High lift flow computations using the code HiFUN

Gopalakrishna N., **Balakrishnan N.**

Computational Aerodynamics Laboratory,
Department of Aerospace Engineering
Indian Institute of Science
Bangalore 560 012, Karnataka, India

Yuvraj Patil, Ravindra K., Nikhil V. Shende

S & I Engineering Solutions Pvt. Ltd.,
Bangalore 560 054, Karnataka, India

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Outline

- Introduction
- Grids used
- Iterative convergence
- Grid convergence
- Effect of additional components
- Reynolds number effect
- Turbulence model effect
- Unsteady hysteresis study for NASA Trap Wing
- Conclusions

CFD Process

- Flow computations using HiFUN, a commercial flow solver by S & I Engineering Solutions (SandI) available at CAd Lab.
- A_uns_hex grid (from Boeing) and B_uns_mix grid (from DLR) family provided by the HiLiftPW-2 committee is used.
- Free stream initialization (except hysterisis study)
- Postprocessing is carried out using TECPLOT available at SERC, IISc.

Features of code HIFUN

HIFUN: **HI**gh Resolution **F**low Solver on **UN**structured Meshes

- Unstructured cell centre finite volume methodology.
- Higher order accuracy: linear reconstruction procedure.
- Flux limiting: Venkatakrishnan Limiter.
- Inviscid flux computation: Roe scheme.
- Convergence acceleration: matrix free symmetric Gauss Seidel relaxation procedure.
- Viscous flux discretization: Green–Gauss theorem based diamond path reconstruction.
- Eddy viscosity computation: Spalart Allmaras (Standard), K-Omega SST & K-Omega TNT Turbulence Models.
- Parallelization: MPI.
- Dual Time Stepping.

Grid details

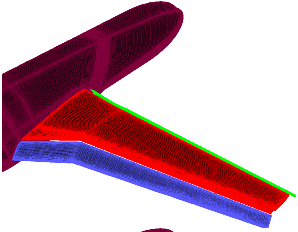
Grid Convergence Study (Case1)

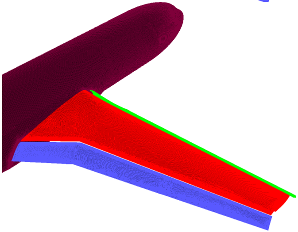
$M_\infty = 0.175$, $Re_\infty = 15.1$ million

Grid Family	Type	Size
A_Uns_Hex	Coarse	9,556,725
	Medium	31,998,440
	Fine	100,561,536
B_Uns_mix	Coarse	21,356,048
	Medium	59,066,549
	Fine	165,246,813

Reynolds Number Study (Case2)

Grid Family	Re_∞	Type	Size
B_Uns_mix	1.35 million	Medium	76,972,998
	15.1 million	Medium	73,740,331

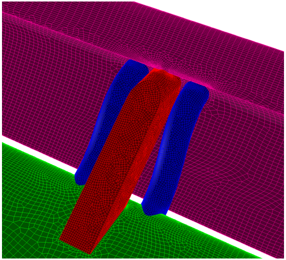




Grid details

Reynolds Number Study (Case3)

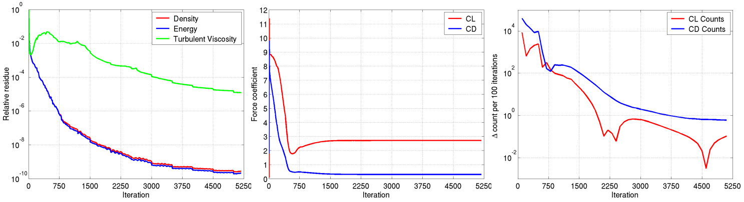
Grid Family	Re_∞	Type	Size
B_Uns_mix	1.35 million	Medium	75,547,314
	15.1 million	Medium	81,603,665



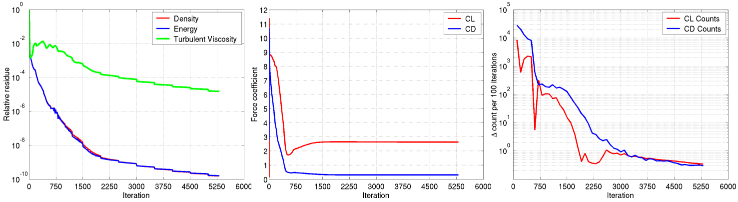
Residue & Force Coefficient Convergence, Case1 Config2

$M_\infty = 0.175$, $Re_\infty = 15.1$ million, $\alpha = 16$ degree

A_uns_hex Fine Grid

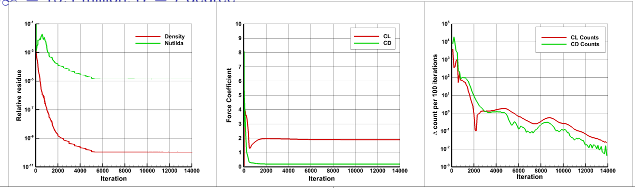


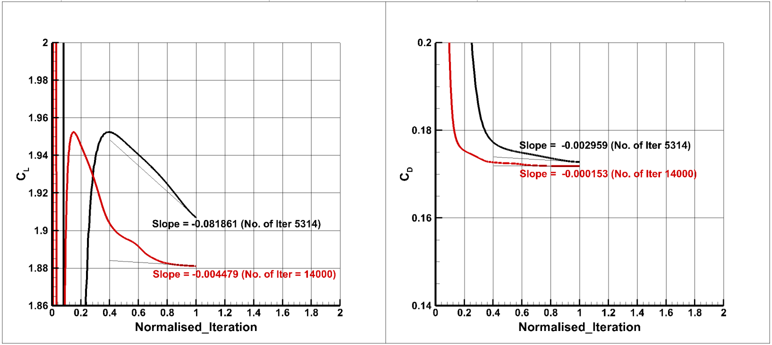
B_uns_mix Medium Grid



Residue & Force Coefficient Convergence, Case1 Config2, B_uns_mix Medium Grid

$M_\infty = 0.175$, $Re_\infty = 15.1$ million, $\alpha = 7$ degree



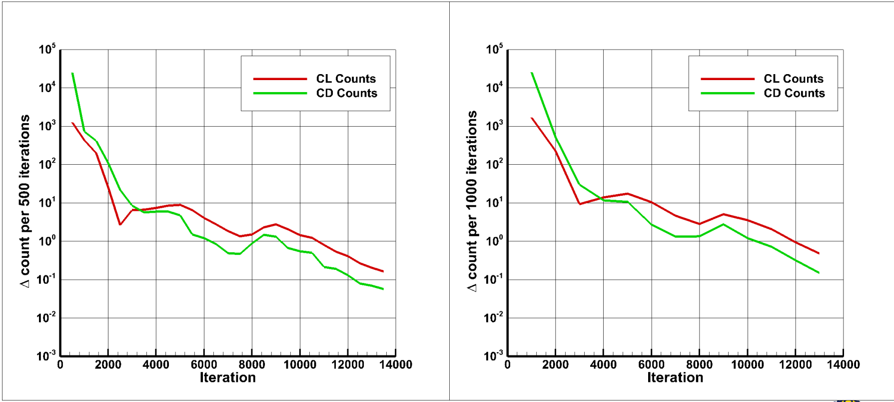


- It is possible to obtain higher level of iterative convergence by just running the code for more number of iterations.

Residue & Force Coefficient Convergence, Case1 Config2, B_uns_mix

Medium Grid

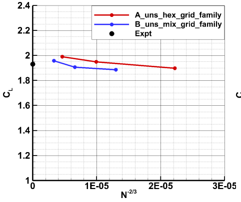
$M_\infty = 0.175$, $Re_\infty = 15.1$ million, $\alpha = 7$ degree



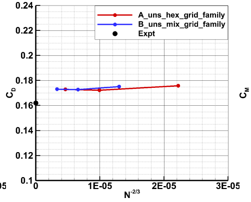
Grid Convergence Study, Case1 Config2

High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7\&16$ degrees

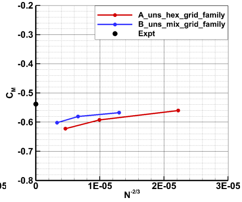
α = 7.0 deg



CL

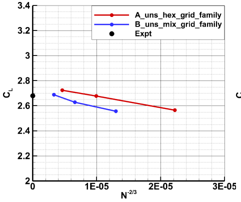


CD

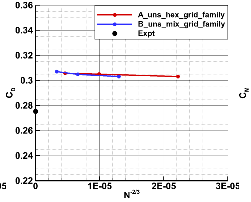


CM

α = 16.0 deg



CL



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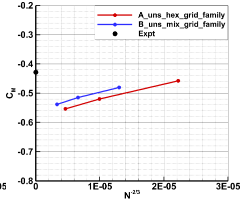


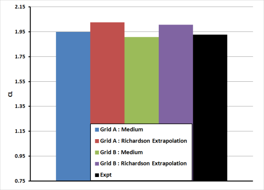
CM

- 1 CL count = 10^{-3} 1 CD count = 10^{-4} 1 CM count = 10^{-3}

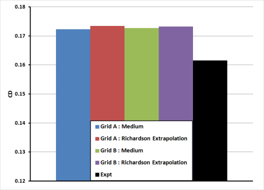
Force & Moment (Case1 Config2, A_uns_hex & B_uns_mix grid)

