High-Lift Prediction Workshops: Retrospective, Lessons Learned, and Future Prospects
ICAS PAPER 2024-1217

Christopher L. Rumsey
NASA Langley Research Center

OUTLINE

- Introduction
- General organization and conduct of the High-Lift Prediction Workshops (HLPWs)
- Lessons learned from the HLPWs (1 through 5)
- Overall workshop trends and the future of high-lift CFD prediction

THE FUTURE OF FLIGHT?

INTRODUCTION

- The aeronautical CFD community has been struggling for many years to accurately and consistently predict flows over swept, medium-to-high-aspect ratio wings for landing/take-off (high-lift) configurations
  - Success would enable CFD usability over a wider range of the flight envelope, possibly leading to broader adoption of Certification by Analysis in the aircraft design process
- The AIAA High-Lift Prediction Workshop (HLPW) series was initiated in 2010
  - Bringing experts together with the common goal of assessing and improving CFD for high-lift flows
  - There have been five workshops to date

GENERAL ORGANIZATION AND CONDUCT

- The HLPWs are run by a steering committee
- Always makes use of high-lift configurations for which the geometry and measured data have unrestricted public availability, forming the basis for international cooperation and collaboration
  - Lately, the focus has been on the high-Lift version of the Common Research Model (CRM-HL), which is being tested broadly in an “ecosystem” of multiple models across many wind tunnels
- Broad participation across companies, universities, and research organizations is encouraged

GENERAL ORGANIZATION AND CONDUCT, cont'd

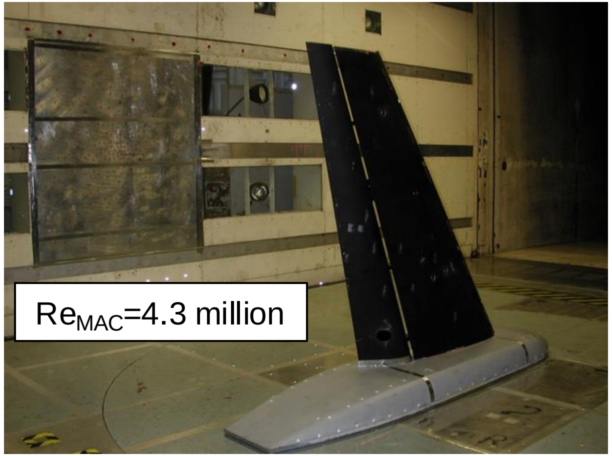
- HLPW-1 and 2
  - Traditional workshop: participants work independently and submit/present their results; workshop is first time everyone sees the collective results
  - Mostly compared Reynolds-averaged Navier-Stokes (RANS) participant CFD results against wind tunnel data
- HLPW-3
  - Similar, but also partnered the with the AIAA Geometry and Mesh Generation Workshop (GMGW)

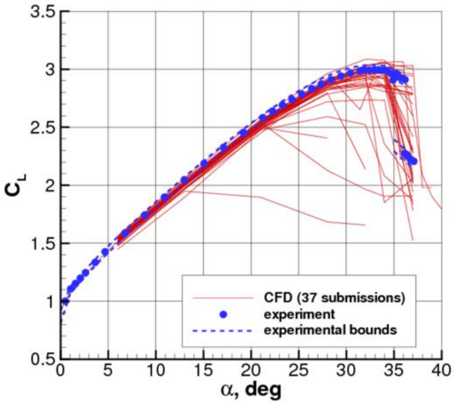
GENERAL ORGANIZATION AND CONDUCT, cont'd

- HLPW-4
  - Continued with GMGW partnership
  - Introduced concept of Technology Focus Group (TFG), each with different CFD methodology focus
    - RANS, ADAPT (mesh adaptation), HO (high-order), HRLES (hybrid RANS/large eddy simulation), WMLES (wall-modeled large eddy simulation)
    - The latter two groups cover the burgeoning field of scale-resolving simulations (SRS)
    - Significant TFG-centric collaborative work conducted up front (via virtual meetings), prior to the workshop itself (participants see progress, which can affect their own trajectory prior to final submission)
- HLPW-5
  - Continued the TFG approach

