Computational Studies of the NASA High-Lift Trap Wing Using Structured and Unstructured Grid Solvers

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Outline

- Background
  - Lessons learned from HiLiftPW-1

- Objectives

- Grid effects
  - Unstructured hybrid mesh generation w/ suppressed marching direction method at concave corners

- Prediction of boundary layer transitions
  - LSTAB based on $e^N$ method

- Flow solvers & flow conditions

- Results
  - Grid convergence of $CL$ & $CD$
  - Transition prediction

- Concluding remarks
Background

- 1st AIAA CFD High Lift Prediction Workshop in 2010
  - NASA Trap wing: Full-span slat & flap, simplified wing tip
  - Summary by Rumsey et al. (AIAA 2011-0939)
- Identified areas needing additional attention for CFD
  - Outboard flap trailing edge region
    - Higher variability among CFD
  - Effect of initial conditions on CFD solutions
  - Bluff wing tip region
    - Vortices from the slat & wing tip grow & burst over the wing
    - Tendency to under-predict $C_p$ suction levels near the wing tip
    - Accurate prediction of behavior of the vortices, their breakdown & their interaction over the wing may be important
  - Influence of transition

**Cp at 98% span**

**Flap Cp in span-wise**

- Large loss of $Pt$
- Grid dependency
- Turbulent model dependency

$\alpha = 28^\circ$
Comparison of flap SOB separation (\(\alpha = 13^\circ\), Medium)

- CFD simulations w/ 2 solvers in JAXA
  - TAS code for unstructured grids
  - UPACS for structured grids
- Flap SOB flow separation by UPACS showing better agreement with exp.
- Due to difference in corner grid topology?
  - Str-JAXA grids are much finer

Exp.
\(\alpha\)-uncorr = 12°
\(\alpha\)-corr ~ 15.5°
Comparison of SOB Separation in DPW-3

Murayama & Yamamoto, AIAA 2007-0258

- Orthogonal mesh is more independent of approx methods in viscous term
  - Higher-quality elements
  - Less artificial viscosity
- Similar approach in hybrid meshing?
New Hybrid surface and volume meshing method

To create good-quality semi-structured surface quads around selected ridges with minimum user-interventions
- Advancing-layers type method & special treatment at concave corners

To improve the hybrid volume meshing method so that good-quality elements can be easily created at concave corners
- Suppressed marching direction method

Wing tip

Around TE

New approach
2.24 M nodes

Reference
4.46 M nodes
Comparison of flap SOB separation ($\alpha = 13^\circ$, Medium)

- Dependency of the separation to turbulent models
  - Yamamoto et al., AIAA-2012-2895 (11:30 AM, Tuesday, June 26)
Influence of laminar-to-turbulent transition

- Trend of under-predicted $C_L$ especially at $\alpha = 13^\circ$
  - Several reports importance of including the transition for better comparison w/ exp
- Transition prediction method developed in JAXA will be evaluated

Grid convergence from summary of HiliftPW-1 (AIAA 2011-0939)
Objectives

- We have recently performed supplementary computational studies for the Trap Wing model

  (1) Grid effects
  - To compare results with JAXA structured grids & several unstructured hybrid grids by different mesh generators
    - Including new hybrid meshes with the suppressed marching direction method
  - To investigate differences in the wing tip region and the side-of-body region

(2) Prediction of boundary layer transitions
- To evaluate a transition prediction method based on $e^N$ method
(1) Grid effects

- Comparison of JAXA structured grids and several unstructured hybrid grids by different mesh generators
- To investigate the wing tip region and the side-of body region

Grids used in this study

- JAXA multi-block structured grids using Gridgen, Str-OneTo-One-E (SX12-JAXA)
  - Coarse, Medium, Fine
- JAXA unstructured hybrid grids, Unst-Mixed-Nodecentered-C using MEGG3D (UH16-JAXA)
  - Coarse, Medium, Fine
- Committee-provided Uwyo unstructured hybrid grids, Unst-Mixed-FromTet-Nodecentered-A-v1 using VGRID
  - Coarse, Medium, Fine
- Committee-provided DLR unstructured hybrid grids, Unst-Mixed-FromTet-Nodecentered-B using Solar
  - Coarse, Medium
- New JAXA unstructured hybrid grids, Unst-Mixed-Nodecentered-JAXA New using MEGG3D
  - Coarse, Medium-coarse
JAXA multi-block structured grids (SX12-JAXA, Gridgen)

- O-O grid topology near the model surface
  - To guarantee better orthogonality within the boundary layer
- C-O grid topology at outward
- **O-H grid topology** at wing-body junction
  - High-density grid at the corner of wing-body junction

441 blocks

Coarse (12M)  Medium (37M)  Fine (124M)
JAXA unstructured hybrid grids (UH16-JAXA, MEGG3D)

