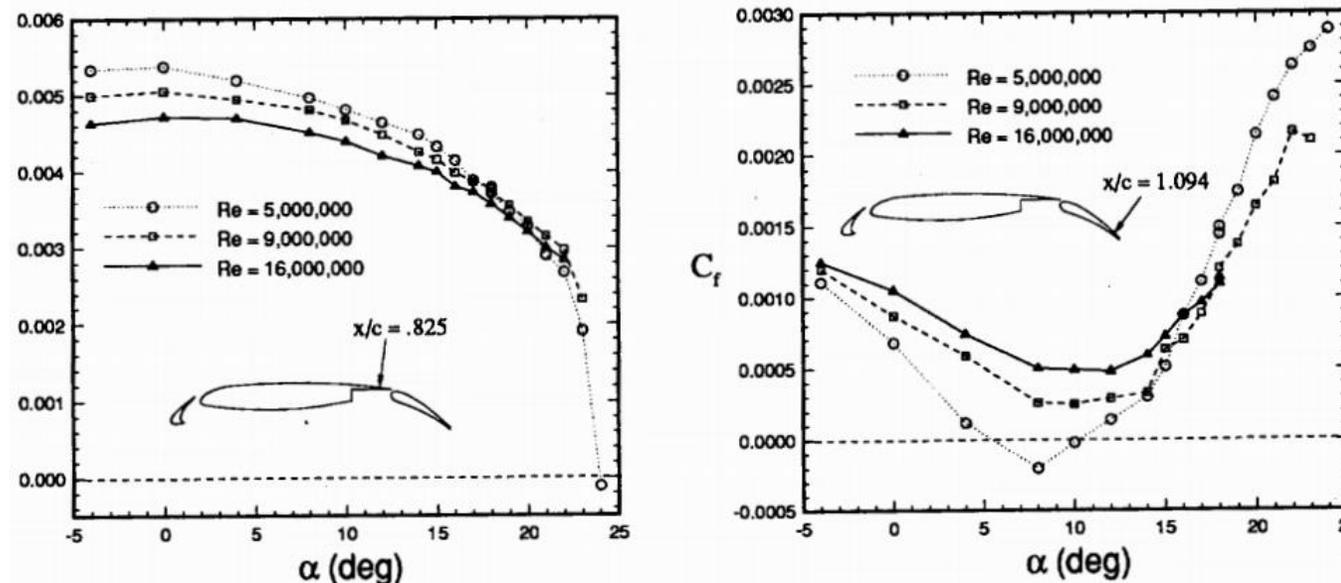


**Fig. 2** Typical lift prediction with RANS model (Zhang, 2012)

# Case Study Description

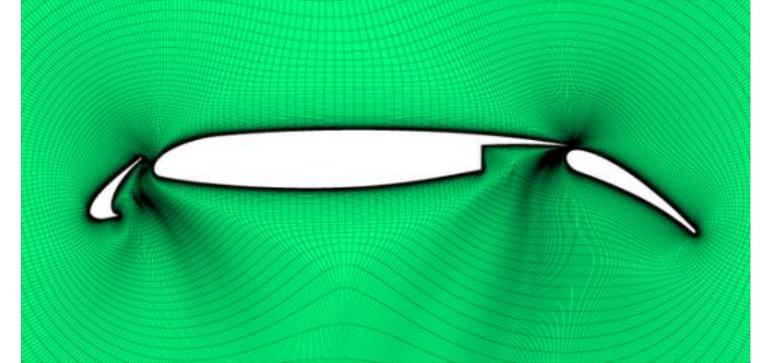
Past wind tunnel experiments on 30P30N airfoil (1994, Klausmeyer) indicate that:-

- Separation after  $C_{Lmax}$  is triggered by flow reversal in the main element wake.
- Attached flow on the flap at  $C_{Lmax}$  but separation at the lower angle-of-attack ( $6^\circ < \alpha < 10^\circ$ ) approach condition.
- Skin friction behaviour on the flap trailing edge exhibiting reverse Reynolds number trends at low angles-of-attack.
- When  $Re_c = 5$  million, flap separation occurs at 8 degrees angle-of-attack, but remains attached at higher or lower angles.