LESSONS LEARNED, HLPW-1

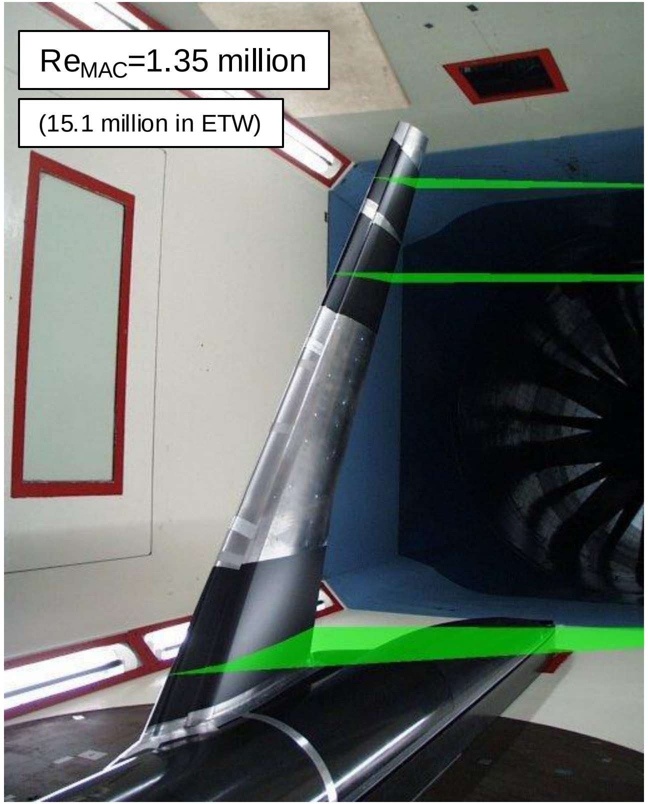
- NASA semispan Trapezoidal Wing-Body in NASA 14x22 wind tunnel
- Included exploration of flap deflection effect
- 21 participants; 39 sets of CFD data
- Grids typically had well less than 100 million unknowns
- CFD tended to underpredict lift; big spread near stall
- No support brackets were included in the CFD (when they were, predicted lift was even lower)
- Evidence of multiple solutions ("low lift branch") at high AoA
  - "Warm starts" emerged as a way to attempt to avoid early CFD stall
- Effects of flap deflection overpredicted near CLmax





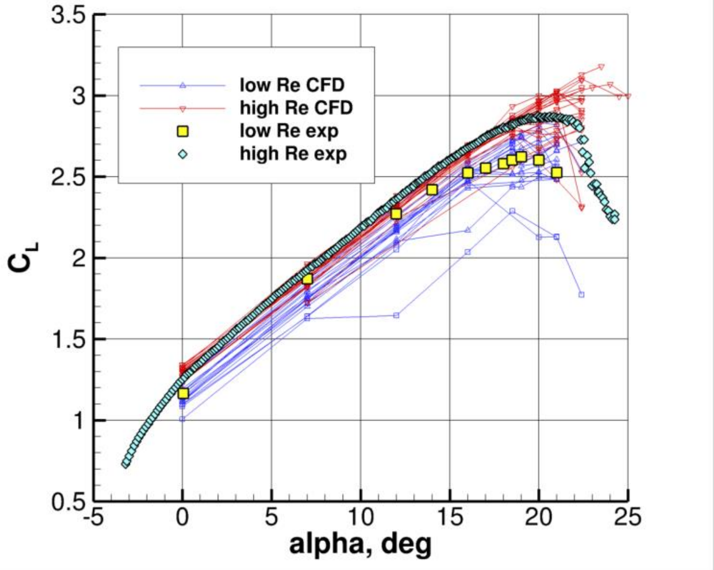
LESSONS LEARNED, HLPW-2

- DLR-F11 semispan model in Airbus B-LSWT and European Transonic wind tunnel (ETW)
- Included exploration of Reynolds number effect
- 26 participants; 48 sets of CFD data
- Grids somewhat finer than HLPW-1, but still typically had well less than 100 million unknowns
- A CFD verification study was included for the first time
- It was noted (from oil flow photos) that near stall the slat brackets were influential in causing wedge-shaped regions of separated flow near the rear portion of the main wing
  - This same key feature was noted for all workshops thereafter!
  - Recognized that bracket hardware MUST be included in CFD to have a chance of capturing the flow physics near CLmax (with no brackets, CFD tended to overpredict CLmax at Re_{MAC}=15.1 M)