High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million

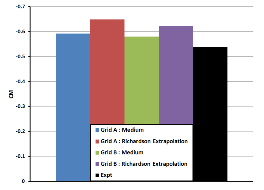
α = 7.0 deg



CL

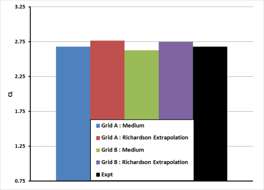


CD

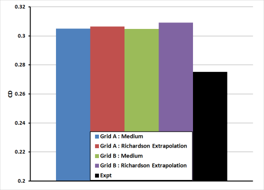


CM

α = 16.0 deg



CL



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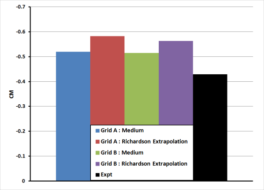
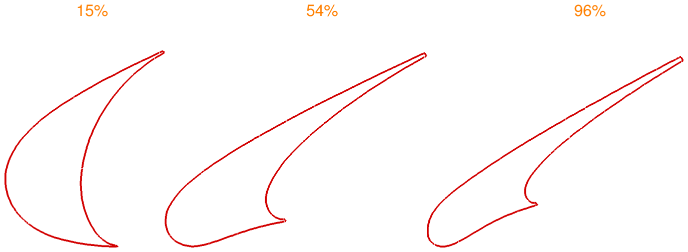


CM

Sectional Cp: Sectional view of Slat (Case1 Config2)

Slat

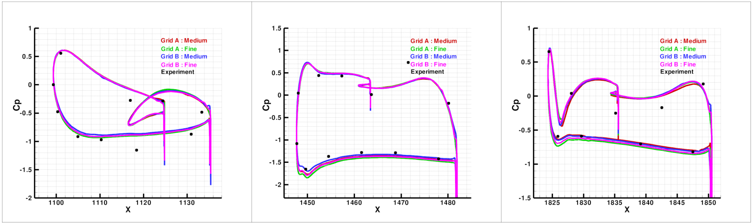


Cp distribution on the Stat (A_uns_hex & B_uns_mix grid family)

$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ & 16 degrees

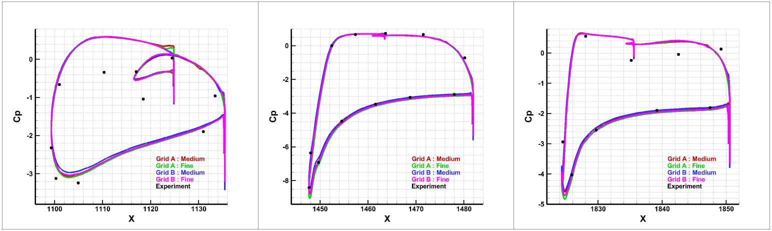
α = 7.0 deg

15% 54% 96%



α = 16.0 deg

15% 54% 96%



Sectional Cp: Sectional view of Main (Case1 Config2)

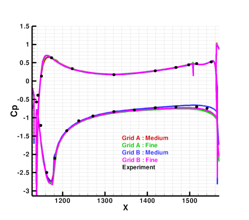
Main

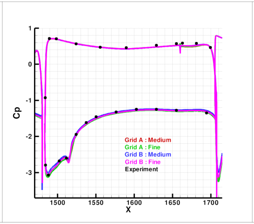
Cp distribution on the Main (A_uns_hex & B_uns_mix grid family)

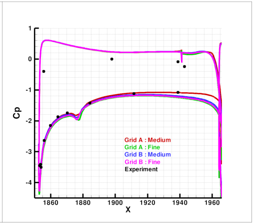
$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg

15% 54% 96%

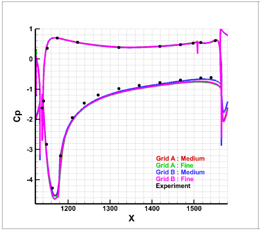


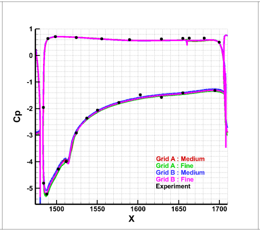


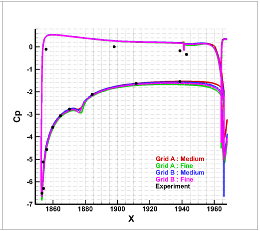


α = 16.0 deg

15% 54% 96%

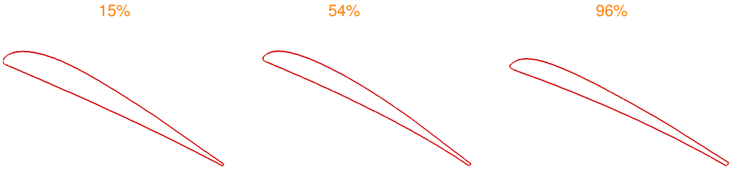






Sectional Cp: Sectional view of Flap (Case1 Config2)

Flap

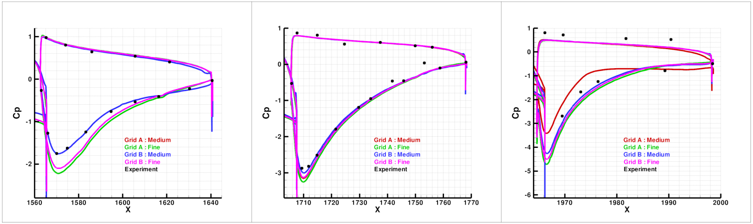


Cp distribution on the Flap (A_uns_hex & B_uns_mix grid family)

$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ & 16 degrees

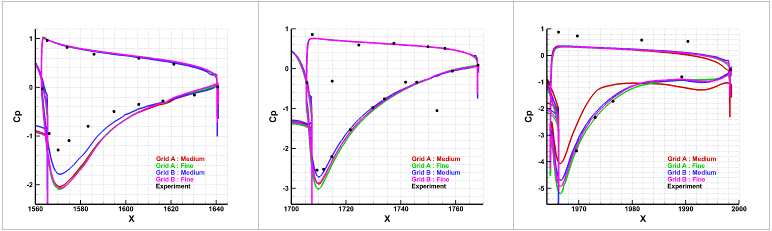
α = 7.0 deg

15% 54% 96%



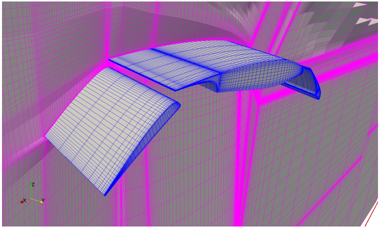
α = 16.0 deg

15% 54% 96%

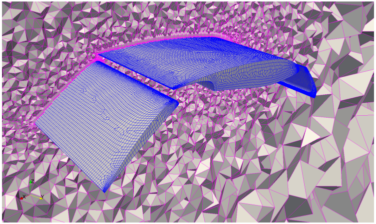


Grid View (A_uns_hex & B_uns_mix grid: Coarse)

Comparison of grids at 96 % of span



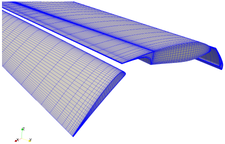
Grid A

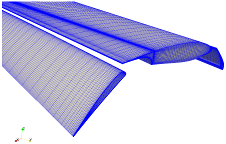


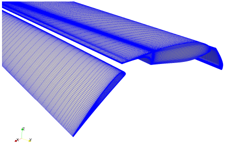
Grid B

Grid View (A_uns_hex & B_uns_mix grid family)

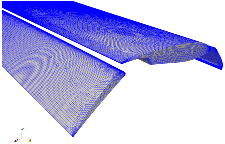
Grid A

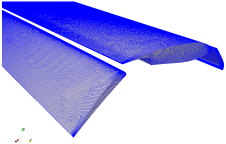


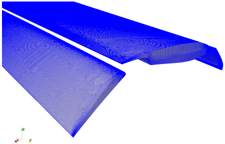




Grid B





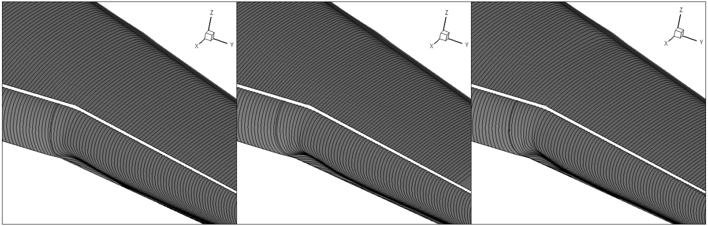


Coarse Medium Fine

Surface Streamlines (A_uns_hex & B_uns_mix grid family)

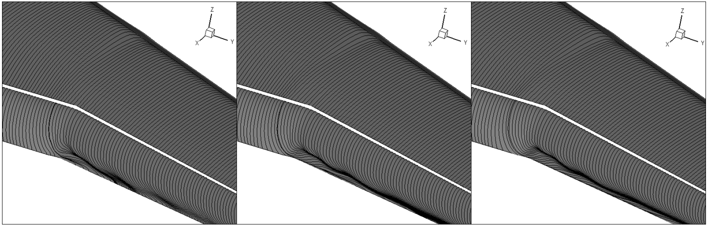
$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 16$ degrees

Grid A



Coarse Medium Fine

Grid B

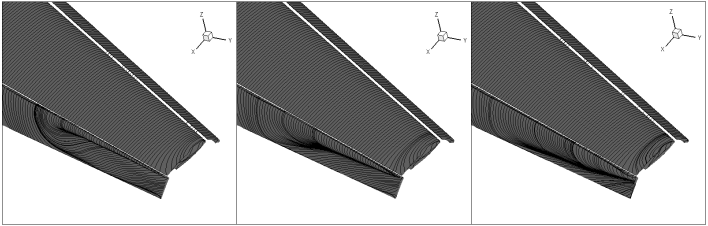


Coarse Medium Fine

Surface Streamlines (A_uns_hex & B_uns_mix grid family)

