Zonal hybrid RANS-LES modeling using a Low-Reynolds-Number $k - \omega$ approach

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Outline

1. Introduction
2. Modeling and simulation method
3. Results
4. Conclusions

Introduction

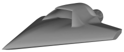
Introduction

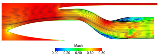
Project overview

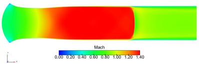
- Research within two NFFP projects
- MADEF: Methodology for Aerodynamic Design and Analysis of Efficient Aerial Vehicles
  - Turbulence resolving methods
  - Shape optimization
- MIAU: Methods for Improved Accuracy in Unsteady Aerodynamics
  - Turbulence resolving methods
  - High order methods
  - Aero acoustics

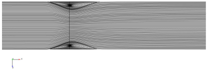
Project overview

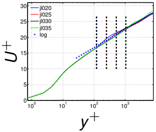
Complex flows











Fundamental flows

Inlet ducts
-Dominated by viscous flow
-Pressure induced/shallow separations
-Shock boundary-layer interaction

Flow over wings
-Buffeting
-Large-scale separations at high angle of attack
-Laminar to turbulent transition

Weapon bays
-Large scale turbulence which can affect the store separation
-Acoustic phenomena

Transonic duct flow
-Boundary-layer turbulence
-Shock/boundary-layer interaction
-Shallow separations
-Local corner separations

Research in hybrid RANS-LES modeling
-Detached Eddy Simulation
-Zonal RANS-LES
-Embedded LES

RANS results of transonic duct flow[1]

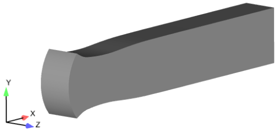


Figure 1: Transonic duct flow configuration.

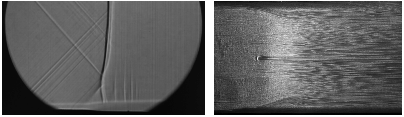
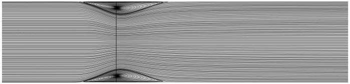
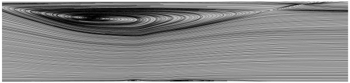


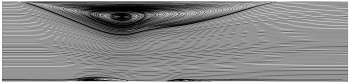
Figure 2: Experiment: shock wave with λ-foot (left) and oil flow visualization of corner separation bubble at the shock (right).



(a) Low-Reynolds-Number $k-\omega$ (PDH-LRN).



(b) Spalart-Allmaras.



(c) Menter $k-\omega$ SST.

Figure 3: RANS results: streamlines at bottom wall in the SBLI region.

[1] Arvidson, Davidson, Peng, Feasibility of Hybrid RANS-LES of Shock/Boundary-Layer Interaction in a Duct, Progress in Hybrid RANS-LES Modelling, NNFM, 2012, vol. 117, p. 245-256

Hybrid RANS-LES results of transonic duct flow[1]

- DDES based on Spalart-Allmaras fails to accurately predict the corner separation bubble and the shock
- SA-IDDES gives an improved SBLI prediction compared to SA-DDES but with an exaggerated corner separation bubble
- Improved RANS-LES modeling is needed to accurately capture the SBLI flow physics

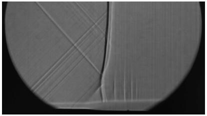
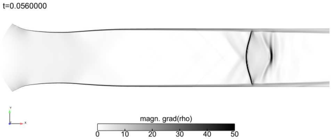
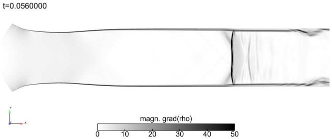


Figure 4: Experiment: shock wave with λ-foot.



(a) SA-DDES.



(b) SA-IDDES.

Figure 5: RANS-LES results: instantaneous shock patterns visualized by magnitude of density gradients.

[1] Arvidson, Peng, Davidson, Prediction of Transonic Duct Flow Using a Zonal Hybrid RANS-LES Modeling Approach, Progress in Hybrid RANS-LES Modelling, NNFM, 2015, vol. 130, p. 229-241

Way forward...

- Based on the results from the RANS and hybrid RANS-LES simulations, a hybrid RANS-LES model based on the PDH-LRN model has been developed
- We have chosen a zonal approach where the RANS and LES regions are prescribed
- The RANS-LES hybridization of the PDH-LRN model is made by modifying the dissipation term in the transport equation for the turbulent kinetic energy

Modeling and simulation methods

Base model: PDH-LRN $k-\omega$[1]

$$\frac{D\rho k}{Dt} = \tau_{ij}\frac{\partial u_i}{\partial x_j} - D^k + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \quad (1)$$

$$\frac{D\rho\omega}{Dt} = C_{\omega_1} f_\omega \frac{\omega}{k}\tau_{ij}\frac{\partial u_i}{\partial x_j} - C_{\omega 2}\rho\omega^2 \quad (2)$$

$$+ \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] + C_\omega \frac{\mu_t}{k}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j} \quad (3)$$

$$\mu_t = C_\mu f_\mu \frac{\rho k}{\omega} \quad (4)$$

[1] Peng, Davidson and Holmberg, A Modified Low-Reynolds-Number $k-\omega$ Model for Recirculating Flows, Journal of Fluids Engineering, vol. 119, 1997