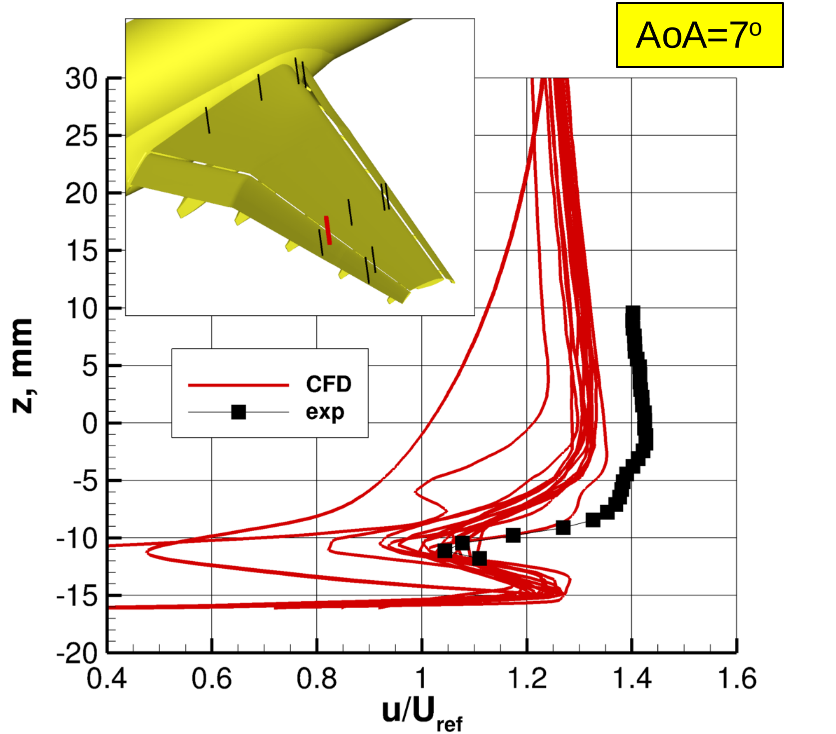
LESSONS LEARNED, HLPW-2, cont'd

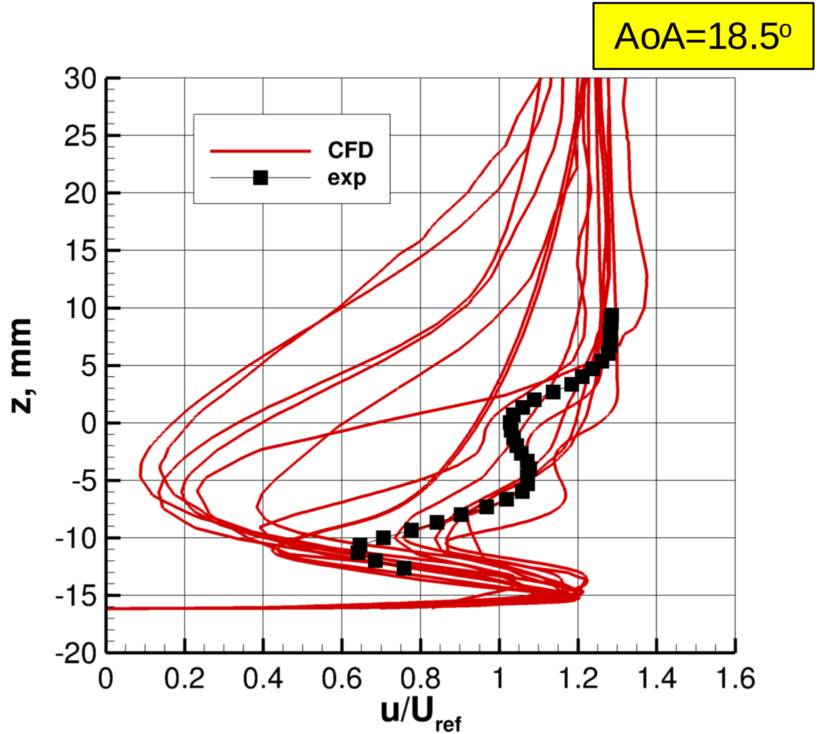
- CFD again yielded big spread in forces and moment near stall
- Reynolds number trend only qualitatively captured
  - Surprisingly large band of CFD results at low Re, even at low AoA
- CFD exhibited difficulty iteratively converging the cases
- CFD was compared with velocity profiles (from PIV)
  - Generally poor comparisons; very wide range of predictions (see next page)



LESSONS LEARNED, HLPW-2, cont'd

Example velocity profiles on flap of DLR-F11, Re_{MAC}=1.35 M

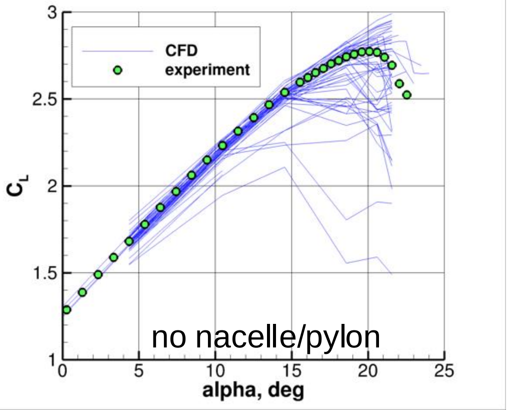


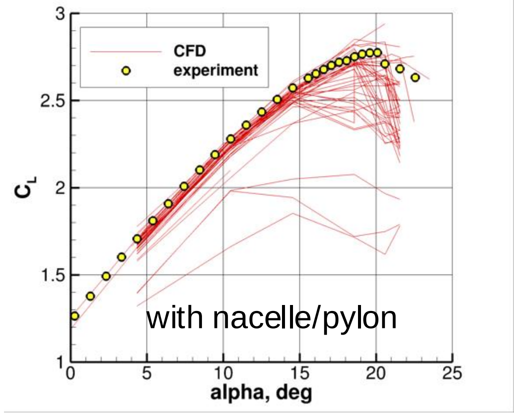


LESSONS LEARNED, HLPW-3

- JAXA semispan Standard Model (JSM) in JAXA-LWT1 wind tunnel (and preliminary study of CRM-HL)
- Included exploration of nacelle/pylon installation effects
- 35 participants; 79 sets of CFD data
- Grids ranged from 20-230 million unknowns
- In SA verification test, only 32% passed
- Some of the variation seen among CFD results at workshops may be due to codes that have not verified their turbulence model implementations
  - Other variation from insufficient iterative convergence and/or insufficient mesh convergence
- CFD again yielded big spread in forces and moment near stall
- When RANS happened to agree with C_L near CLmax, it was fortuitous; but a <u>scale-resolving</u> Lattice-Boltzmann method appeared to agree for the right reasons (see next page)