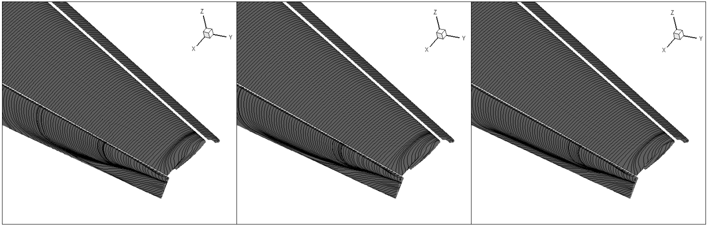
$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 16$ degrees

Grid A



Coarse Medium Fine

Grid B

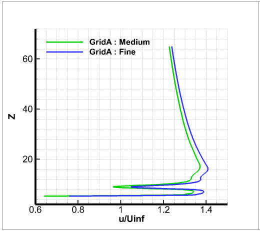


Coarse Medium Fine

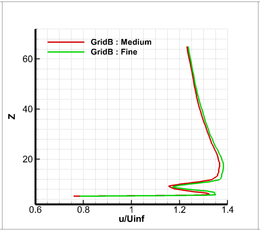
Velocity Profiles (A_uns_hex & B_uns_mix grid family)

$M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ degrees

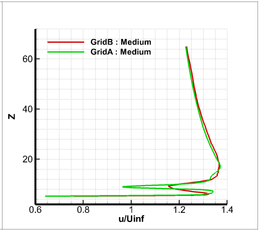
Plane 3, Location: 3E1



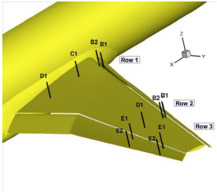
Grid A



Grid B

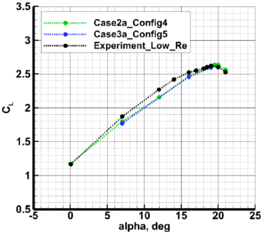


Medium Grid: A and B

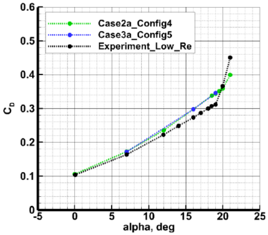


Additional Components: Force & Moment v.s α (Case2a Config4, Case3a Config5, B_uns_mix medium grid)

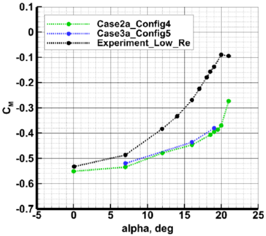
Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million



CL vs α



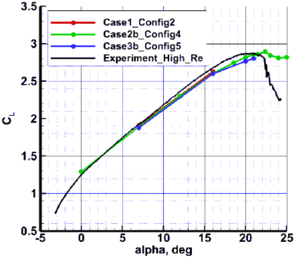
CD vs α



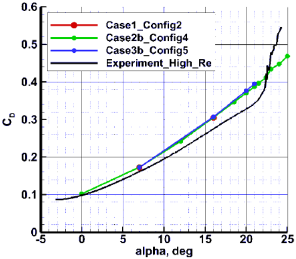
CM vs α

Force & Moment v.s α (Case1 Config 2, Case2b Config4, Case3b Config5, B_uns_mix medium grid)

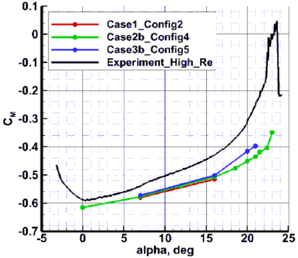
High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million



CL vs α



CD vs α



Force & Moment v.s α (Case2 Config4, B_uns_mix medium grid)

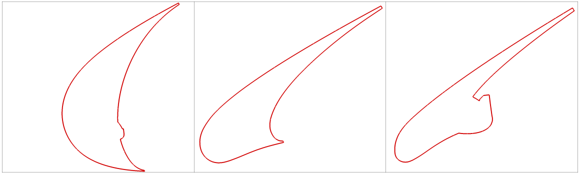
$M_\infty = 0.175$, $Re_\infty = 1.35$ million and 15.10 million

Flow condition	Low Reynolds number		High Reynolds number	
Parameter	CL_{max}	α_{max}	CL_{max}	α_{max}
HiFUN	2.6361	20^o	2.8954	22.40^o
Experiments	2.6228	$\sim 19^o$	2.8730	$\sim 20^o$

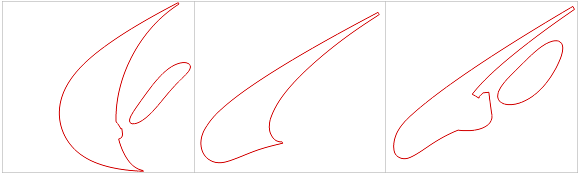
- For low Re case, the numerical predictions of CL_{max} and α_{max} are comparable to experiments
- For high Re case, the numerical predictions of CL_{max} and α_{max} are higher compared to experiments

Sectional Cp: Sectional view of Slat (Case2 Config4, Case3 Config5)

Case 2 Config4: With support brackets



Case 3 Config5: With support brackets and pressure tube bundles

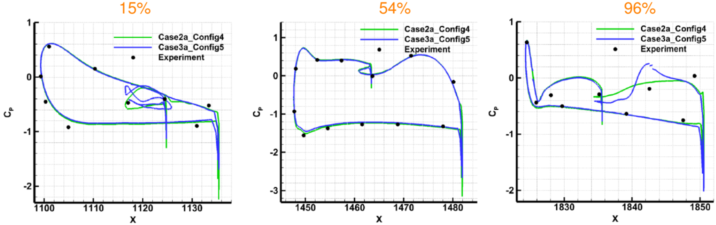


15% 54% 96%

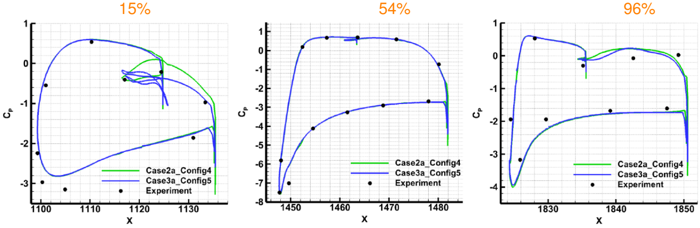
Cp distribution on the Slat (Case1 Config 2, Case2a Config4, Case3a Config5, B_uns_mix medium grid)

Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg



α = 16.0 deg

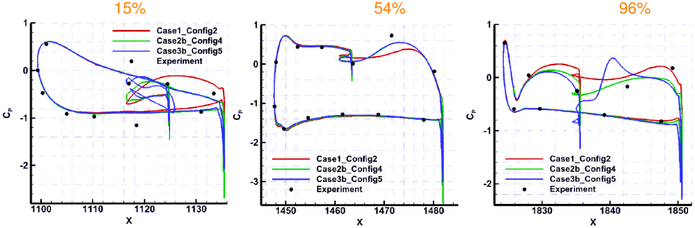


- Good match between CFD and experiment.

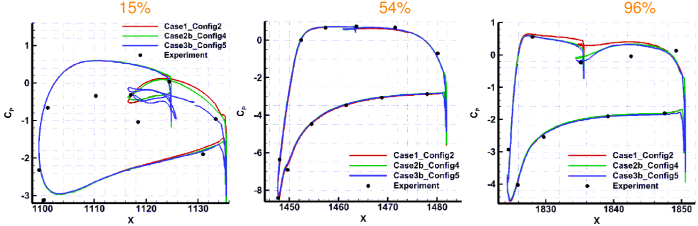
Cp distribution on the Slat (Case1 Config 2, Case2b Config4, Case3b Config5, B_uns_mix medium grid)

High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg



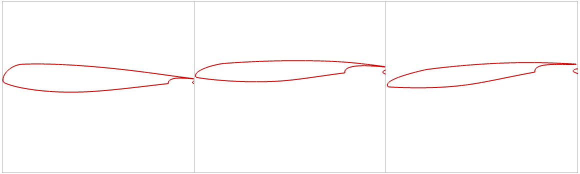
α = 16.0 deg



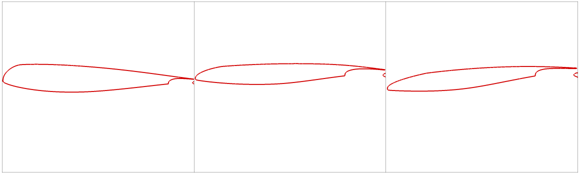
- Good match between CFD and experiment.

Sectional Cp: Sectional view of Main (Case2 Config4, Case3 Config5)

Case 2 Config4: With support brackets



Case 3 Config5: With support brackets and pressure tube bundles

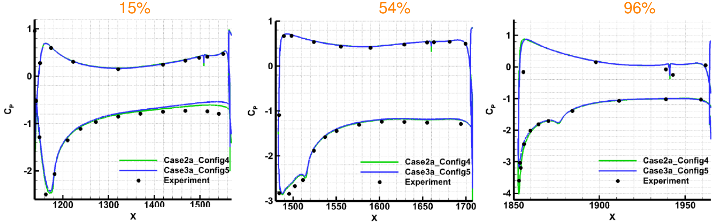


15% 54% 96%

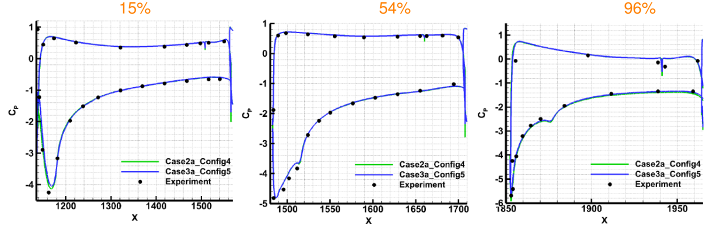
Cp distribution on the Main (Case1 Config 2, Case2a Config4, Case3a Config5, B_uns_mix medium grid)

Low Re case: $M_{\infty} = 0.175$, $Re_{\infty} = 1.35$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg



α = 16.0 deg

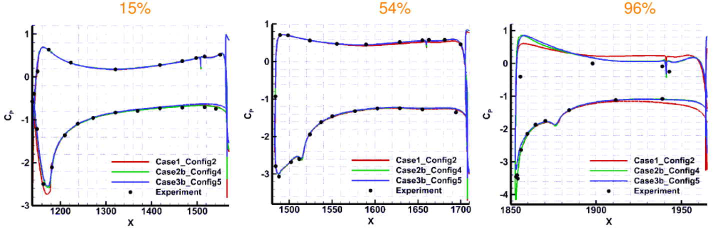


- Good match between CFD and experiment.