Zonal RANS-LES formulation[1]

$$D^k = C_k f_k \rho k \omega = \rho f_k \frac{k^{3/2}}{l_t} \tag{5}$$

$$l_t = l_{RANS} = k^{1/2} / \left(C_k \omega \right) \tag{6}$$

$$l_t = l_{LES} = \Psi_{PDH} C_{LES} \Delta \tag{7}$$

$$\Psi_{PDH} = \min \left[10, f_k \left(\frac{f_\omega}{f_\mu} \right)^{3/4} \right] \tag{8}$$

- The RANS-LES interface is prescribed at a specific grid line

[1] Arvidson, Davidson and Peng, Hybrid RANS-LES Modeling Based on a Low-Reynolds-Number $k - \omega$ Model, AIAA Journal, 2016

LES length scales

$$\Delta_{dw} = \min\left(\max\left[C_{dw} d_w, C_{dw}\Delta_{max}, \Delta_{nstep}\right], \Delta_{max}\right) \tag{9}$$

$$\Delta_{max} = \max\left(\Delta_x, \Delta_y, \Delta_z\right) \tag{10}$$

$$\Delta_{vol} = \left(\Delta_x\Delta_y\Delta_z\right)^{1/3} \tag{11}$$

$$\begin{aligned} \Delta_\Omega &= \sqrt{N_x^2\Delta_y\Delta_z + N_y^2\Delta_x\Delta_z + N_z^2\Delta_x\Delta_y} \\ \boldsymbol{N} &= \frac{\boldsymbol{\Omega}}{\| \boldsymbol{\Omega} \|}, \quad \boldsymbol{\Omega} = \nabla \times \boldsymbol{u} \end{aligned} \tag{12}$$

Flow solvers

- Incompressible Navier-Stokes solver: CALC[1]
    - Developed by Chalmers
    - Structured, single block
    - 2nd order accurate in time and space
- Compressible Navier-Stokes solver: Edge[2]
    - Developed by FOI
    - Unstructured
    - 2nd order accurate in time and space

[1] Davidson and Peng, Hybrid LES-RANS modelling: a one-equation SGS model combined with a $k-\omega$ model for predicting recirculating flows, International Journal for Numerical Methods in Fluids, 2003, vol. 43, p. 1003-1018

[2] Eliasson, EDGE, a Navier-Stokes Slover for Unstructured Grids, 2001, Scientific report, FOI-R-0298-SE

Results

- Decaying homogeneous isotropic turbulence
- **Fully developed channel flow**
- Channel flow using embedded LES
- **Hump flow**
- **Transonic duct flow**
- Spatially developing boundary layer flow

Fully developed channel flow, $Re_\tau = 8000$

Table 1: Grid used in fully developed channel flow.

Re_τ	$(x/\delta, y/\delta, z/\delta)$	(n_x, n_y, n_z)	$(\Delta x^+, \Delta y^+, \Delta z^+)$
8000	$(3.2, 2, 1.6)$	$(64, 96, 64)$	$(400, 1.7 - 1050, 200)$

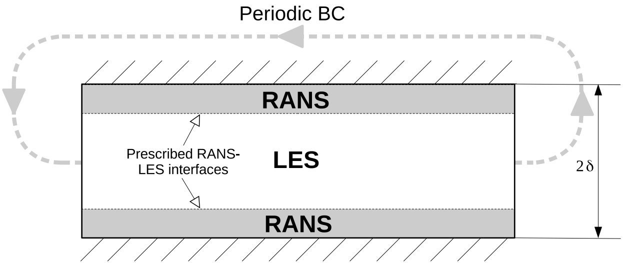
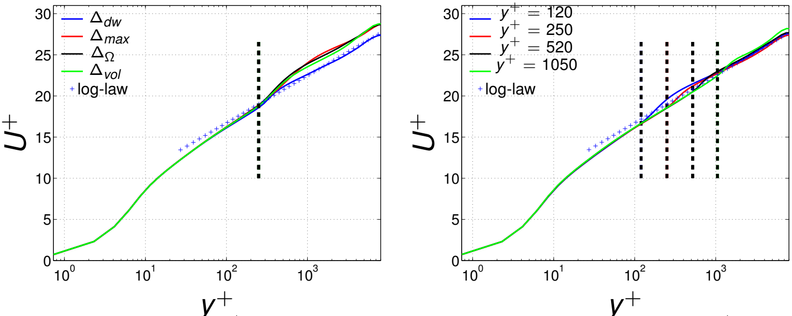


Figure 6: Computational domain with interfaces.

Fully developed channel flow, $Re_\tau = 8000$[1]



(a) Different Δ, $y^+_{switch} = 250$.