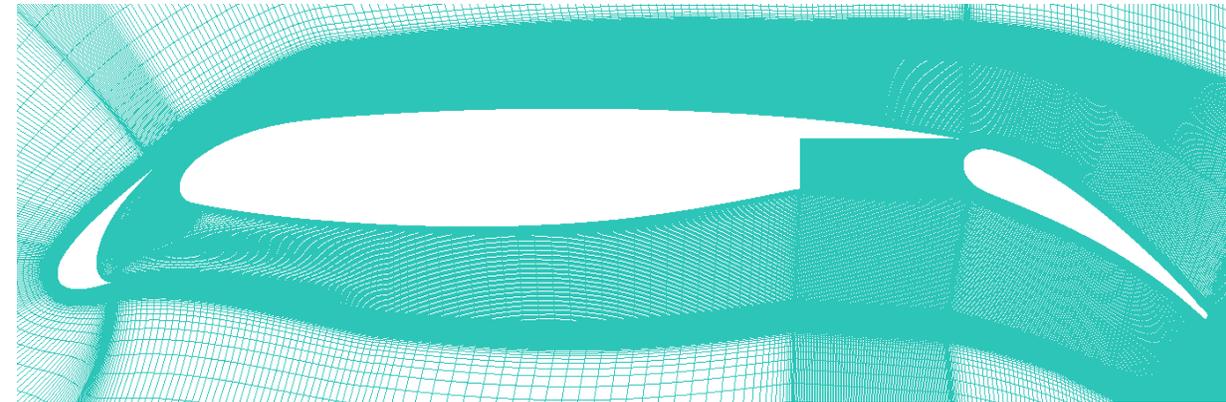
**Fig. 3**  $C_L$  and  $C_f$  behaviour of the 30P30N's flap with AoA and Re (Klausmeyer, 1994)

- Baseline model is studied using RANS, DES and DDES models
  - Calculations are conducted with Ansys 16.0 Fluent and CFX
  - Mesh generation conducted with ICEM software, CH-grid with a far-field of 30 chord lengths and 30 chord length H-Box
  - Angle of attack and turbulence model settings shown in Table 1.



Model	AoA (°)	Turbulence Model	Grid number
RANS Steady	0, 4, 8	SA/SST	150296
RANS Transient	10, 12, 14, 15, 16, 17, 18, 19, 20, 20.5, 21, 21.5, 22, 23, 24	SST	150296
(D)DES	8, 10, 12, 19, 20, 20.5, 21, 21.5, 22, 23, 24, 25	SST	3006525

**Table.1** Calculation setup



**Fig. 4** DDES Mesh around the airfoil

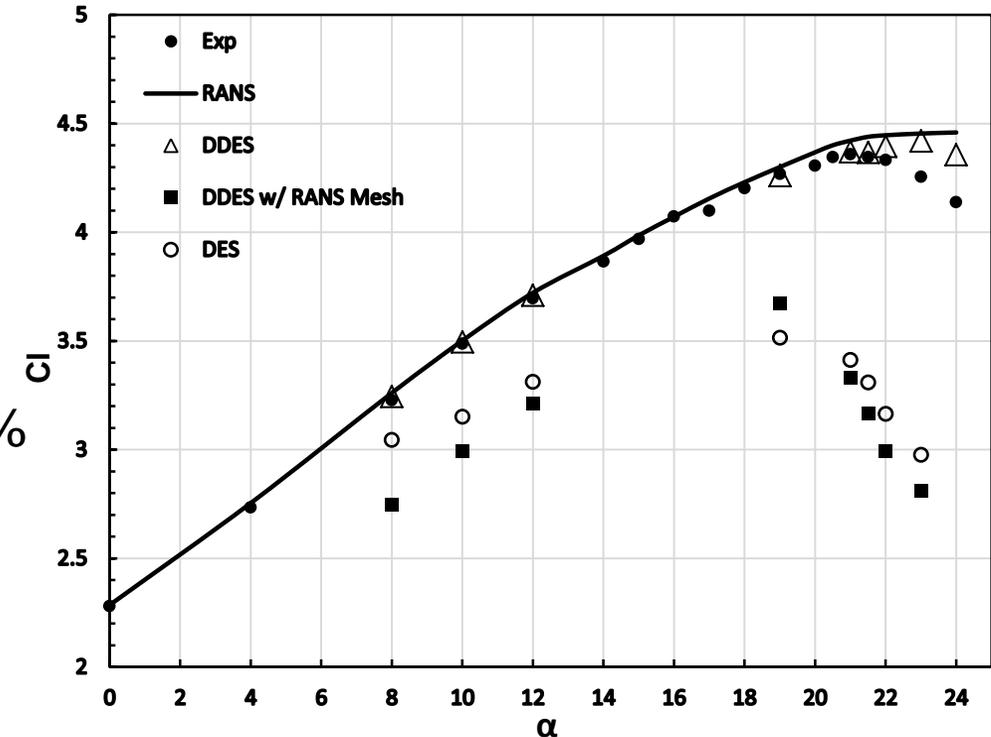
Extensive refinement in areas behind main element wake and over trailing edge flap.

Mesh check for BL thickness conducted to ensure that local BL thickness > 5 times grid spacing to avoid triggering of LES mode inside the BL.