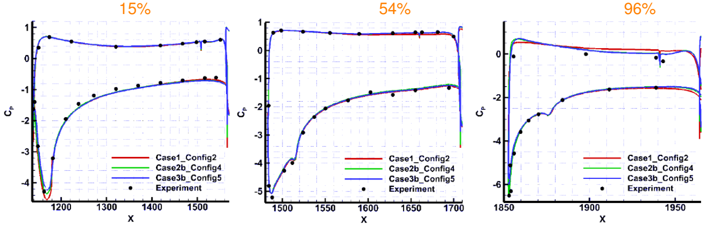
Cp distribution on the Main (Case1 Config 2, Case2b Config4, Case3b Config5, B_uns_mix medium grid)

High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg



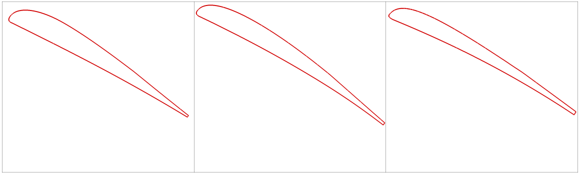
α = 16.0 deg



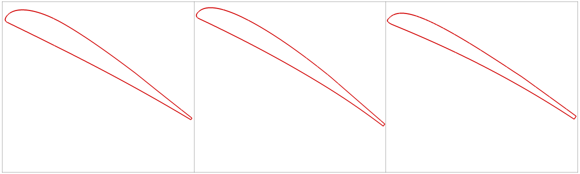
- Good match between CFD and experiment.

Sectional Cp: Sectional view of Flap (Case2 Config4, Case3 Config5)

Case 2 Config4: With support brackets



Case 3 Config5: With support brackets and pressure tube bundles

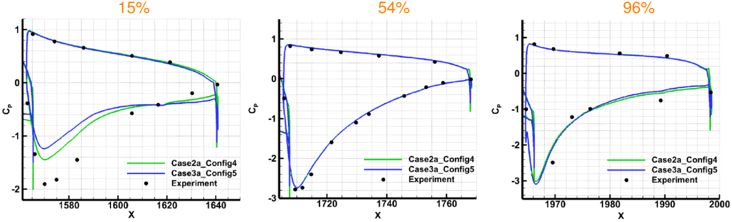


15% 54% 96%

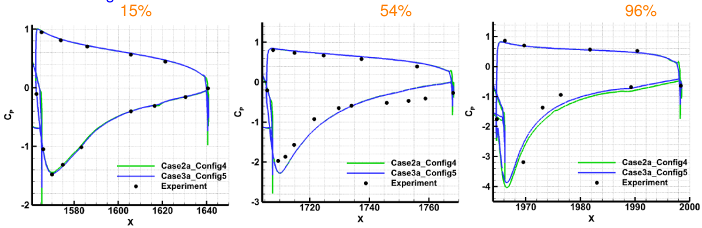
Cp distribution on the Flap (Case1 Config 2, Case2a Config4, Case3a Config5, B_uns_mix medium grid)

Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, $\alpha = 7$ & 16 degrees

α = 7.0 deg



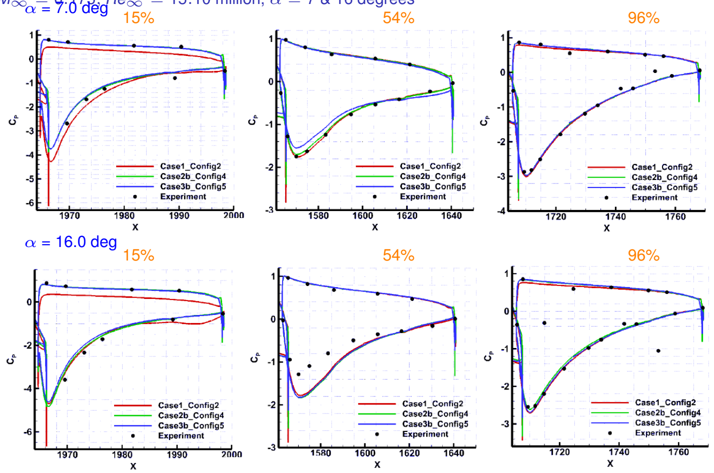
α = 16.0 deg



- Good match between CFD and experiment except at mid-chord location of 15% flap for $\alpha = 7$ degrees.

Cp distribution on the Flap (Case1 Config 2, Case2b Config4, Case3b Config5, B_uns_mix medium grid)

High Re case: $M_{\infty} = 0.175$, $Re_{\infty} = 15.10$ million, $\alpha = 7$ & 16 degrees

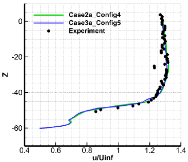


- Good match between CFD and experiment except at mid-chord location of 54 % flap for $\alpha = 16$ degrees.
- Pressure distribution near wing tip for DLR F11 match well with the experimental data in contrast to the comparison seen for low aspect ratio Trap wing

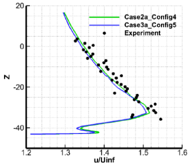
Velocity profiles **Plane 1**: Y = 246.386, (Case2a Config4 and Case3a Config5)

Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, α **= 7 deg**

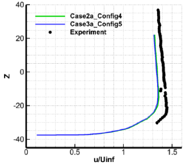
1B1



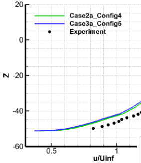
1B2



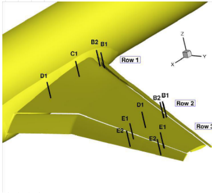
1C1



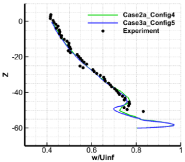
1D1



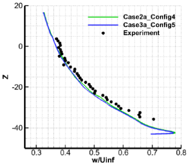
u/U_{inf}



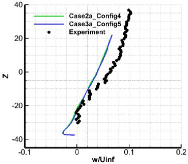
1B1



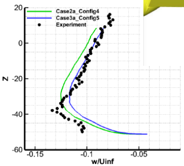
1B2



1C1



1D1

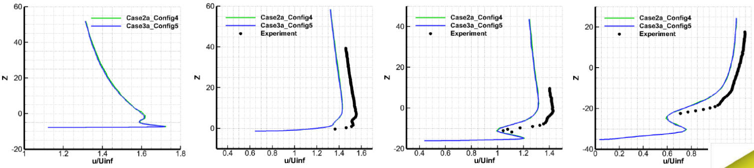


w/U_{inf}

Velocity profiles **Plane 2**: Y = 979.596, (Case2a Config4 and Case3a Config5)

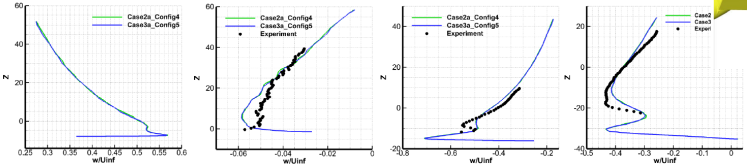
Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, α **= 7 deg**

2B1 2D1 2E1 2E2

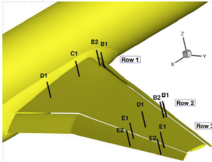


u/U_{inf}

2B1 2D1 2E1 2E2

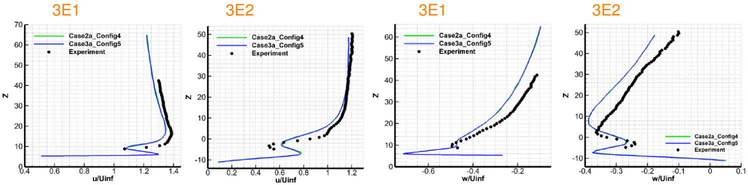


w/U_{inf}

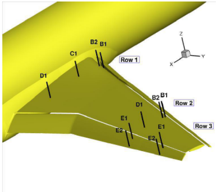


Velocity profiles **Plane 3**: Y = 1223.999, (Case2a Config4 and Case3a Config5)

Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, α **= 7 deg**



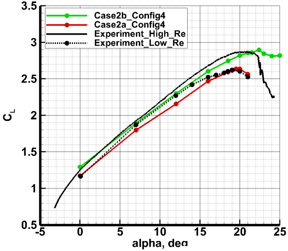
u/U_{inf} w/U_{inf}



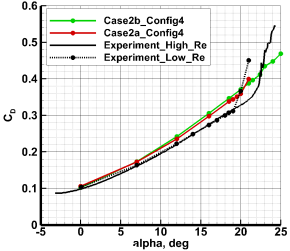
- Except at location 1D1, the presence of support brackets and pressure bundles does not lead to significant change in the velocity profile
- Velocity profiles obtained for DLR F11 match well with the experimental data in contrast to the comparison seen for Trap wing

Reynolds Number Effect: Force & Moment v.s α (Case2 Config4, B_uns_mix medium grid)

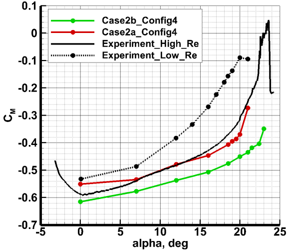
$M_\infty = 0.175$, $Re_\infty = 1.35$ million &15.10 million