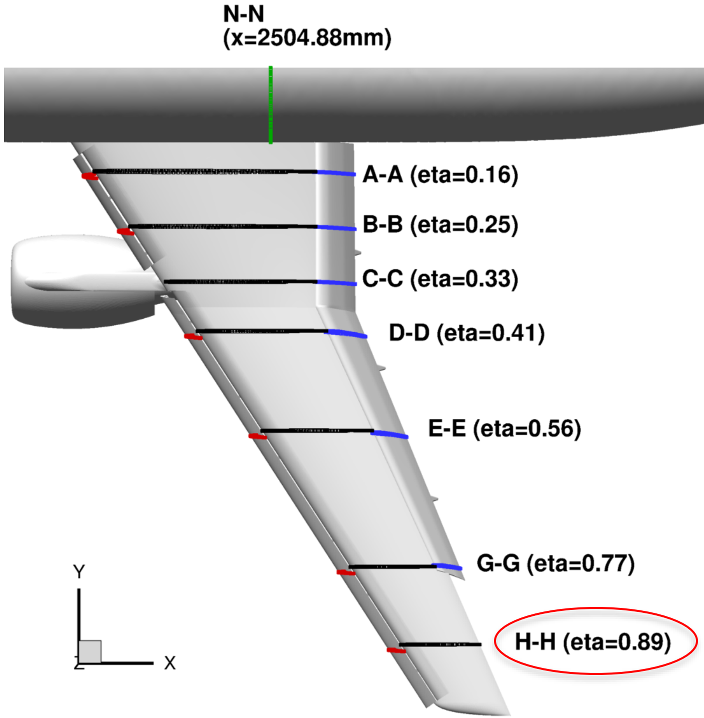
Re_{MAC}=1.93 million

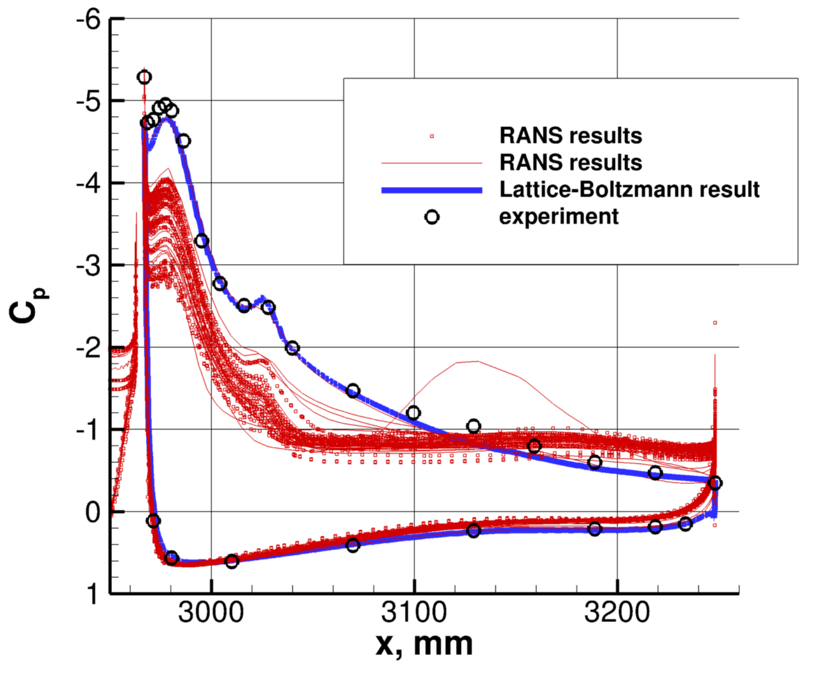




LESSONS LEARNED, HLPW-3, cont'd

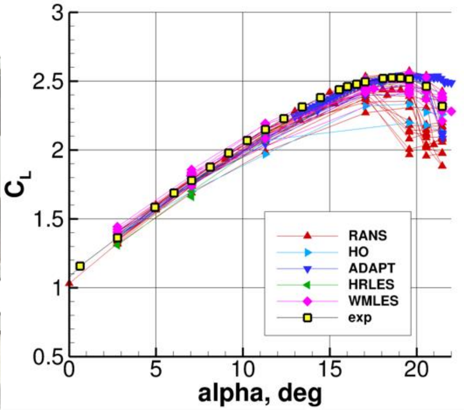
Example surface pressure coefficients on JSM, Re_{MAC}=1.93 M, AoA=18.58°