- Surface grid (Isotropic triangles)
  - Direct advancing front method by Ito et al.
- Volume grid (Tetrahedra, Prisms, Pyramids)
  - Delauney (tetra) → insertion of prismatic layer (prism)
- **Extruded prisms** on no-slip walls, including at wing-body junction


Committee-provided unstructured hybrid grids

- University of Wyoming using VGRID
  - Unst-Mixed-FromTet-Nodecentered-A-v1: Unst-MFTNAv1
- DLR using Solar
  - Unst-Mixed-Nodecentered-B-v1: Unst-MNBv1
- Comparison of medium grids
  - Extruded elements at wing-body junction

Unst-JAXA grid (UH16) (28M)
Unst-MFTNAv1 grid (11M)
Unst-MNBv1 grid (37M)

- Thinner layers at corner
- Less flap resolution
- Less nodes
New JAXA unstructured hybrid grids (MEGG3D)

- **Surface grid**
  - Advancing-layers type method w/ special treatment at concave corners
  - Direct advancing front method for surface triangulation
- **Volume grid**
  - Advancing-layers type method w/ suppressed marching direction method
  - Advancing front method for tetrahedral meshing
- **Orthogonal hexes** at wing-body junction

Coarse (18M) Medium-coarse (24M)
Numerical methods & flow conditions

- Modification to S-A model (SA-noft2-R (Crot=1)) to suppress excessive eddy viscosity after separation
  - w/o trip related terms
  - w/ modification to production term: $S = \min(\sqrt{2\Omega^2}, \sqrt{2S^2})$
- Restart from result at lower $\alpha$ to obtain results at higher $\alpha$
- Slat & flap setting: Config 1
- No slat & flap brackets included
- $M = 0.2$, $Re = 4.3 \times 10^6$, $T = 520^\circ R$ & $\alpha = 13^\circ, 28^\circ$
Grid convergence of $C_L$

- Good agreement among CFD results on finer grids
- Good correlation between UPACS for SX12-JAXA & TAS for UH16-JAXA on expected grid converged solutions, $C_L(N\rightarrow\infty)$
- Similar values & trends by JAXA-New & UH16-JAXA

- $\alpha = 13^\circ$
  - Mild slopes of grid convergence
  - Good agreement among CFD results, but lower $C_L$ than exp.

- $\alpha = 28^\circ$
  - More variations and steeper slopes of grid convergence
  - Higher $C_L(N\rightarrow\infty)$ than exp.

$N$ (grid points) $\approx \infty \quad 100M \quad 32M \quad 11M \quad 6M \quad 4M$
Comparison of flow separation on flap ($\alpha = 13^\circ$, Medium)

CFD results show larger flap TE flow separation than exp.  
$\rightarrow$ CFD: fully turb, Exp: free transition

$\alpha$-uncorr = 12°, $\alpha$-corr ~ 15.5°
Comparison of flow separation on flap ($\alpha = 13^\circ$, Medium)

**CFD results show larger flap TE flow separation than exp.**

$\rightarrow$ CFD: fully turb, Exp: free transition

$\alpha$-uncorr = 12$^\circ$, $\alpha$-corr $\sim$ 15.5$^\circ$
Grid convergence of $C_D$

- Similar trends with $CL$
- Reasonable agreement among CFD results on finer grids at $\alpha = 13^\circ$
- Good correlation between UPACS for SX12-JAXA & TAS for UH16-JAXA on expected grid converged solutions, $C_D(N\to\infty)$
- Similar values and trends by JAXA-New & UH16-JAXA

- $\alpha = 13^\circ$
  - Mild slopes of grid convergence
  - Good agreement among CFD results, but lower $C_D$ than exp.

- $\alpha = 28^\circ$
  - More variations and steeper slopes of grid convergence
  - More scattering of $C_D(N\to\infty)$ among CFD results
  - Higher $C_D(N\to\infty)$ than exp.

$N$ (grid points) $\approx \infty \quad 100M \quad 32M \quad 11M \quad 6M \quad 4M$
Comparison of flow separation at flap-body junction

- SX12-JAXA grid & JAXA-New grid have smaller, better-quality, more orthogonal hexes at the corner.
- Finer grids predicted the large corner flow separation
  - The flow separation by JAXA-New grid still remains smaller than that of SX12-JAXA grid by UPACS
  - Grid dependency will be investigated furthermore

$C_f$ and grid distribution at $\alpha = 13^\circ$
Comparison of flow separation at flap-body junction

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$C_f$ and grid distribution at $\alpha = 13^\circ$
Comparison of tip vortices between JAXA grids

- JAXA-New grids have much finer faces on the tips and predict stronger vortices from the edges of the tips.
- However, $C_p$ at 98% semi-span station was not improved.
  - More elements are probably needed in the volume.