CL vs α



CD vs α

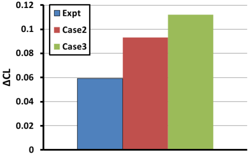


CM vs α

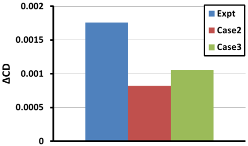
Force & Moment v.s α (Case2a Config4, Case3a Config5, B_uns_mix medium grid)

$M_\infty = 0.175$, $Re_\infty = 1.35$ million &15.10 million

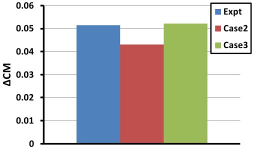
α = 7.0 deg



ΔCL

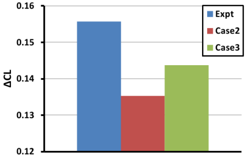


ΔCD

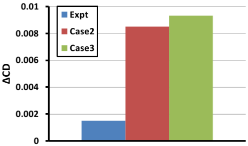


ΔCM

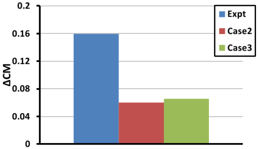
α = 16.0 deg



ΔCL



ΔCD

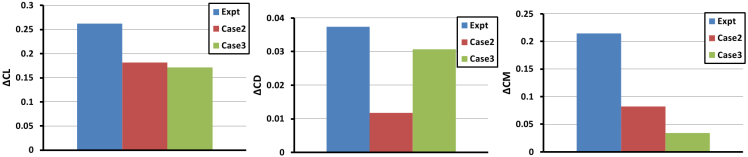


ΔCM

Force & Moment v.s α (Case2a Config4, Case3a Config5, B_uns_mix medium grid)

$M_\infty = 0.175$, $Re_\infty = 1.35$ million &15.10 million

α = 20.0 deg



ΔCL ΔCD ΔCM

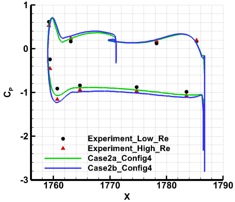
- Qualitative trends are predicted correctly
- Predicted quantitative trends are not satisfactory

Cp distribution (Case2a Config4, Case2b Config4, B_uns_mix medium grid)

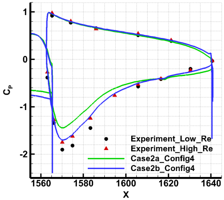
$M_\infty = 0.175$, $Re_\infty = 1.35$ million &15.10 million

α = 7.0 deg

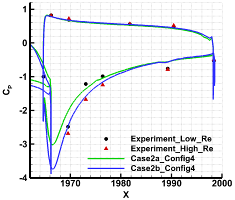
Slat 89%



Flap 15%



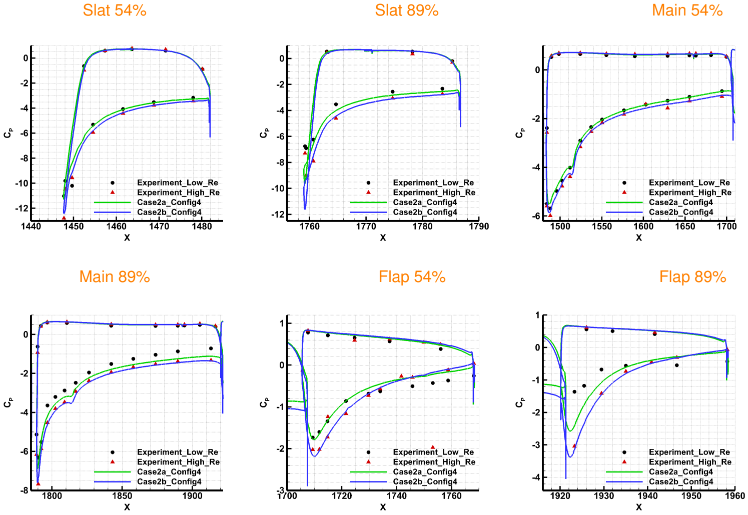
Flap 96%



Cp distribution (Case2a Config4, Case2b Config4, B_uns_mix medium grid)

$M_\infty = 0.175$, $Re_\infty = 1.35$ million &15.10 million

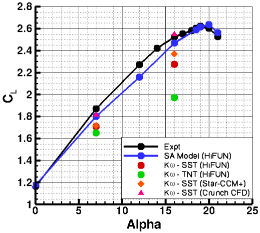
α = 20.0 deg



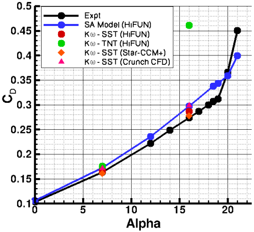
- Except on 15% flap at $\alpha = 7$ degree, trends in Reynolds number variation are predicted correctly

Turbulence model effect: Force & Moment v.s α (Case2a Config4, B_uns_mix medium grid)

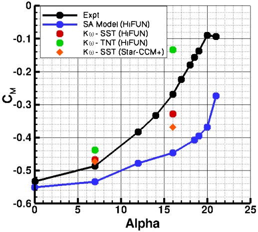
Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million



CL vs α

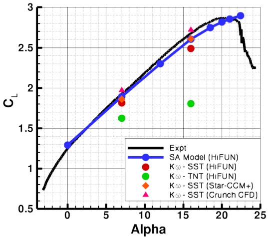


CD vs α

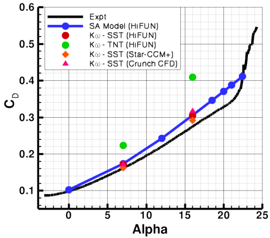


Force & Moment v.s α (Case2a Config4, B_uns_mix medium grid)

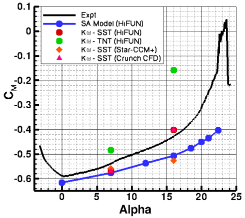
High Re case: $M_\infty = 0.175$, $Re_\infty = 15.10$ million



CL vs α



CD vs α



CM vs α

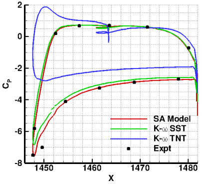
- In general, $k-\omega$ TNT model is found to be less robust compared to other two models

Cp distribution at 54% section (Case2 Config4, B_uns_mix medium grid)

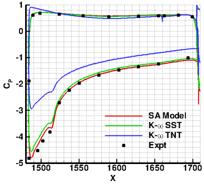
M_∞ = 0.175, α = 16.0 deg

Low Re case: $Re_\infty = 1.35$ million

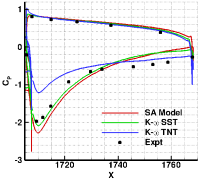
Slat



Main

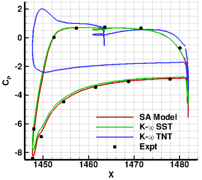


Flap

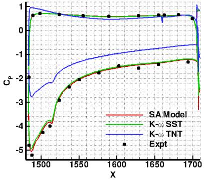


High Re case: $Re_\infty = 15.10$ million

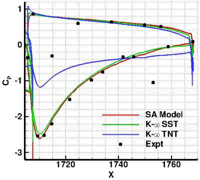
Slat



Main



Flap

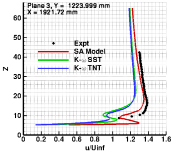


- $k-\omega$ TNT model predicts significantly different C_p distribution on slat compared to other two models
- $k-\omega$ TNT model significantly under predicts suction peak on upper surface of main and flap elements compared to other two models

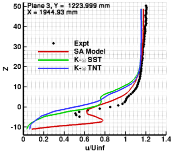
u/U_{inf} profiles **Plane 3**: Y = 1223.999, (Case2a Config4)

Low Re case: $M_\infty = 0.175$, $Re_\infty = 1.35$ million, α **= 7 deg**

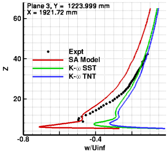
3E1



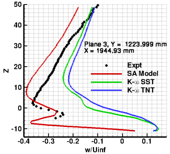
3E2



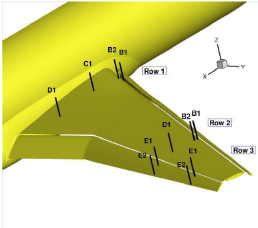
3E1



3E2



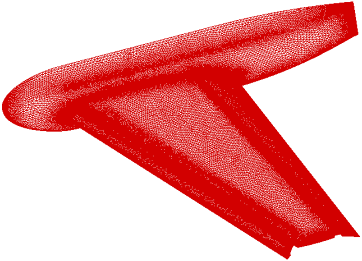
u/U_{inf} w/U_{inf}

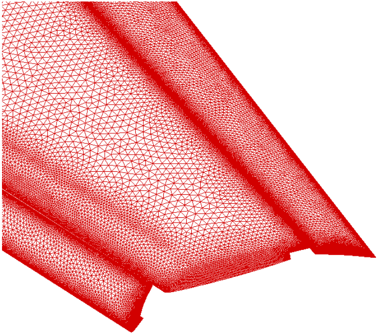


- Velocity profiles predicted by Spalart Allmaras model compare well with experimental data than other two turbulence model

Hysteresis Study (NASA Trap wing, 22 Million medium grid)

- Free stream Mach number is 0.2, Reynolds number based on MAC is 4.3 million
- Grid : Unstructured grid generated for HiLift PW1
- Experiments: Pitch and Pause Mechanism; 20 s rotation + 8 s data acquisition + 2 s data writing