Note: both DES and DDES are used  
SA is found to be similar to SST so I kept using SST in further calculations  
Time step for transient runs: 0.002 second

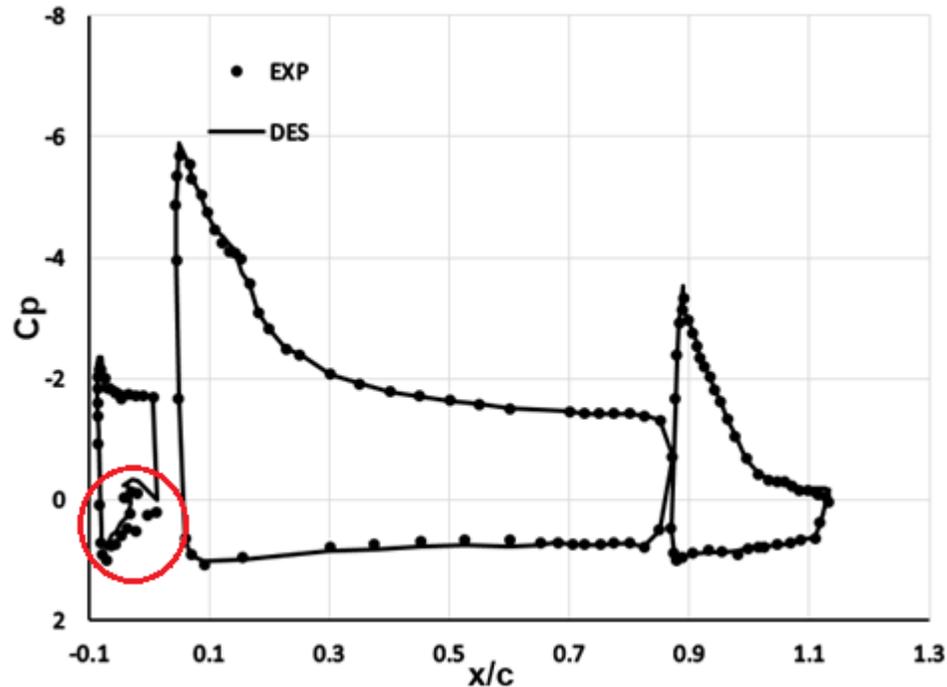
# Results: Baseline $C_L$ Variation

- DES and DDES data only for 8-12° and 19-25°
- DDES and RANS agree well with Exp at low AoA
- Both RANS and DDES over-predicts lift at  $\alpha \geq 19^\circ$
- DDES predicts  $CL_{max} = 23^\circ$  at 4% disparity, 1% more accurate than RANS
- DDES is more accurate as  $\alpha$  increases
- DDES ran with same mesh as RANS produces much worse results
- DES suffered **grid induced separation** and separated at main element trailing edge