(b) $\Delta = \Delta_{dw}$ at different y^+_{switch}.

Figure 7: Fully developed channel flow, $Re_\tau = 8000$. Streamwise time-averaged velocity.

[1] Arvidson, Davidson and Peng, Hybrid RANS-LES Modeling Based on a Low-Reynolds-Number $k - \omega$ Model, AIAA Journal, 2016

Hump flow

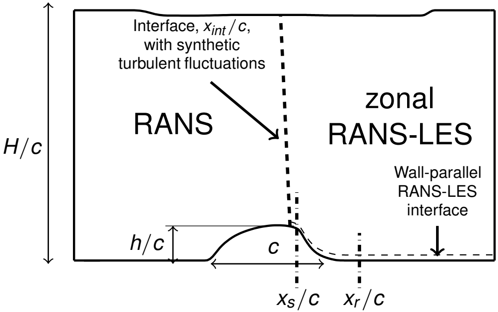
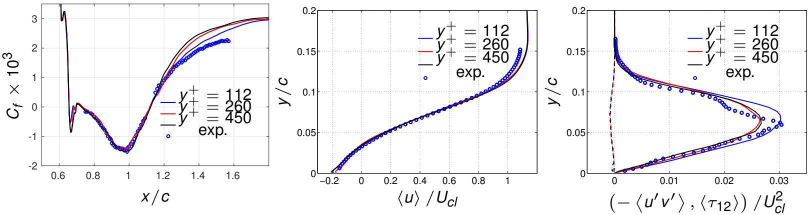


Figure 8: Hump configuration. Computational domain with interface ($x_{int}/c = 0.60$), flow separation ($x_s/c = 0.65$) and re-attachment ($x_r/c = 1.1$) lines. Not to scale.

Hump flow[1]



(a) Skin friction. (b) Streamwise velocity. (c) Shear stress.

Figure 9: Hump flow using embedded LES, $\Delta = \Delta_{dw}$. (b) and (c) at $x/c = 1.0$.

[1] Arvidson, Davidson and Peng, Hybrid RANS-LES Modeling Based on a Low-Reynolds-Number $k - \omega$ Model, AIAA Journal, 2016

Transonic duct flow[1]

- Zonal RANS-LES based on PDH-LRN gives an improved prediction of the SBLI flow physics compared to SA-DDES and SA-IDDES
- The corner separation bubble is slightly over-predicted as well as the cross flow downstream of the SBLI region
- Due to the exaggerated cross flow, the secondary shocks are slightly stronger in the simulation compared to the experiment

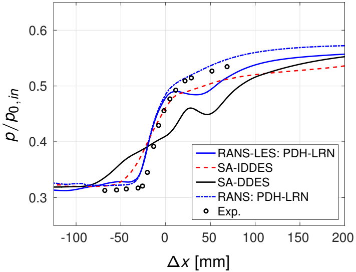
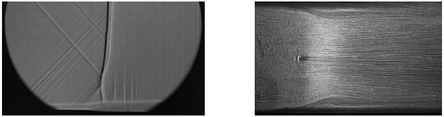


Figure 11: Wall pressure.



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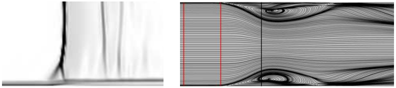

Figure 12: PDH-LRN based zonal RANS-LES. Left: instantaneous shock pattern; right: time-averaged stream lines at bottom wall.

[1] Arvidson, Peng, Davidson, Prediction of Transonic Duct Flow Using a Zonal Hybrid RANS-LES Modeling Approach, Progress in Hybrid RANS-LES Modelling, NNFM, 2015, vol. 130, p. 229-241

Conclusions

Conclusions

Conclusions (1/2)

- A $k - \omega$ based zonal RANS-LES modeling approach has been developed and evaluated for different turbulent flows
- An interface formulation for embedded LES, based on commutation terms on the LES side, has been successfully used in the hump flow, channel flow using embedded LES and spatially developing boundary layer
- The importance of a proper LES length scale with regards to log-layer mismatch has been highlighted in fully developed channel flow
  - The LES length scale based on the wall distance (Δ_{dw}) is superior in predicting attached boundary layer flows
  - In combination with the $k - \omega$ based RANS-LES model, the LES length Δ_{dw} significantly mitigates the log-layer mismatch
  - It is shown in channel flow that a weak dependency of the near-wall RANS-LES switch location is given with the used modeling approach

Conclusions (2/2)

- An improved prediction of the shock/boundary-layer interaction has been shown for the transonic duct flow
  - The model predicts well the characteristics of the λ-shaped shock, but with a slightly exaggerated corner separation bubble and too strong secondary shocks
  - The outer part of the corner separation bubble is resolved with LES and gives a well predicted bubble onset relative to the shock
- On-going and future work
  - Improve the RANS-LES interface formulation in order to further speed up the development of resolved turbulence in the LES region
  - Improve and generalize the hybrid RANS-LES modeling approach to be able to use the methodology for industrial applications

Thank you!