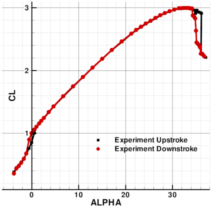




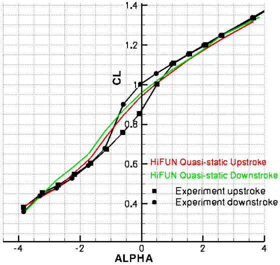
- Both quasi-steady and unsteady simulations are carried out
- For quasi-steady simulation:
  - α range: -3.834^o to 3.645^o
  - 20 steps in upstroke/downstroke
- For unsteady simulation:
  - α range: -3.834^o to 3.645^o
  - $\frac{d\alpha}{dt} = 1.25^o/s$
  - Physical time step = 0.0025 seconds (100 sub-iterations)
  - Total number of physical time steps are 2394

Hysteresis Study (NASA Trap wing, medium grid)

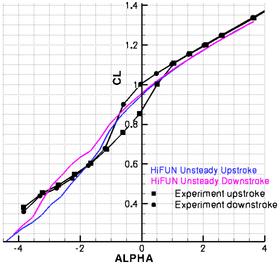
$M_\infty = 0.2$, $Re_\infty = 4.3$ million, Lift Curve



Experiment



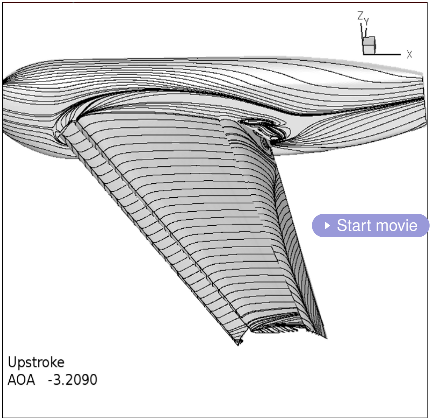
HiFUN: Quasi-static simulation

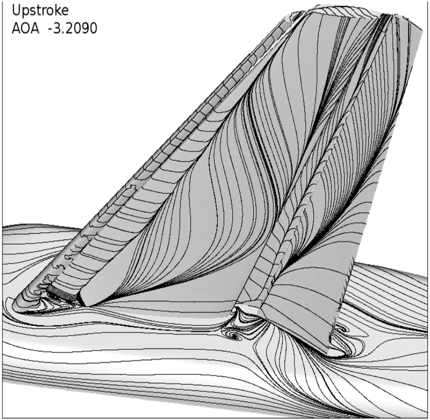


HiFUN: Unsteady simulation

- Quasi-steady simulations show only a marginal change in lift coefficient during upstroke and down-stroke
- Unsteady simulations show the lower leg hysteresis in the lift curve around $\alpha = -2^o$ as against experimental curve which shows hysteresis around $\alpha = 0^o$

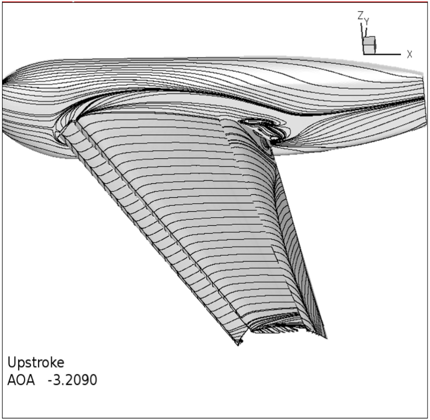
Unsteady RANS Simulations

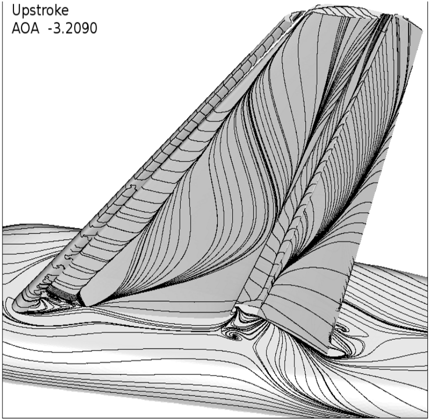




Start movie

Unsteady RANS Simulations





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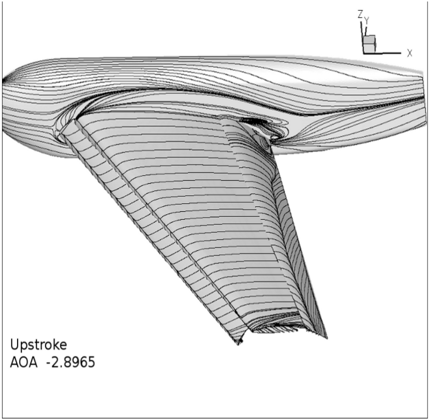

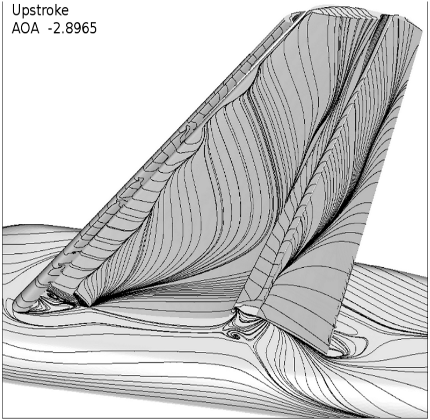

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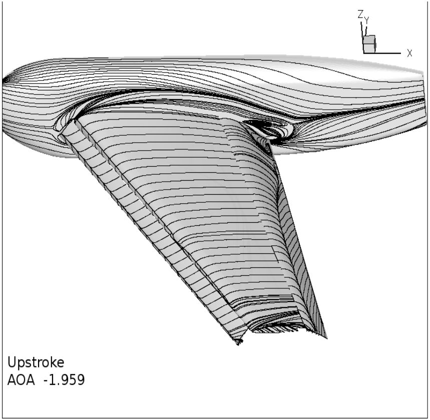

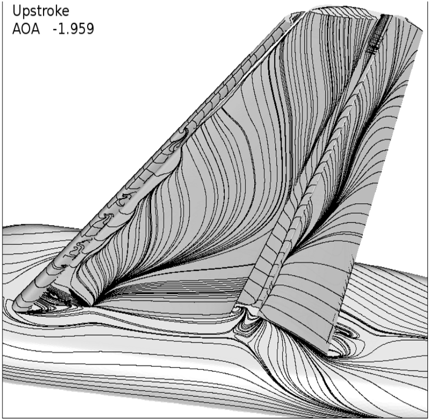

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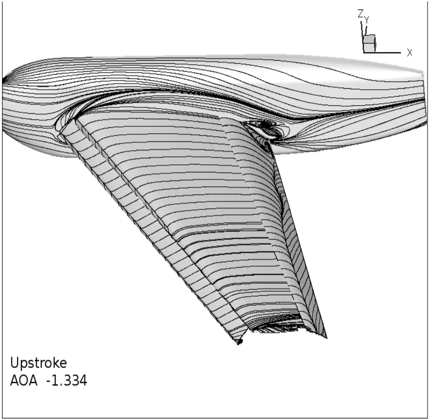

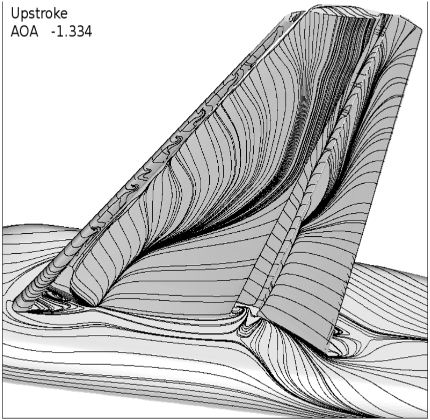

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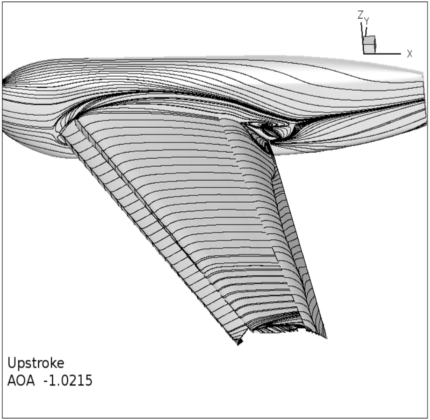

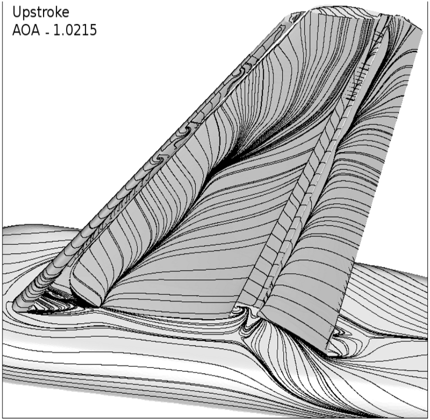

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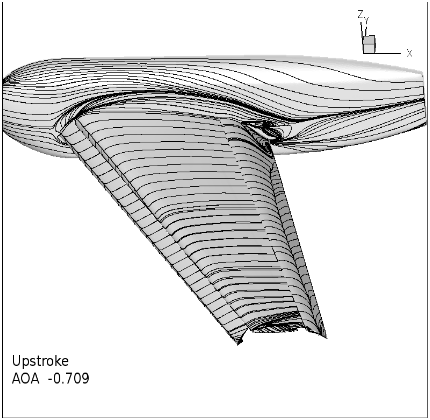