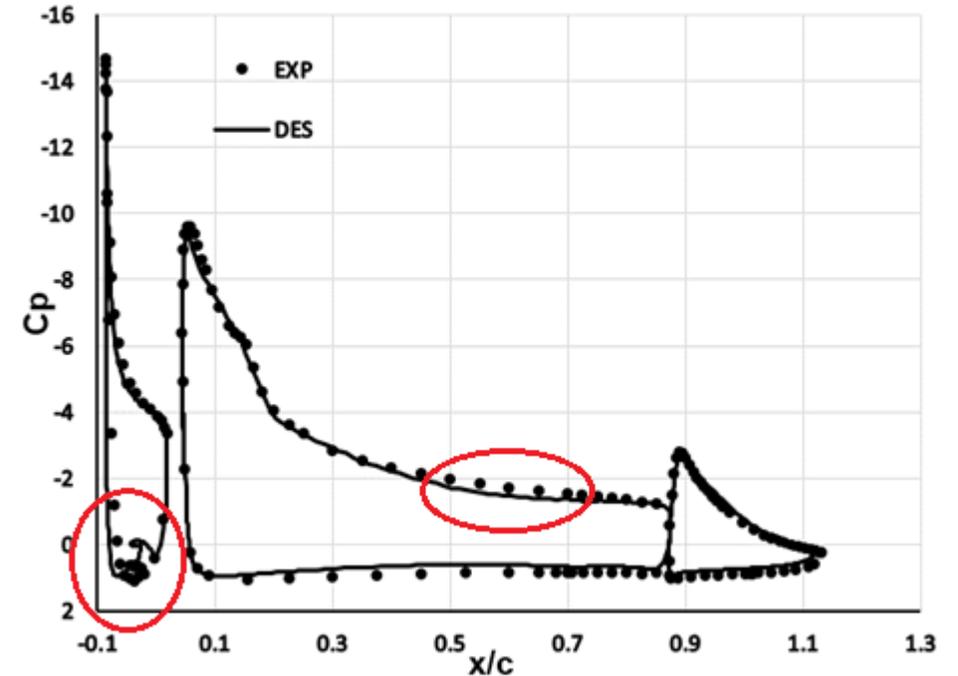


**Fig. 5**  $C_L$  – angle of attack( $\alpha$ ) chart

$\alpha = 8^\circ$



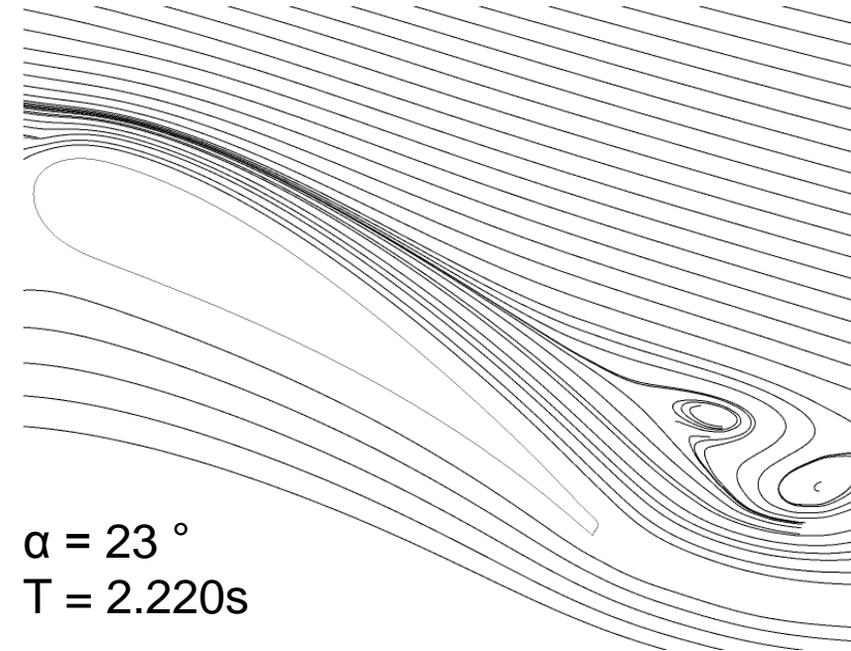
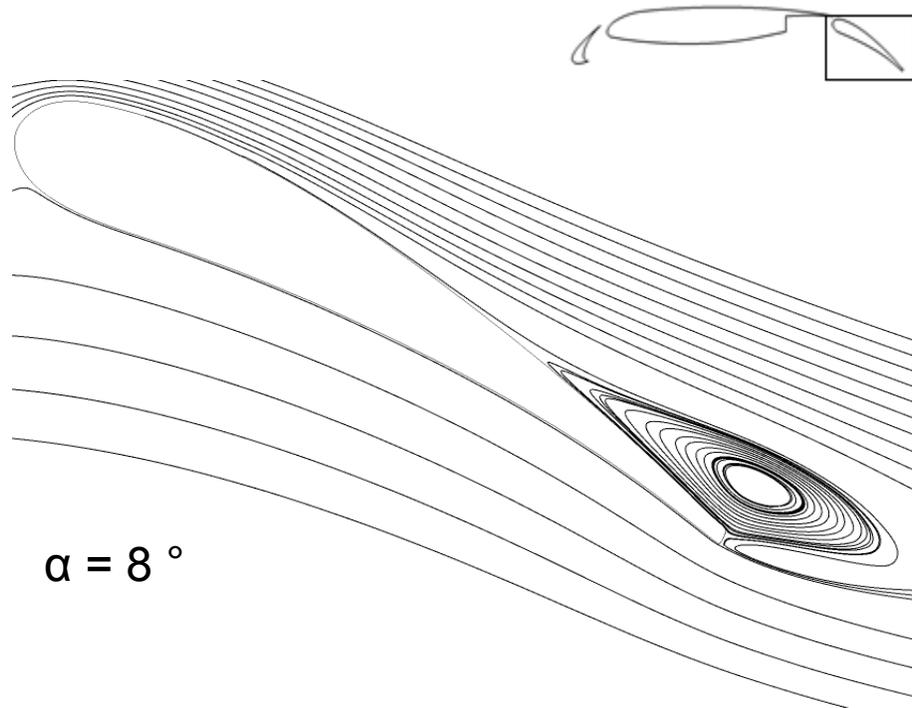
$\alpha = 19^\circ$



DES  $C_p$ –  $x/c$  chart at  $\alpha = 8^\circ$  and  $\alpha = 19^\circ$ .

- For  $\alpha = 8^\circ$ , pressure distribution in the slat cove area shows some disparity against experiment, possibly due to local flow instability triggering the LES switch while local mesh quality is inadequate for LES.
- For  $\alpha = 19^\circ$ , same problem seems to be occurring near the slat, also along the main element upper & lower surfaces. Reason for this is being investigated.

