ASSESSMENT OF HYBRID URANS/LES TURBULENCE MODELING FOR ICE FLOW SIMULATION: A ZDES STUDY

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Outline

✓ Motivations

✓ Modeling

✓ Implementation/calibration

✓ Engine-like flow benchmarks

✓ Conclusions
Motivations

Why hybrid URANS/LES turbulence modeling?

- LES popularity constantly increasing through years, whereas…

Per-year number of published papers with relevant LES and hybrid ICE flow applications (source: www.scopus.com)
Motivations

Why hybrid URANS/LES turbulence modeling?

- LES popularity constantly increasing through years, whereas...
- ...hybrid URANS/LES methods are still relatively unexplored for ICE flow modeling

Per-year number of published papers with relevant LES and hybrid ICE flow applications (source: www.scopus.com)
Motivations

Why hybrid URANS/LES turbulence modeling?

Assuming that the scale-resolving capability is mostly preserved, hybrids can bring significant improvements:

- increased computational efficiency and robustness;
- easier management of inlet and wall BCs.

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**Motivations**

**Why hybrid URANS/LES turbulence modeling?**

- Assuming that the scale-resolving capability is mostly preserved, hybrids can bring significant **improvements**:
  - increased computational efficiency and robustness;
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- Several approaches has already shown a good potential (LNS, SAS, DES)

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**Goals of our work:**
- Development of a zonal DES-based turbulence simulation method for ICE flow predictions
- Validation of the proposed methodology on well-established flow benchmarks

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The Detached Eddy Simulation (DES) principle

- Steady, attached zones of the flow efficiently simulated by URANS
- LES triggering in massive separation, by length scales switching in the eddy viscosity destruction mechanism (from modeled to grid-dependent)
- All seamlessly managed by a single modeling framework (RANS-based)
- Very good accuracy in massively separated external flows
Starting point: improved RANS k-g model

Main features:

- Originally derived from the k-ω by Kalitzin et al. (1996); the ω-equation is reformulated in terms of the root-squared turbulent time scale $g = \sqrt{k/ε} = 1/\sqrt{β_ω}$.

- Straightforward wall bc ($g \to 0$) and linear near-wall scaling ($g \sim y^+$).

- Modified by the authors including realizability constraints for the turbulent time scale $τ$.

Equations:

$$\frac{∂(u_i g)}{∂x_i} = \frac{∂}{∂x_i} \left[ \left( v + \frac{v_i}{σ_g} \right) \frac{∂g}{∂x_i} \right] - \frac{α g^3}{2kτ} P_k + \frac{βg}{2β^*τ} \quad (1)$$

$$\frac{∂(u_i k)}{∂x_i} = \frac{∂}{∂x_i} \left[ \left( v + \frac{v_i}{σ_k} \right) \frac{∂k}{∂x_i} \right] + P_k - \frac{k}{τ} \quad (2)$$

$$ν_i = β^*kτ \quad (3)$$

$$τ = \min \left( g^2, \frac{a}{β^* \sqrt{6|S|^2}} \right) \quad ; \quad a \leq 1 \quad (4)$$
**DES reformulation**

**Basis:**

Strelets (2001) showed that a two-equation model can be reduced to a DES model by implementing a “grid sensitive” length scale in the destruction term of the k-equation

\[
\begin{align*}
    \frac{\partial k}{\partial t} + \frac{\partial (u_i k)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \left( v + \frac{v_l}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + P_k - D
\end{align*}
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**Destruction term modification (1)**

\[
\frac{\partial k}{\partial t} + \frac{\partial \left( u_i k \right)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \nu + \nu_l \right) \frac{\partial k}{\partial x_i} \right] + P_k - D
\]

\[
D_{RANS} = \frac{k^{3/2}}{l_{RANS}}; \quad l_{RANS} = k^{1/2} \cdot \tau
\]

\[
D_{DES} = \frac{k^{3/2}}{l_{DES}}; \quad l_{DES} = \min \left( l_{RANS}, C_{DES} \cdot \Delta \right)
\]

\[
\Delta = f \left( grid \right)
\]

\[
C_{DES} = O \left( 1 \right)
\]
**DES reformulation**

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**Destruction term modification (2)**

\[
\begin{align*}
\frac{\partial k}{\partial t} + \frac{\partial (u_i k)}{\partial x_i} &= \frac{\partial}{\partial x_i} \left[ \left( v + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + P_k - D \\
D_{RANS} &= \frac{k^{3/2}}{l_{RANS}}; \quad l_{RANS} = k^{1/2} \cdot \tau \\
D_{DES} &= \frac{k^{3/2}}{l_{DES}}; \quad l_{DES} = \min\left( l_{RANS}, C_{DES} \cdot \Delta \right) \\
D_{DES} &= F_{DES} \cdot D_{RANS} \\
F_{DES} &= \max\left( \frac{l_{RANS}}{(C_{DES} \cdot \Delta)}, 1 \right)
\end{align*}
\]
Application of the DDES concept