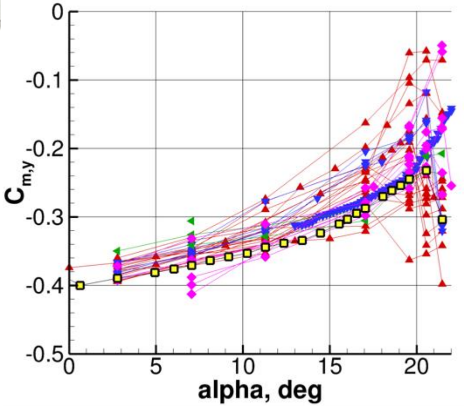




LESSONS LEARNED, HLPW-4

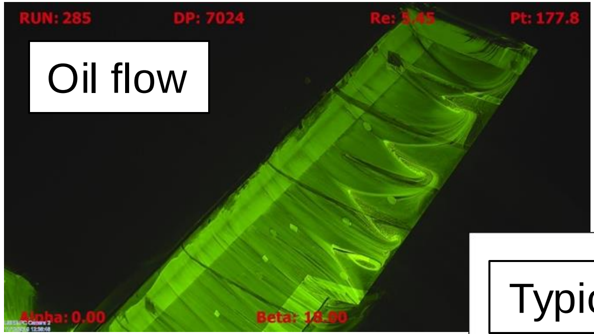
- CRM-HL (NASA 10% semispan test article) in QinetiQ wind tunnel
- Included exploration of flap increment effects at low AoA
- 44 participants; 184 sets of CFD data
- Over 170 meshes created/submitted for this workshop!... Grids ranged from 150-600 million unknowns
- In SA verification test, all but 2 participants passed (dramatic improvement from HLPW-3)
- Nonetheless, RANS results still showed big spread near stall
- Flap increment effects were generally NOT captured well
- TFG conclusions:
  - RANS: predicts incorrect flow physics when separation is present (near CLmax or when flap is separated at low AoA)
  - ADAPT: helps bring better consistency to RANS
  - HRLES and WMLES: not fully consistent, but are most promising near CLmax (see next page)