# Results: Flap Flow Streamline



DES Flow Streamline at  $\alpha = 8^\circ$  and  $\alpha = 23^\circ$

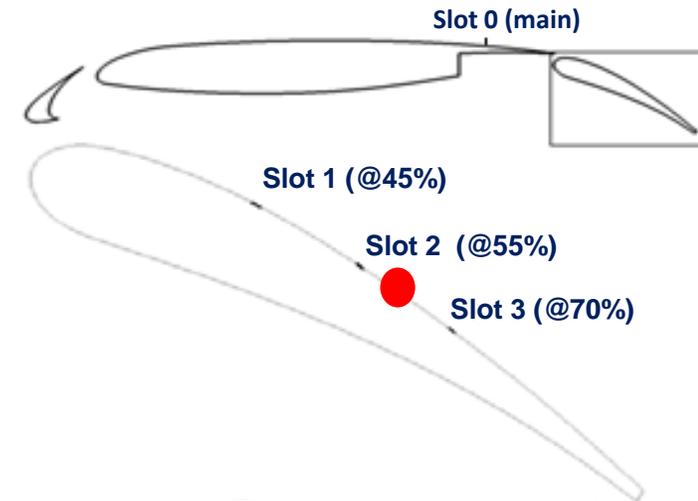
- Both DDES and RANS predicted surface flow separation at lower angle ( $\alpha = 8^\circ$ )
- Separation behaviour at  $23^\circ$  (flap trailing edge separation and flow reversal in main-element wake) is recreated by DDES

# Conclusion: Baseline Model

- The performance of the high lift configuration is limited by flow separation (pressure drag, lift losses, unsteadiness, noise)
- The original DES97 model performs much worse than RANS model even at low  $\alpha$  due to grid induced separation.
- DDES is sufficient, while also unnecessary for lift prediction at low  $\alpha$ , where RANS is effective and less computationally demanding.
- When RANS loses accuracy beyond stall, applying DES method can improve lift prediction accuracy, especially when flow phenomenon includes separation and/or flow reversal.

# Steady (Oblique) Blowing: Setup

- Practically, steady blowing should be simple; requiring only pressurised air
- Proven technology to delay separation (weakens effects of APGs)
- Steady blown airfoil performance calculated using DDES method, with identical mesh and solver setup.
- Calculation is done at  $\alpha = 8^\circ$  and  $\alpha = 25^\circ$ .
- Blowing slot is defined by changing a section of flap upper surface boundary condition to **Inlet with constant flow velocity**.
- A slot is set on the main element trailing edge at 85% of chord for  $\alpha = 25^\circ$  (upstream of separation point).
- 3 slot positions are set on the upper surface of the flap, at 45% & 55% (upstream of S.P), and 70% (downstream of S.P) flap chord for  $\alpha = 8^\circ$  case.



Flap blowing slot positions  
for  $\alpha = 8^\circ$

● Separation point

# Steady Blowing on Flap: Setup

- Momentum coefficient is defined as 
$$C_{\mu} = \frac{h}{c} \cdot \left(\frac{V_s}{V_{\infty}}\right)^2$$
- Blow out angle  $\theta$  is the angle between nozzle outflow and airfoil surface tangent line (when  $\theta = 0$ , flow is tangential to airfoil surface).

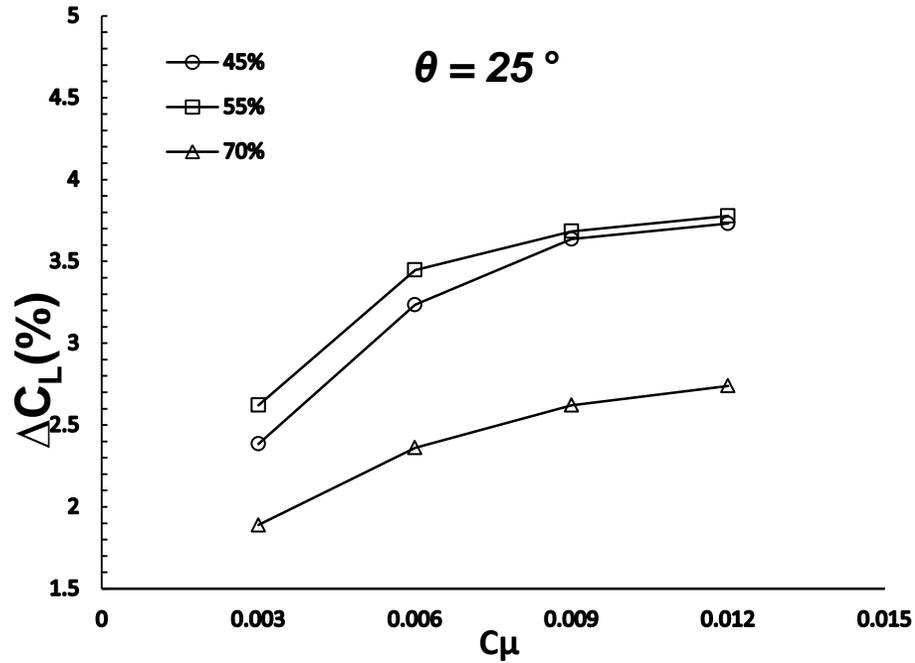
Momentum coefficient $C_{\mu}$	0.003	0.006	0.009	0.012
Blow out angle $\theta(^{\circ})$	20	25	30	
Slot position $x/C_{flap}$	45%	55%	70%	
Slot width $h$ (m)	0.0015 $c_{stow}$ (stowed chord)			
Angle of attack $\alpha (^{\circ})$	8			