Vorticity and grid distribution at $\alpha = 28^\circ$

UH16-JAXA grids, $\leq 72$M nodes

JAXA-New grids, $\leq 24$M nodes
Comparison of tip vortices between JAXA grids

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Vorticity and grid distribution at $\alpha = 28^\circ$

UH16-JAXA grids, ≤ 72M nodes

JAXA-New grids, ≤ 24M nodes
(2) Prediction of boundary layer transitions

- Our approach: $e^N$ based method using RANS CFD $C_p$
  - Tollmien-Schlichting (TS) instability
  - Cross Flow (CF) instability
  - Laminar separation bubbles (LSB)

- We have not considered
  - Attachment line contamination due to the transport of turbulence from fuselage, etc.
  - Re-laminairisation due to strong acceleration of flow
  - Bypass transition due to the wake flow of fore wing element

- Predicted locations compared w/ those by Eliasson et al. (AIAA 2011-3009) available on HiLiftPW website
  - Prescribed $N = 5, 7, 10$ for comparison
Developed in JAXA NEXST (National EXperimental Supersonic Transport) Projects

Yoshida et al.

- CFD computation
  - Surface $C_p$
- Laminar boundary layer computation
  - Velocity profile
- Stability analysis (Eigenvalue analysis)
- $e^N$ method (Envelope method)
- $N$ value map
  - Threshold of $N$ for transition
  - Prediction of Transition

- Stability analysis
  - Performed at several span locations
- Laminar boundary layer computation
  - Kaups & Cebeci method using $C_p$
    - Conical flow approximation
  - Laminar separation is detected based on the shape factor, $H$
- $N$-factor
  - Obtained by envelope method using integration of amplification rates of each small disturbance
- Prediction of transition
  - $N = 5, 7, 10$
  - If transition due to TS and CF does not occur before the laminar separation, transition starts just before the separation location

# Results after only one cycle are presented
# First CFD comp. is performed assuming fully turbulent flow
Predicted transition location: $\alpha = 13^\circ$, upper surf

- Computational conditions
  - SX12-JAXA grid
  - $N = 5, 7, 10$
  - Span = 17%, 41%, 65%, 85%, 95%

- Upper surface of slat
  - Most regions remain laminar
  - Transition location at outer span location changes by $N$

- Upper surfaces of main and flap
  - Most transitions are caused by laminar separation bubble

- Good agreement w/ Eliasson et al.
Predicted transition location: $\alpha = 13^\circ$, lower surf

- **Computational conditions**
  - SX12-JAXA grid
  - $N = 5, 7, 10$
  - Span = 17%, 41%, 65%, 85%, 95%

- **Lower surface of slat**
  - Most regions remain laminar until cusp

- **Lower surfaces of main and flap**
  - Most transitions are caused by natural transition
  - The results show slightly earlier onset of transitions than Eliasson et al., but similar trend of changes by $N$

- Good correlation w/ Eliasson et al.
Predicted transition location: $\alpha = 28^\circ$, upper surf

- **Computational conditions**
  - SX12-JAXA grid
  - $N = 5, 7, 10$
  - Span = 17%, 41%, 65%, 85%, 95%

- **Upper surface of slat**
  - *Most regions are turbulent*
    - Cf. Laminar at $\alpha = 13^\circ$

- **Upper surfaces of main and flap**
  - *Most transitions are caused by laminar separation bubble*
  - Similar to the result at $\alpha = 13^\circ$

- **Good agreement w/ Eliasson et al.**
Predicted transition location: $\alpha = 28^\circ$, lower surf

- Computational conditions
  - SX12-JAXA grid
  - $N = 5, 7, 10$
  - Span = 17%, 41%, 65%, 85%, 95%

- Lower surface of slat
  - Most regions remain laminar until cusp
    - Nearly identical with $\alpha = 13^\circ$

- Lower surfaces of main and flap
  - Most transitions are caused by natural transition
    - Main: delayed onset than $\alpha = 13^\circ$
    - Flap: slightly changed from $\alpha = 13^\circ$

- The results show earlier onset of transitions than Eliasson et al., but similar trend of changes by $N$

- Good correlation w/ Eliasson et al.
Concluding Remarks

- Computational studies have recently been performed to supplement HiLiftPW-1
- The influence of grid resolution around wing tip & SOB regions were investigated with two new unstructured hybrid grids
  - Finer, high-quality near-field meshes around the flap-body junction generated larger corner flow separation
  - The improvement of grid resolution on the surface around wing tip was not effective to improve the under-predicted $C_p$ suction peaks
  - Further studies on more extensive grid refinement & influence of turbulence models may be required to capture flow physics in those regions
- A transition prediction method based on $e^N$ method was evaluated by compared with data from Eliasson et al.
  - Predicted transition locations caused by laminar separation bubbles agreed well
  - Overall tendency of the transition patterns & locations agreed reasonably well with each other