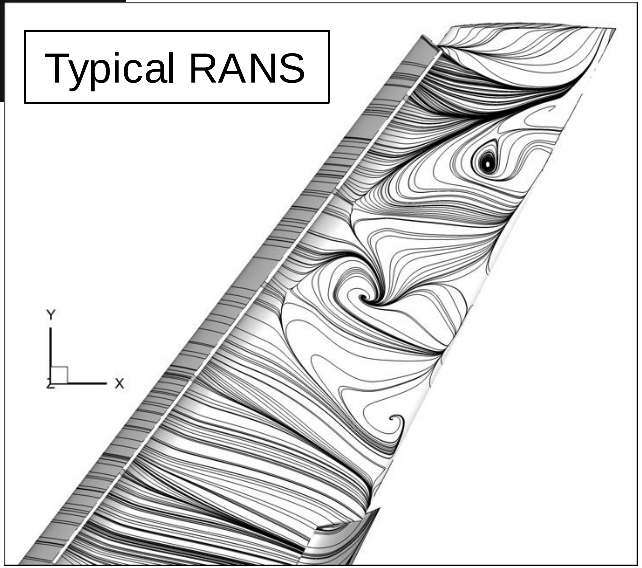


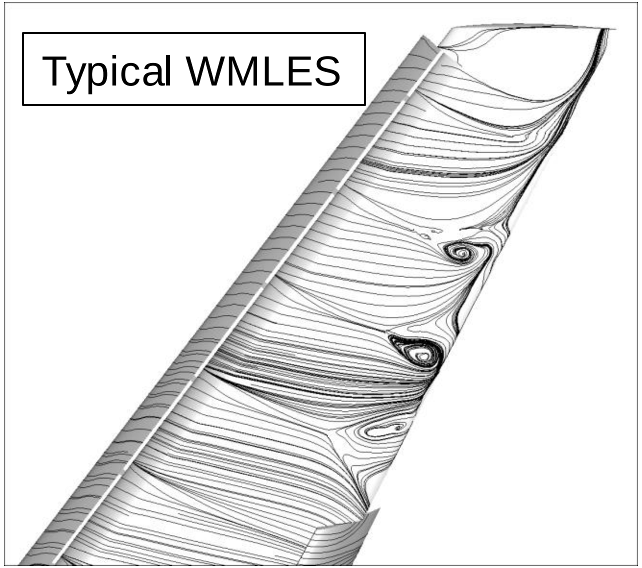


LESSONS LEARNED, HLPW-4, cont'd

Example streamlines on outboard wing of CRM-HL, Re_{MAC}=5.49 M, AoA=19.57°

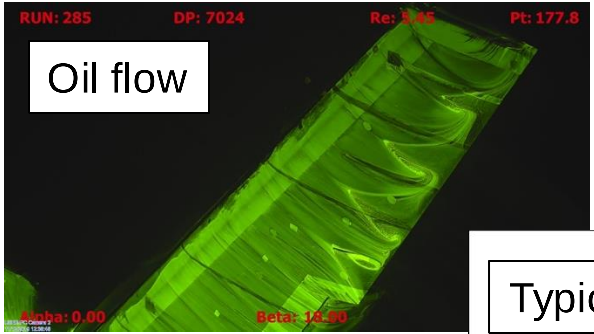




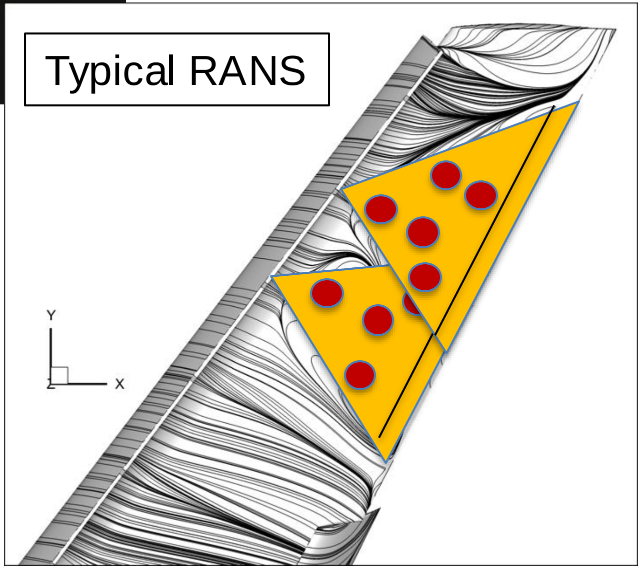


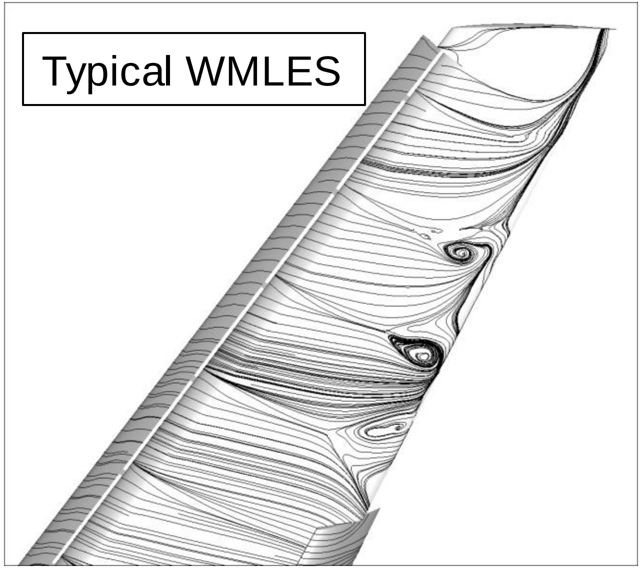
LESSONS LEARNED, HLPW-4, cont’d

Example streamlines on outboard wing of CRM-HL, Re_{MAC}=5.49 M, AoA=19.57^{o}



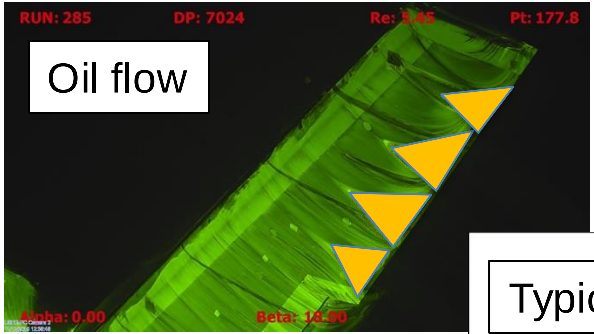
So-called RANS “pizza slices” cover nearly entire chord of outboard wing