**Table. 2** List of blowing parameters for  $\alpha = 8^{\circ}$  case

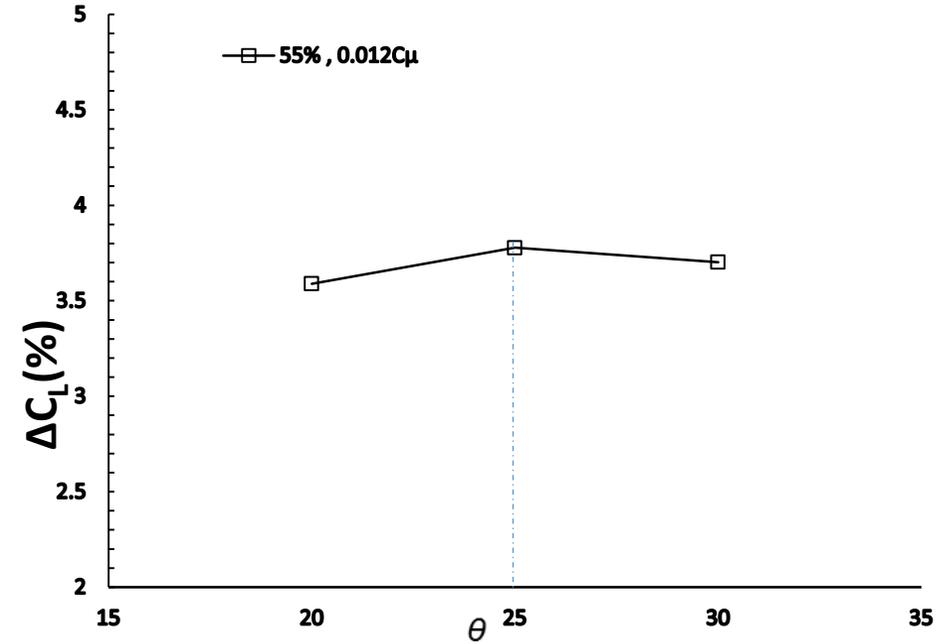
Momentum coefficient $C_{\mu}$	0.010	0.013	0.016	0.019
Blow out angle $\theta (^{\circ})$	20	25	30	
Slot position $x/C_{main}$	85%			
Slot height (m)	0.003 $c_{stow}$			
Angle of attack $\alpha (^{\circ})$	25			

**Table. 3** List of blowing parameters for  $\alpha = 25^{\circ}$  case.

# Lift Gain Results: $\alpha = 8^\circ$



DDES Predicted lift difference ( $\Delta C_L = \frac{C_L - C_{L0}}{C_{L0}}$ ) at different nozzle positions and momentum coefficient at  $\alpha = 8^\circ$ .