The concept:

- Avoid Modeled Stress Depletion (MSD) in grids with ambiguous near-wall spacing ($C_{DES}\cdot\Delta < BL$ thickness)

- Spalart et. al (2006) proposed the use of a "delaying function" to force the extension of the pure RANS region towards BL's outer edge

- Adaptation of the delaying function to the present formulation

DDES form of the destruction term:

$$D_{DDES} = F_{DDES} \cdot D_{RANS}$$

$$F_{DDES} = \max \left\{ \phi_d \left[ \frac{l_{RANS}}{(C_{DES}\cdot\Delta)} \right], 1 \right\}$$

$$\phi_d = 1 - \tanh \left[ \left( k_d \cdot r_d \right)^3 \right]$$

- $k_d =$ constant
- $r_d =$ function of flow quantities and wall distance

$$\phi_d \to 0 \quad ; \quad F_{DDES} \to 1 \quad \text{Forced RANS mode}$$
Why Zonal-DES?

**Seamless (D)DES:**

- URANS-to-LES managed entirely by the model (user decisional load kept to a minimum), but...
- ...the triggering mechanism is not always efficient in complex internal flows (too early/too late transition*)

**Zonal (D)DES:**

- URANS and LES (or DES) regions explicitly marked by the user
- Better control of the solution behavior (at the expense of nontrivial a-priori decisions)
- Potentially good candidate for complete ICE simulation (e.g., ducts in RANS mode, in-cylinder in LES mode)

*V. K. Krastev et al., SAE 2015-24-2414

**Zonal form of the destruction term:**

\[
D_{DDES}^* = F_{DDES}^* \cdot D_{RANS} \\
F_{DDES}^* = C_{z1} \cdot F_{DDES} + (1 - C_{z1}) F_{ZDES} \\
F_{ZDES} = C_{z2} + (1 - C_{z2}) \cdot \left( \frac{I_{RANS}}{C_{DES} \cdot \Delta} \right)
\]
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Overview

Why OpenFOAM®?

- **Open source** unstructured finite volume computational framework
- Quite extensively validated for LES
- **Hexa-dominant** automatic mesher (SHM) with local volumetric refinement
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\[\text{Potentially attractive for zonal methods}\]
Overview

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Methodology calibration:

1. Numerical schemes choice
   - Focus on convective transport in LES mode
2. **C_{DES}** constant calibration
   - Checking model’s consistency in LES mode ($l_{DES} \equiv C_{DES} \cdot \Delta$)
   - Focus on the $C_{DES}$ constant calibration

Potentially attractive for zonal methods
Turbulence box: momentum convection schemes

- Standart test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction; spatial discretization obtained with $N^3$ perfectly cubic cells ($N=64$)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
- To evaluate convection schemes, Euler equations are solved (zero-viscosity, no SGS modeling)
- Three alternatives considered:
  1. Central Differencing (CD)
  2. Linear Upwind Stabilized Transport (LUST)
  3. Filtered Central Differencing (FCD)
Turbulence box: momentum convection schemes

- Volume-averaged kinetic energy of the flow monitored through time

- LUST is highly dissipative compared to CD

- FCD is in between, the amount of dissipation depending on the filtering parameter $0<\varphi<1$

FCD with $\varphi = 0.25$ chosen as a compromise between energy conservation and stability
Turbulence box: $C_{DES}$ calibration

- Standart test for DNS and SGS models
- Cubic domain with cyclic BCs in each direction; spatial discretization obtained with $N^3$ perfectly cubic cells ($N=64$)
- Flow field initialized with an incompressible divergence-free turbulent spectrum
- Turbulence is left to spontaneously decay driven by the $k$-$\omega$ pure LES model ($l_{DES} \equiv C_{DES} \cdot \Delta$)
- $C_{DES}$ is decreased, starting from $C_{DES} = 0.78$ ($k$-$\omega$ SST DES standard value)
- Energy spectra evaluated at different simulation times
Turbulence box: $C_{\text{DES}}$ calibration

- 3D spectra compared to Comte-Bellot and Corrsin's experimental data
- FCD 0.25 set for momentum convection, bounded NVD scheme for $k$ and $g$
- The initial energy decay is well described by the $k$-g LES model, regardless of $C_{\text{DES}}$
- For longer decaying times $C_{\text{DES}} = 0.5$ is the best-matching option