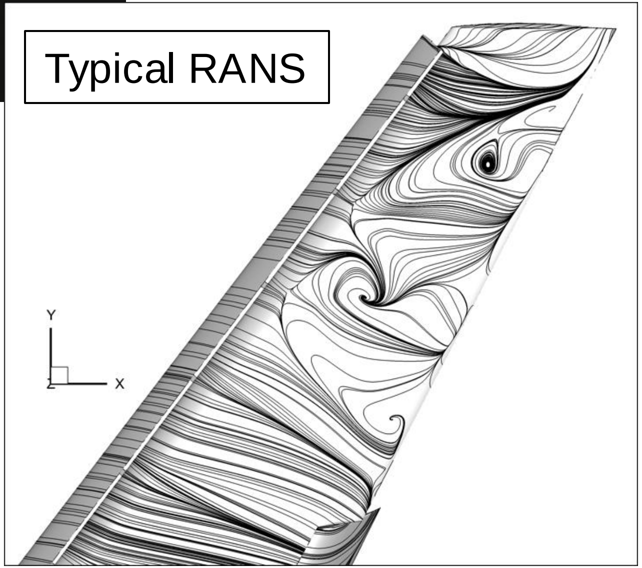


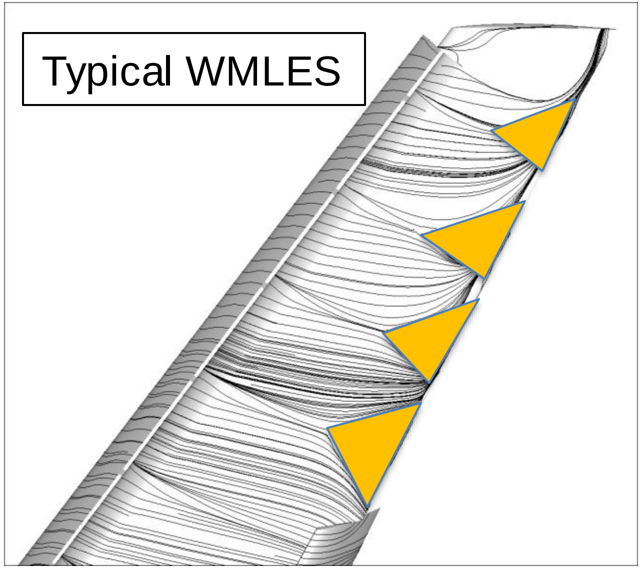
LESSONS LEARNED, HLPW-4, cont'd

Example streamlines on outboard wing of CRM-HL, Re_{MAC}=5.49 M, AoA=19.57°

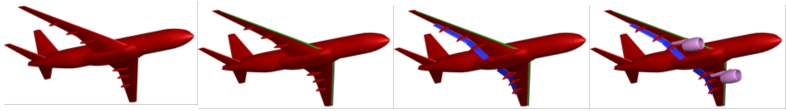


Reality is more like small triangular pastries

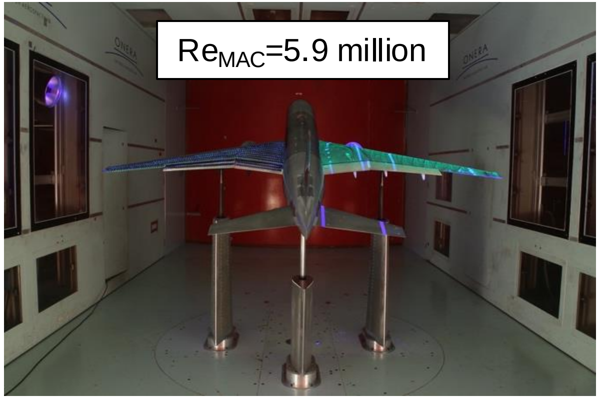


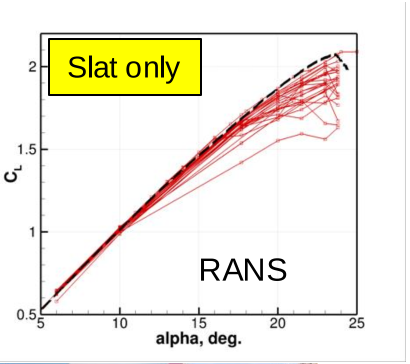


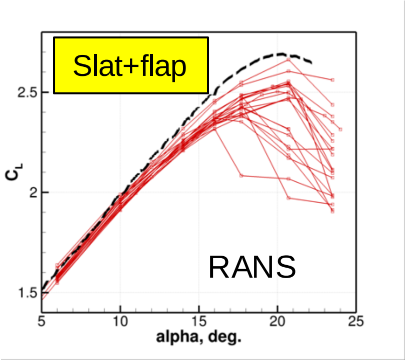
(Preliminary) LESSONS LEARNED, HLPW-5

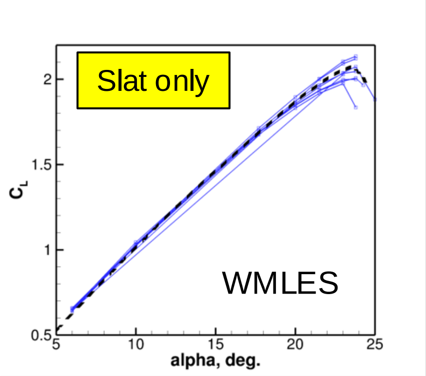


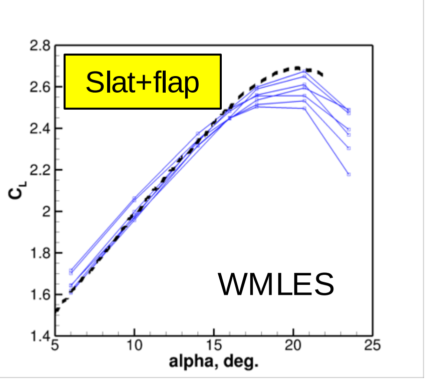
- CRM-HL (ONERA 5.1% fullspan test article) in ONERA F1 wind tunnel
- Included exploration of component buildup effects
- 103 participants; 99 (case 1) + 189 (case 2) + 77 (case 3) = 365 sets of CFD data
- Over 245 meshes created/submitted for this workshop!... Huge range of grid sizes, up to many billions of unknowns (for WMLES)
- Inclusion of flap notably hampers the ability of CFD to capture CLmax
- RANS still predicts big spread and incorrect physics (“pizza slices”) near CLmax, with the flow around slat brackets its biggest nemesis to achieving iterative convergence
- WMLES and HRLES show correct qualitative stall-onset mechanisms; but some issues remain (e.g., transition onset handling, separation state of the flap at low AoA)











OVERALL TRENDS and THE FUTURE

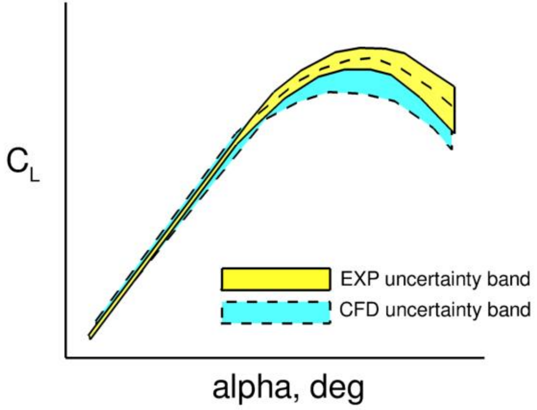
- Consistency between codes and CFD uncertainty
  - Because of the focus placed on verification/consistency in the AIAA workshops, this has been gradually improving
    - As more participants and codes are shown to agree for various verification cases, others are encouraged to figure out what they are doing differently in their codes (wanting to agree with the pack)
    - Strong consistency helps establish reference solutions and codes that can be trusted
    - Pushes causes of disagreements to discretization error and iterative convergence error
  - I believe the trend of increasing consistency between codes will continue