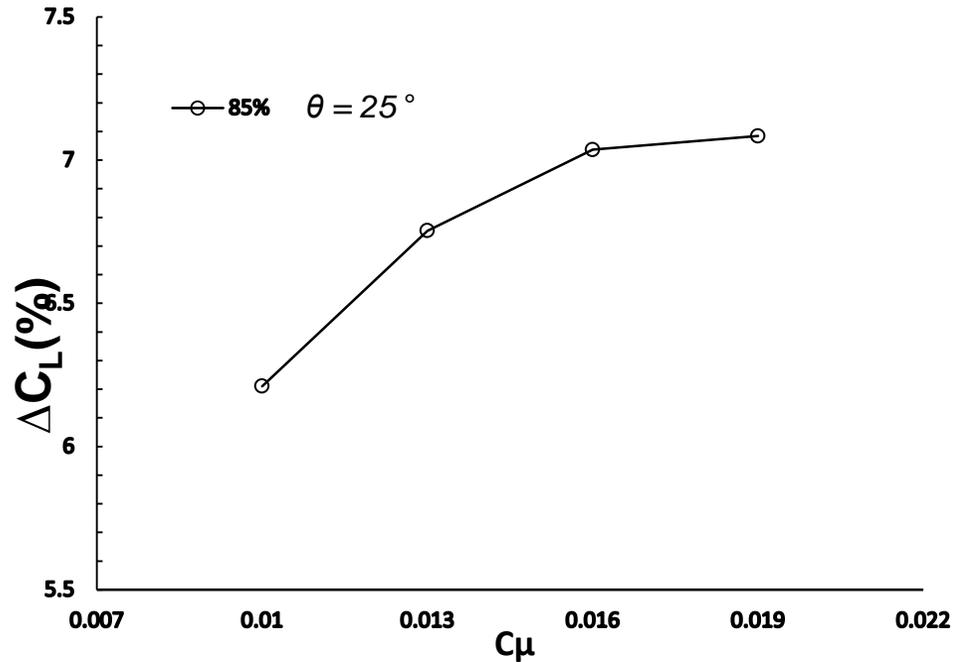


TE Flap

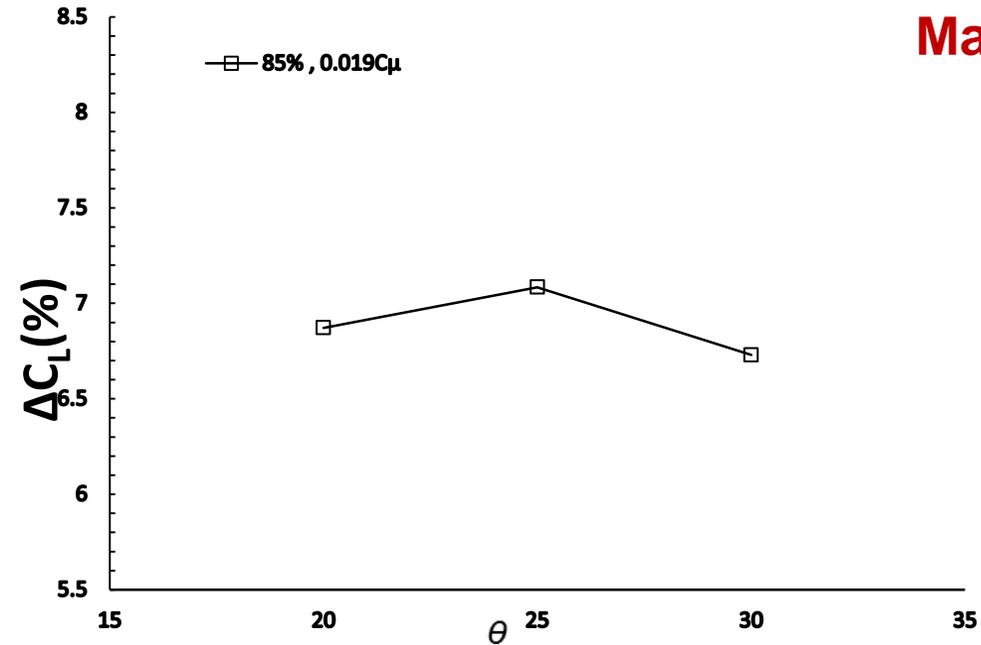
DDES Predicted lift difference at different blow out angle at  $\alpha = 8^\circ$ .

- More gain in lift with increased momentum coefficient
- Blowing on upper flap surface is most efficient when blowing slot is at **55% flap chord with a blow out angle of 25°**
- When blowing slot is placed within the separation bubble the lift enhancement decays significantly.

# Lift Gain Results: $\alpha = 25^\circ$



Predicted lift difference ( $\Delta C_L = \frac{C_L - C_{L0}}{C_{L0}}$ ) at different nozzle positions and momentum coefficient at  $\alpha = 25^\circ$ .



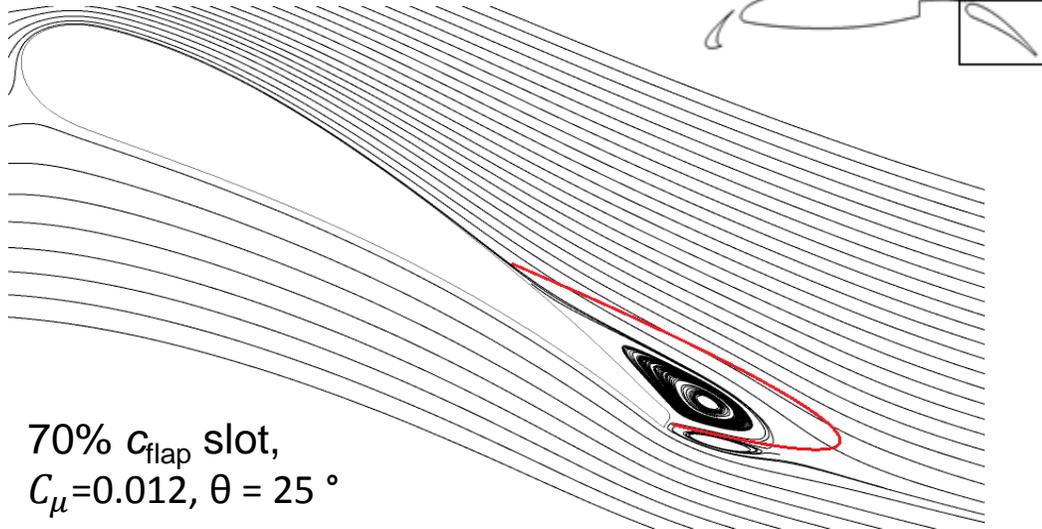
Predicted lift difference at different blow out angle at  $\alpha = 25^\circ$