$C_{\text{DES}} = 0.5$ chosen as baseline value
**Axisymmetric sudden expansion**

**Preliminary remarks (1):**

- Sudden circular flow expansion with/without imposed swirling motion at the inlet (Dellenback et al., 1988)
- Swirling case taken as reference ($S_i = 0.6$), inlet bulk Reynolds number $Re_b \approx 3 \cdot 10^4$
Axisymmetric sudden expansion

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- Swirling case taken as reference ($S_i = 0.6$), inlet bulk Reynolds number $Re_b \approx 3 \cdot 10^4$

- Unstructured hexa-dominant grids, with extrusion layers at the walls:
  - Coarse grid, $R0 = D_u$, $R5 = D_u/2^5$, $4 \cdot 10^5$ cells;
  - Fine grid, $R0 = D_u$, $R6 = D_u/2^6$, $2.36 \cdot 10^6$ cells.
**Axisymmetric sudden expansion**

**Preliminary remarks (2):**

- Two different settings tested:
  1. Pure RANS, $C_{z1} = 0$, $C_{z2} = 1$, Linear Upwind (LU) scheme
**Axisymmetric sudden expansion**

**Preliminary remarks (2):**

- Two different settings tested:
  
  I. Pure RANS, $C_{z1} = 0$, $C_{z2} = 1$, Linear Upwind (LU) scheme

  II. ZDES + numerical schemes splitting, $C_{z1} = 0$, $C_{z2} = 1 + \text{LU}$, $C_{z2} = 0 + \text{FCD 0.25}$
**Axisymmetric sudden expansion**

**Preliminary remarks (3):**

- **ZDES computational procedure:**
  1. RANS solution to initialize the flow (experimental data mapped on inlet);
  2. ZDES run for 2 domain flow throughs with statistics turned off;
  3. ZDES run for 10 flow throughs with statistics on (mean values and fluctuations)
  4. Post-separation turbulence statistics extracted from the resolved flow field time history

- **Boundary conditions:** standard incompressible inflow/outflow, wall functions for k and momentum (y+ < 20)
**Axisymmetric sudden expansion**

**Axial velocities**

- **Results, $S_l = 0.6$:**
  - ZDES slightly improves post-separation mean axial velocity profiles, but the enhancements are not as expected (even for the fine grid case)
  - Much more significant “boost” in the predicted axial turbulence levels, but only in the outer region ($r > 0.5R_d$)
**Axisymmetric sudden expansion**

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**Axial velocity fluctuations**

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- Much more significant “boost” in the predicted axial turbulence levels, but only in the outer region ($r > 0.5R_d$).
Axisymmetric sudden expansion

Tangential velocities

Tangential velocity fluctuations

Results, $S_l = 0.6$:

- Still small improvements (outer region at $x/D_u = 0.5$, more distributed elsewhere)
- Similar trends for tangential turbulence
Axisymmetric sudden expansion
Axisymmetric sudden expansion

Axial velocities

Tangential velocities

Comments, $S_L = 0.6$:

- Role of the URANS mode is to provide accurate mean-flow conditions at the URANS/LES interface
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- The improved k-g RANS has shown close to the k-ω SST results in several tests, but still it is an isotropic eddy viscosity model (well known limitations in swirling flows)
Fixed valve intake port

Preliminary remarks (1):

- Intake port geometry with an axis-centered fixed poppet valve, $Re_b \approx 3 \cdot 10^4$

- LDA measurements of mean flow and RMS fluctuations available at $x = 20$ mm and $x = 70$ mm; DLRM results from Piscaglia et al. (2015) also taken as reference (coarse: $7 \cdot 10^5$ cells; fine: $5 \cdot 10^6$ cells)

- Two levels of maximum grid refinement ($R_0 = D_i/4$): coarse ($R_3, 9.8 \cdot 10^5$ cells) and fine ($R_4, 5.97 \cdot 10^6$ cells)
Benchmarks

Fixed valve intake port

Preliminary remarks (2):

- Two different settings tested:
  1. Pure RANS, $C_{z1} = 0$, $C_{z2} = 1$, Linear Upwind (LU) scheme
Preliminary remarks (2):

- Two different settings tested:
  
  I. Pure RANS, $C_z1 = 0$, $C_z2 = 1$, Linear Upwind (LU) scheme
  
  II. ZDES + numerical schemes splitting, $C_z1 = 0$, $C_z2 = 1 + LU$, $C_z2 = 0 + FCD 0.25$
Fixed valve intake port

Preliminary remarks (3):