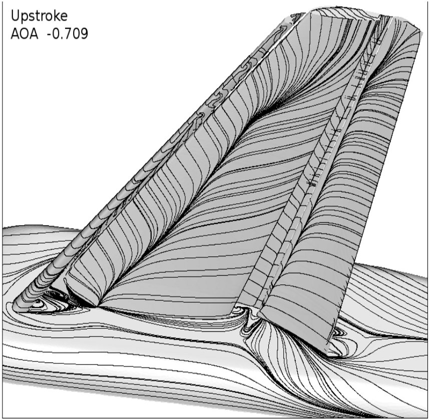

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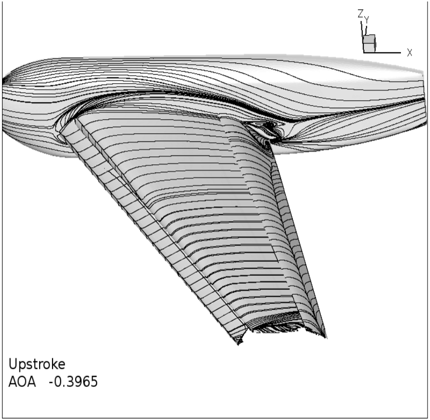

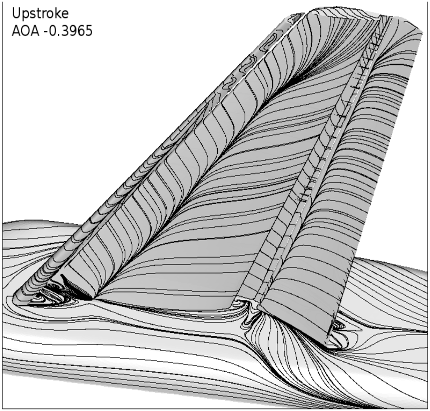

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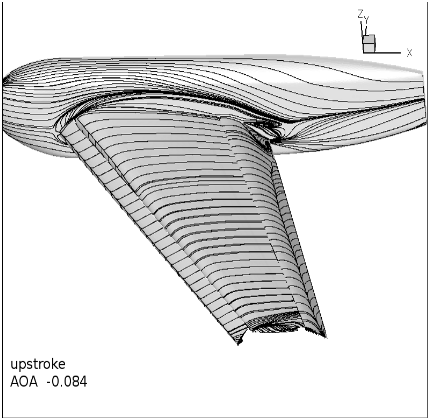

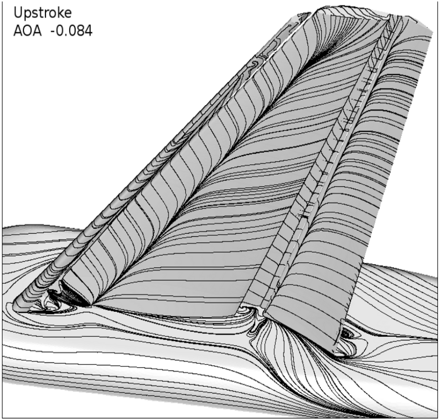

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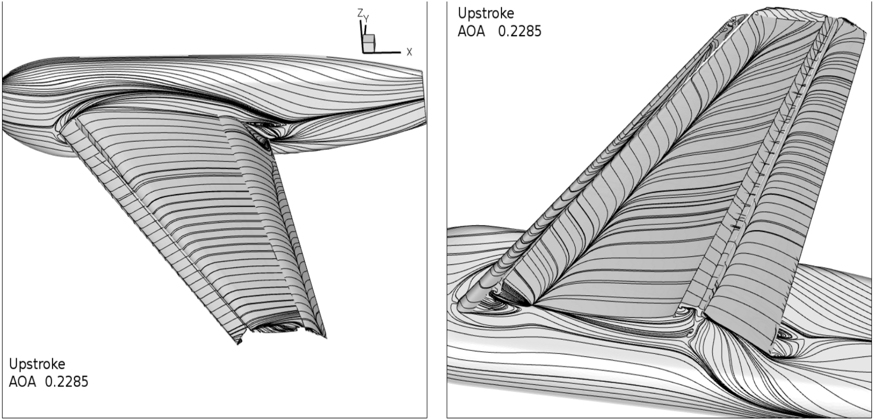

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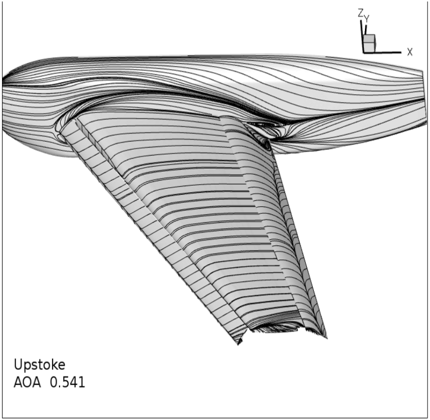

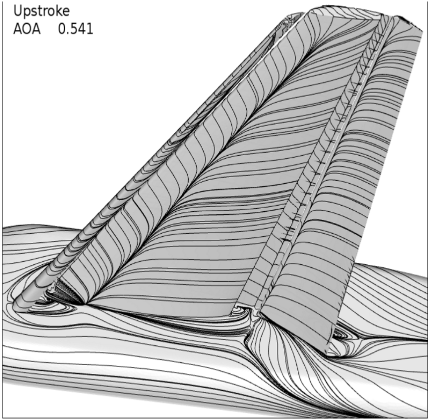

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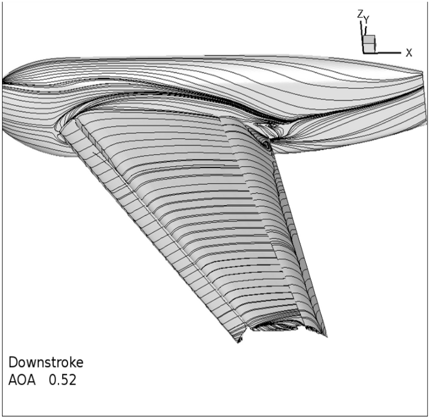

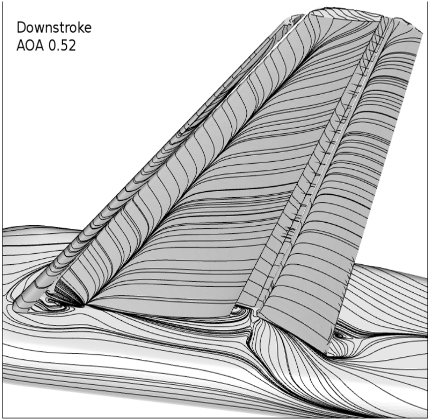

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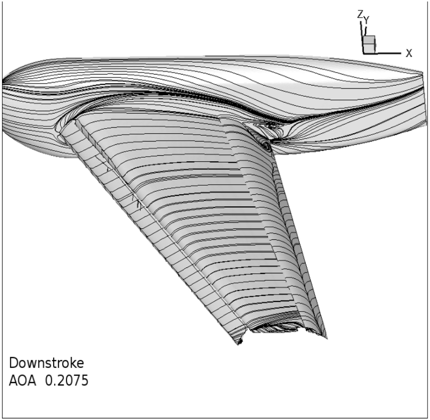

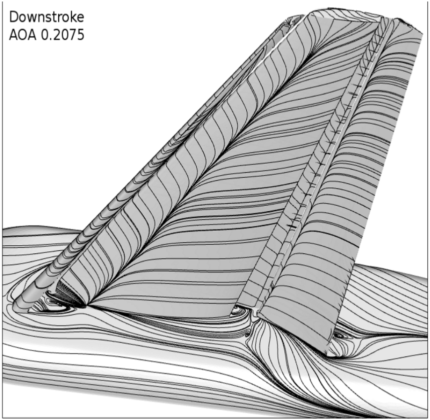

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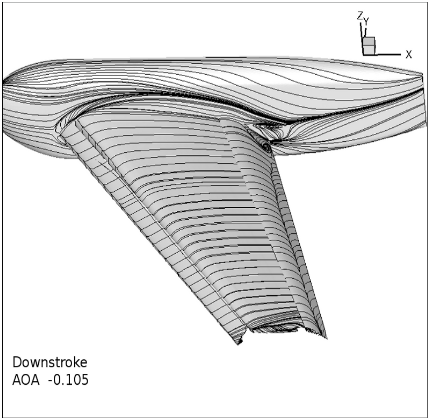

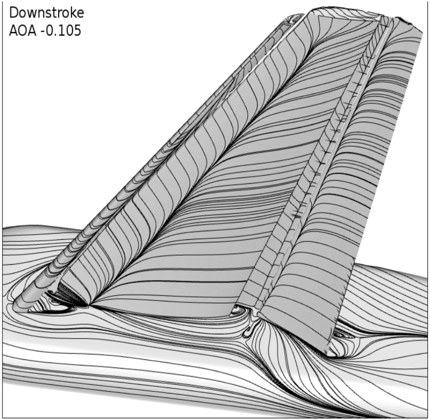

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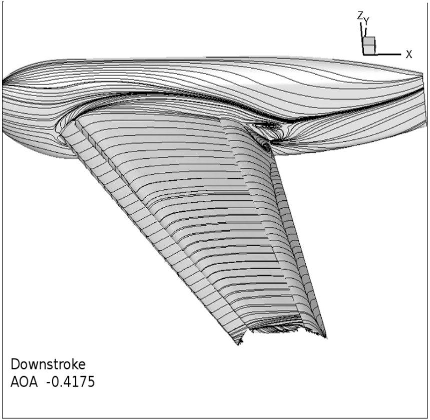