OVERALL TRENDS and THE FUTURE

- Experimental uncertainty (the "ecosystem")
  - As additional testing of the CRM-HL occurs with different models and different tunnels, we will gain a better understanding of the experimental uncertainties near CLmax
  - Improved understanding of the flow physics will also emerge, particularly due to concerted efforts to collect off-body data
  - I believe (someday soon) we will see plots like this:

(EXP would represent trusted results for a given configuration, corrected to free air)

(CFD would represent expected results for a given model or method using a trusted (verified) CFD code)



OVERALL TRENDS and THE FUTURE

- CFD assumptions vs. reality
  - To date, CFD has typically run “fully turbulent” in free air (comparing against wall-corrected wind tunnel data)
  - Although some of the following has already been done in the past, future workshops will likely include more concerted efforts to:
    - Run CFD with wind tunnel walls included (will need to coordinate CFD boundary conditions between codes, and also ensure consistency with wind tunnel BCs)
    - Explore effects of aeroelasticity
    - Include transition specifications and/or predictions

OVERALL TRENDS and THE FUTURE

- Scale-resolving simulation (SRS) methods
  - Technologies like WMLES and HRLES will continue to mature
  - They are already acknowledged to be a great improvement over RANS methods for predicting the flow physics associated with high-lift
  - As HPC capabilities grow, more and more engineers will make use of these methods on a regular basis
    - This will improve best practices (for high lift as well as other flows) and engender greater trust in the SRS methods
    - I believe that automated intelligent meshing for SRS will become a reality

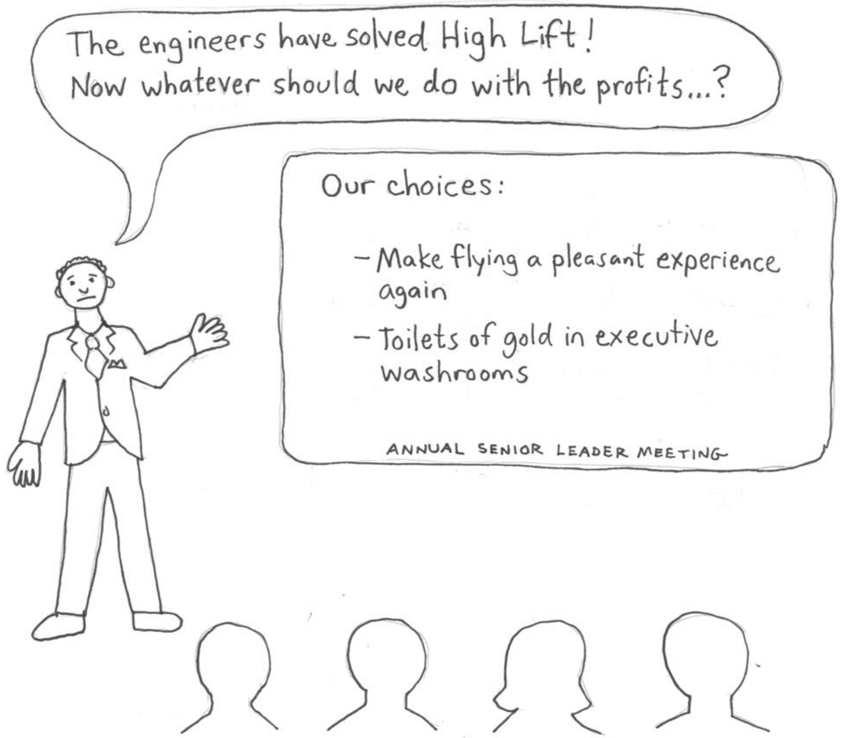
OVERALL TRENDS and THE FUTURE

- The future of RANS
  - Likely focus will be primarily at lower AoAs to provide new reference solutions for particular turbulence models of interest, or as a guide to improving SRS capability for attached flows
  - However, some feel that improved iterative convergence & meshing practices could make RANS more useful, even near CLmax
    - May(?) mitigate the "pizza slice" issue; easier to explore turbulence model improvements
  - Efforts to dramatically and generalizably improve RANS models using machine learning (ML) are currently not very encouraging, but ML is a very rapidly-advancing technology; a game-changing breakthrough could occur someday
    - We are considering adding a ML component to future HLPWs, to help encourage collaboration between ML computer scientists and CFD developers/aeronautical engineers

FINAL WORDS

- Although there is always more to do…
- The HLPWs have already been a fertile ground for:
  - Improved insights into high-lift flow physics
  - Greater understanding of the limitations and uses for traditional CFD methods
  - New technology advancements in high-lift predictive capability
- It has been a great pleasure and honor to have been a part of it!

FINAL CARTOONS



FINAL CARTOONS

END


34th Congress of the
International Council of
the Aeronautical Sciences
Florence
September 9-13
ICAS
CON
GRE
SS
2 0
2 4
ITALY