**Main Element**

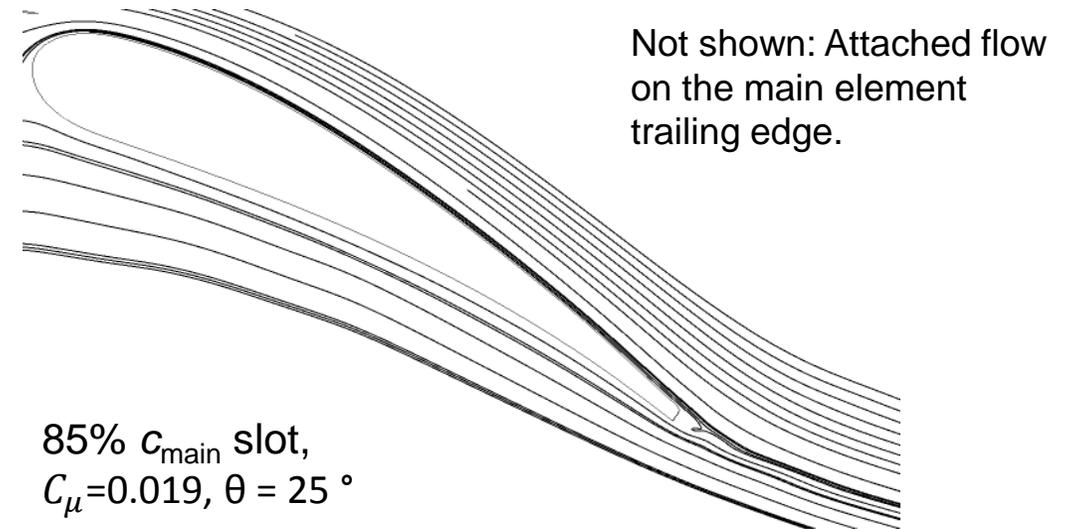
- When blowing slot is set at 85%  $c_{main}$  with a blow out angle of  $25^\circ$ , blowing on the upper flap surface appears to be most effective when momentum coefficient is higher than 0.016
- Changing the blow out angle has a slight impact on lift enhancement

Note: needs more cases to get a full picture for blowout angle

## Visualisation: Mean Flow over Flap



DES flap mean flow stream line at  $\alpha = 8^{\circ}$



DES flap mean flow stream line at  $\alpha = 25^{\circ}$

- At  $\alpha = 8^{\circ}$ , blowing gradually reduces separation, and as  $C_{\mu}$  increases the bubble size decreases and flow remains attached at the trailing edge with  $C_{\mu}=0.009$  onwards.
- At  $\alpha = 25^{\circ}$ , blowing from main element trailing edge slot reduces separation on main element upper surface, increasing the blowing momentum gradually decreases separation.

# Summary

- Basic DES is worse than RANS even at low  $\alpha$  due to grid induced separation.
- DDES is sufficient, while also unnecessary for lift prediction at low  $\alpha$ , where RANS is effective and less computationally demanding.
- When RANS loses accuracy beyond stall, applying DES method can improve lift prediction accuracy, especially when flow phenomenon includes separation and/or flow reversal.
- Steady blowing on flap at low  $\alpha$  improves lift especially when slot is closest to S.P and blowing angle is  $25^\circ$
- Steady blow on main element at high  $\alpha$  (beyond stall) improves lift at a given slot location and blow angle.
- Not all blowing configurations are good for enhancing lift beyond basic design.
- Steady blowing seems either to increase flow momentum into the B.L or redistribute it (increase turbulent mixing) thus energising the BL, reducing effects of APGs, and thus lower separation bubbles and attached flow.

# Ongoing work: Periodic blowing

- Changing existing blowing slot boundary conditions from steady velocity inlet to velocity function  $u(t)$  defined inlet,
  - $u(t) = u_a \cdot \sin \left[ \left( 2\pi \frac{V_\infty}{c_{stow}} f \right) t \right]$ , where  $f$  is the non-dimensional perturbation frequency,  $V_\infty$  is the free stream velocity,  $u_a$  is the velocity amplitude of the oscillation cycle, defined as
    - $u_a = V_\infty \sqrt{\frac{c_{stow}}{h} C_\mu}$
- Result is not yet available

# Future work

- Investigate  $C_D$ ,  $C_P$  and  $C_f$  behaviour with/without flow control
- Investigate possibility of extended stall angle range with flow control
- Full investigation of the flow field with/without flow control, velocity profiles, Strouhal numbers, etc
- Estimate power requirements of actively blown flaps; compare with baseline performance, minimise blowing effort.
- Design sensitivities of blow out angles (e.g. tangential blowing with Coanda effects) and slot width on  $C_L$  and  $C_D$
- Investigate localised blowing versus distributed blowing, slot spacing etc
- Implementing simple feedback active flow control (using results of steady/unsteady blowing)
- Calculation of steady blowing on a 3D infinite wing
- Flow control methods for noise reductions with DES based methods?
- Calculation using recently developed DES based models (SBES and SDES)
- Future optimisation research on multi-element high lift devices (slotless? less complex?, less weight? Less maintenance?)

## Reference

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