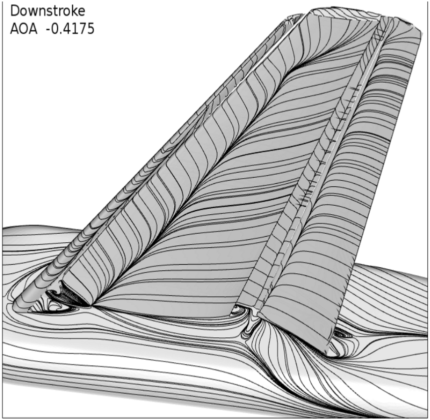

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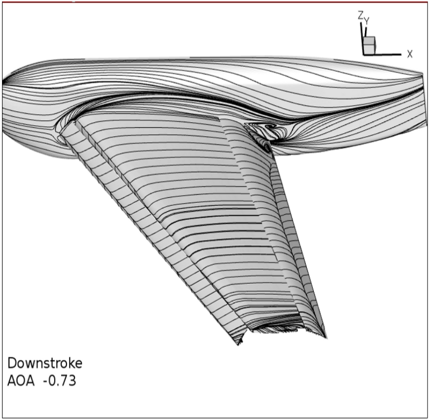

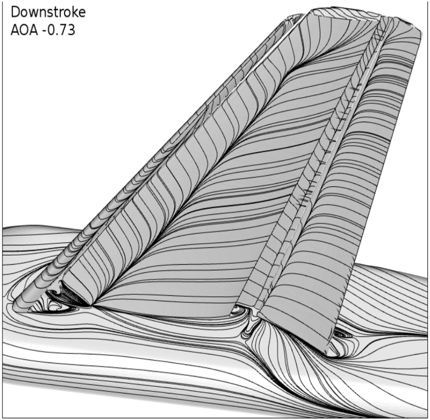

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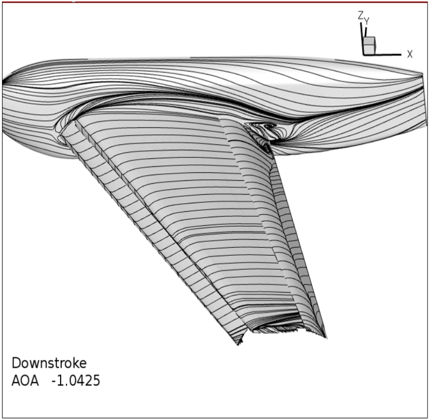

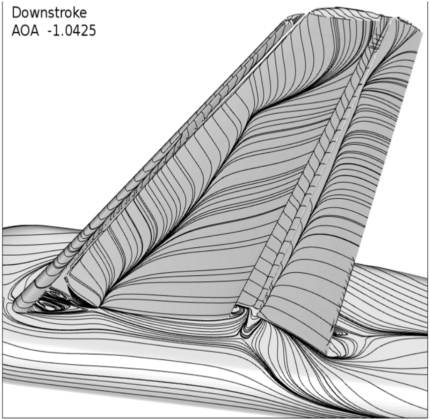

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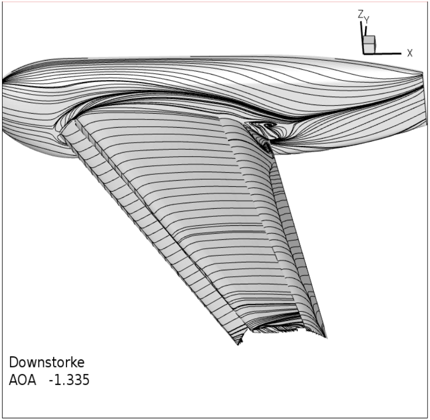

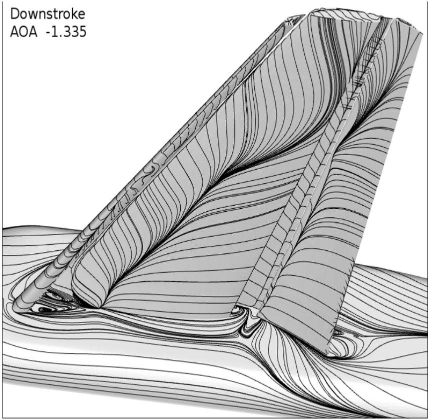

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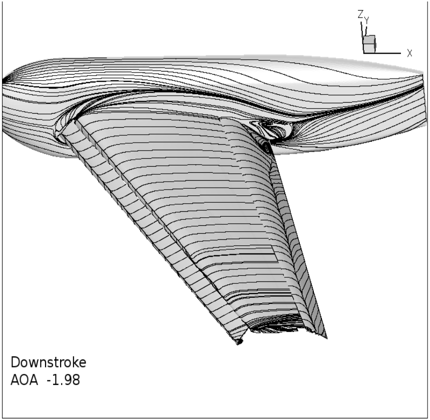

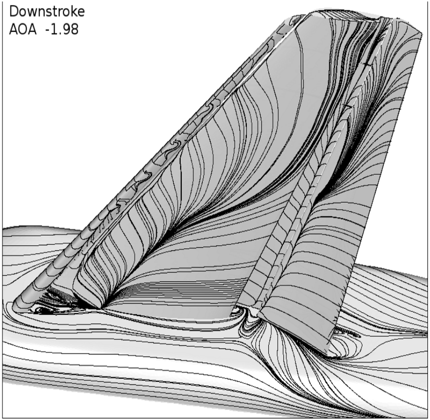

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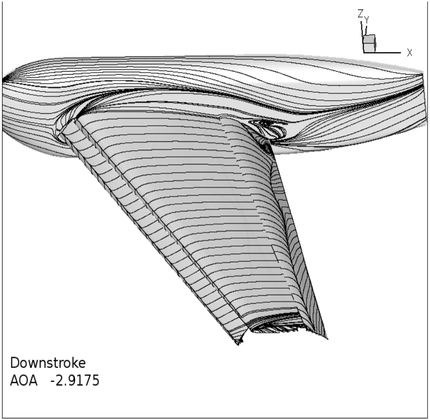

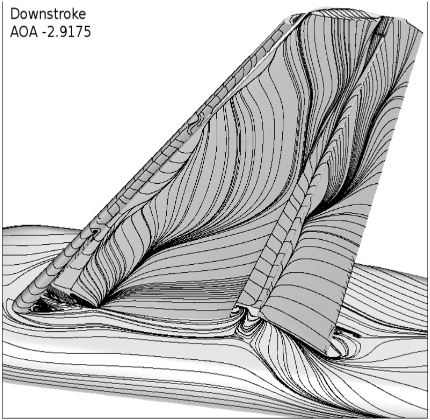

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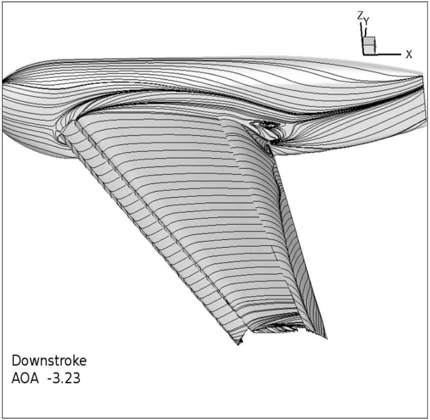

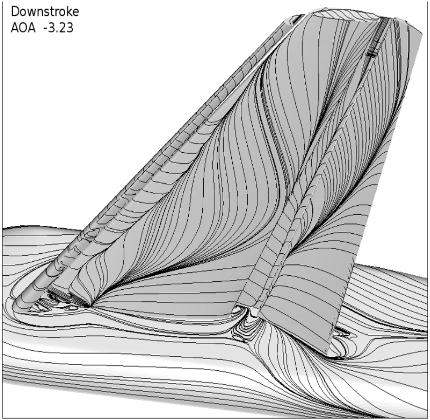

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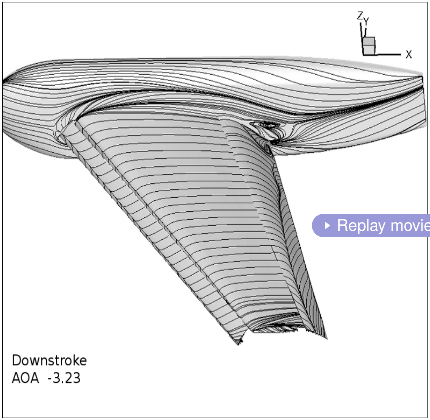
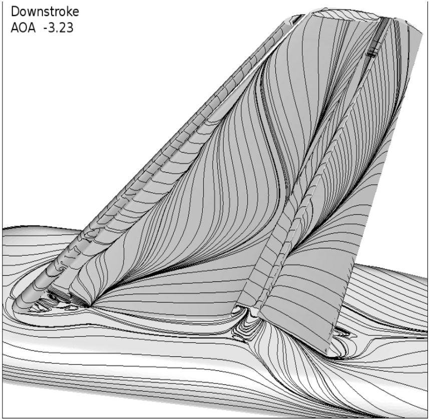


Replay movie



Concluding remarks

Conclusions

- For the incidences considered for grid convergence study, lift and drag are over-predicted and moments are more stabilizing as compared to experiments.
- In general, the pressure distribution predicted by HiFUN shows a good match with the experimental data.
- Wing tip flows are predicted more accurately for high aspect ratio DLR F11 as compared to low aspect ratio NASA trap wing.

Conclusions contd.

- No specific trends in Re study
- From the turbulence model study, it is found that best results can be obtained using Spalart-Allmaras Turbulence model.
- The ability of unsteady HiFUN solver to capture the lower leg hysteresis in the lift curve of NASA Trap wing is established.

Acknowledgments

- Dr. N. Munikrishna, Senior Postdoc, Dept. of Aerospace Engg., IISc., Bangalore.
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- Vignesh, Project Assistant, Dept. of Aerospace Engg., IISc., Bangalore.
- Ramakrishnan, Project Engineer, S & I Engineering Solutions Pvt. Ltd., Bangalore.

Thank you

Thank you

- Gopalakrishna N: gopala81@gmail.com
- Yuvraj Patil: patil.yuvi@gmail.com
- Ravindra K.: deepu.ravindra@gmail.com
- Nikhil Vijay Shende: nikvijay@aero.iisc.ernet.in
- N. Balakrishnan: nbalak@aero.iis.ernet.in