- **ZDES computational procedure:**
  1. RANS solution to initialize the flow (experimental data mapped on inlet);
  2. ZDES run for **2 domain flow through** with statistics turned off;
  3. ZDES run for ~**5 flow throughs** with statistics on (mean values and fluctuations)
  4. All turbulence statistics extracted from the resolved flow field time history

- **Boundary conditions:** standard incompressible inflow/outflow, wall functions for $k$ and momentum ($y^+ < 30$)
Fixed valve intake port

Profiles, \( x = 20 \text{ mm (coarse grid)} \):

- RANS is competitive for the mean velocity profiles prediction, DLRM slightly outperforms ZDES in the peak region.
- The two scale-resolving methods are much superior for turbulence prediction (well captured peaks, differences in the outer region).
Fixed valve intake port

Profiles, \( x = 20 \text{ mm} \) (fine grid):

- ZDES seems to be more sensitive to grid refinement (significant improvements)
- Similar trend for resolved turbulence
Fixed valve intake port

Axial velocities

Contours, coarse grid:

- 2D contours confirm differences between the ZDES-C and the DLRM-C cases
- ZDES seems to have a slightly more diffusive jet structure

Axial velocity fluctuations
Fixed valve intake port

Axial velocities

Contours, fine grid:

- Fine grid cases become much more similar
- DLRM has a less grid-dependent behavior
Fixed valve intake port: evaluating quality of the solution

**TKE ratio**

- Defined as the ratio between resolved and total (modeled + resolved) mean tke:

\[
\rho_{tke} = \frac{\text{tke}_{res}}{\text{tke}_{mod} + \text{tke}_{res}}
\]

- *A-posteriori* resolution parameter (requires converged turbulence statistics).

- Current LES ICE applications are usually able to guarantee \( \rho_{tke} > 0.8 \) in most of the flow domain.

- In general, \( \rho_{tke} \) is not sufficient to characterize the flow resolution level (e.g., L. Davidson, 2009)

**DLRM filtering of the RANS field (1)**

- DLRM belongs to the Limited Numerical Scales (LNS) modeling approaches.

- Based on the dynamic evaluation of a filter function \( G \):

\[
l_{\text{RANS}} = \frac{k^{3/2}}{\varepsilon} = k^{3/2} \cdot \tau
\]

\[
\Delta_f = \alpha \cdot \max \left( \beta \cdot |U| dt, \Delta \right)
\]

\[
l_{\text{DLRM}} = \min \left( l_{\text{RANS}}, \Delta_f \right)
\]

\[
G^2 = \left( \frac{l_{\text{DLRM}}}{l_{\text{RANS}}} \right)^{4/3}
\]
**Fixed valve intake port: evaluating quality of the solution**

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**DLRM filtering of the RANS field (2)**

- In the original dynamic approach, $G$ is used for the run-time filtering of the turbulent quantities of a given RANS turbulence model.

- The filter form is general and can be applied to any two-equation turbulence model.

- When $\Delta f \geq \Delta f_{\text{RANS}}$, the standard RANS behavior is automatically recovered ($G^2 = 1$):
Fixed valve intake port: evaluating quality of the solution

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**DLRM filtering of the RANS field (3)**

- Here, we calculate \( G^2 \) from a converged URANS solution (same CFL and grids as for the ZDES runs)

- Purpose: using \( G^2 \) as an *a-priori* resolution estimator
Fixed valve intake port: evaluating quality of the solution

**TKE ratio (ZDES)**

**$G^2$ (URANS, $\alpha = 3, \beta = 5$)**
Fixed valve intake port: evaluating quality of the solution

**TKE ratio (ZDES)**

**$G^2$ (URANS, $\alpha = 3$, $\beta = 5$)**
Final comments

The results here shown represent a promising basis for future ICE applications and can be summarized as follows:

1. the proposed k-g ZDES model has demonstrated significant turbulence resolving features, even when the overall computational requirements are kept comparable to what typically needed by RANS;

2. the importance of providing accurate mean-flow conditions at the URANS/LES interface has been evidenced;

3. a filtering function $G$, originally developed for dynamic scale-adaptive turbulence modeling, has been evaluated for the a-priori estimate of the grid+time step actual resolution capability; the $G$ distribution, calculated from a converged URANS field, has shown a good correspondence with a typical a-posteriori resolution parameter such as the $\text{tke}$ ratio.

The next development steps will be focused on:

1. eventual swirl correction for the modified k-g RANS;

2. extension to compressible flows and flows with moving boundaries/topological changes;

3. interaction with physical sub-models (combustion);
Acknowledgments

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✓ OpenCFD Ltd.  ✓ OpenFOAM® trademark ownership
Conclusions

References


Thank you!