A NOVEL DES-BASED APPROACH TO IMPROVE TRANSITION FROM RANS TO LES IN FREE SHEAR LAYERS

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Abstract

The contribution presents a novel hybrid RANS-LES approach based on the modification of LES-mode functionality of DES. In particular, the new approach targets significantly improved accuracy over standard DES in situations where an attached boundary layer modelled using RANS merges into a separated shear layer to be resolved by LES. The new approach applies an alternative sub-grid scale model formulation in the LES region of DES that discerns between quasi two-dimensional situations and fully developed three-dimensional flow. In addition, an alternative definition of the grid scale parameter is tested, which accounts for the orientation of the local vorticity vector. The mathematical background of the new approach is outlined and results from suitable test cases to assess core model functionality are shown, including calibration of model constants. As a fundamental test case, the new model is assessed for a spatially developing shear layer. The experience gained from this study is then used to compute a more complex turbulent compressible jet at \( M \approx 0.9 \). The presented approach aims to retain both the non-zonal nature of DES as well as its local formulation that can be readily implemented in general-purpose CFD solvers.

1 Introduction

In the past decade, hybrid RANS-LES models have been seen to offer enhanced physical accuracy over statistical RANS-based models for a wide range of flows, especially for cases featuring strong flow separation. Within the family of hybrid RANS-LES methods, detached-eddy simulation (DES) has become one of the most widespread turbulence resolving approaches since its introduction by Spalart et al (1997). Further development of the method has included a remedy for undesired dependency on grid resolution (DDES proposed by Spalart et al (2006)) and extension of its applicability to include wall-modelled LES functionality (IDDES published by Shur et al (2008)). Despite this significant progress, a core deficiency of non-zonal hybrid RANS-LES models persists. This is often referred to as the “grey area” problem.

The term refers to a region of undefined modelling existing between RANS and LES mode operation, which commonly gives rise to problems in free shear layers separating from attached RANS boundary layers. The non-zonal concept of DES relies on natural instabilities to trigger transition from RANS to resolved turbulence in LES mode in the early shear layer (this was termed “RANS to LES transition” (RLT) region in Mockett et al (2014)). For standard DES variants, the development of resolved scales is often hampered by high levels of turbulent eddy viscosity here, both due to convection from the upstream RANS boundary layer and from strong production in the early shear layer, even though the local grid spacings might allow a more detailed resolution of scales. The strategy we present in this contribution is based on the idea to significantly reduce eddy viscosity in the initial shear layer, which allows for more rapid development of resolved turbulence. We hereby seek to present an extension of the existing DES method that is general, neither compromising model behaviour in other regards nor containing any case-specific fixes. The new formulation furthermore avoids impractical features such as spatial filtering, time averaging or the explicit introduction of artificial fluctuations used in other approaches.

As separating shear layers are a prominent feature of many practical flows, developing means to reduce the “grey area” is clearly a desirable goal to enhance model performance and increase the acceptance of hybrid RANS-LES methods both in academia and industry.

2 Modelling approach

An analysis of standard DES applied in pure LES mode based on the assumption of local equilibrium (of production and dissipation terms) shows that DES is structurally equivalent to the Smagorinsky model:

\[
\nu_{\text{sgs}} = (C_{\text{sgs}} \Delta)^2 D_{\text{sgs}}(u),
\]

where \( C_{\text{sgs}} \) is a calibrated parameter with the same role as the Smagorinsky constant, \( \Delta \) is a measure of the filter width (usually a geometric measure of the lo-
turbulence (DIT), where resulting spectra for the new WALE and σ-DES models are depicted in Figure 1. This also verifies that correct SGS model behaviour is given by the new models in fully developed 3D turbulence. For both new WALE/σ models, the definition of the model parameter \( C_{\text{DES}} \) as well as the model-specific correction function \( \Psi \) remain unaltered compared to standard DES. This means that the interface location between RANS and LES mode also remains unchanged.

Table 1: Formulations of different LES and DES models in LES mode with regard to the generic Eq. 1. For definitions of \( S_W \) and \( S_\sigma \) see references Nicoud et al (1999) and Nicoud et al (2011). Coefficient \( A \) depends on the underlying RANS model and may or may not be constant.

<table>
<thead>
<tr>
<th>Model</th>
<th>( C_{\text{sgs}} )</th>
<th>( D_{\text{sgs}}(u) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smagorinsky</td>
<td>( C_S )</td>
<td>( S^2 ) = 2( S_{ij} S_{ij} )</td>
</tr>
<tr>
<td>WALE</td>
<td>( C_W )</td>
<td>( S_W^2 )</td>
</tr>
<tr>
<td>σ</td>
<td>( C_\sigma )</td>
<td>( S_\sigma^2 )</td>
</tr>
<tr>
<td>DES</td>
<td>( \sqrt{A} C_{\text{DES}} )</td>
<td>( S_{\text{RANS}}^2 )</td>
</tr>
<tr>
<td>WALE-DES</td>
<td>( \sqrt{A} C_{\text{DES}} )</td>
<td>( B_W S_W^2 )</td>
</tr>
<tr>
<td>σ-DES</td>
<td>( \sqrt{A} C_{\text{DES}} )</td>
<td>( B_\sigma S_\sigma^2 )</td>
</tr>
</tbody>
</table>

Figure 1: Comparison of energy spectra for DIT case on 64\(^3\) grid from all models with calibrated model constants. Also shown are spectra obtained using \( \Delta_{\text{w}} \) with and without a coefficient of \( \alpha = 1.025 \).

Modification of grid scale parameter

A new formulation of the grid scale parameter \( \Delta \) has been proposed in Mockett et al (2014), which is also evaluated in this work. As for the proposed new DES-based model, this modification also aims to tackle the “grey area” issue in RLT regions. For DES, the maximum cell diameter is normally used as a measure for the LES filter width, i.e. \( \Delta_{\text{max}} = \max(\Delta_x, \Delta_y, \Delta_z) \). The new formulation is inspired by the idea of Chauvet et al (2007) to take into account the direction of the local vorticity vector to sensitise \( \Delta \) to the flow field. This concept was later generalised by Deck (2012) for unstructured grids. Given a cell with
its cell centre vector being \( \vec{r} \) and its vertices located at \( \vec{r}_n \) (\( n = 1...n_{\text{max}} \), where \( n_{\text{max}} \) is the number of cell vertices), the modified formulation reads:

\[
\tilde{\Delta}_\omega = \alpha \cdot \frac{1}{\sqrt{\sum_{n,m=1...8} \max\{|I_n - I_m|\}}},
\]

where \( I_n = \vec{n} \times (\vec{r}_n - \vec{r}) \), \( \vec{n} \) is the normalised vorticity vector and \( \alpha = 1 \) is a constant. The improvement of \( \tilde{\Delta}_\omega \) relative to \( \Delta_{\text{max}} \) can be seen for e.g. free shear layers meshed effectively using anisotropic grids. In such cases when the vorticity axis is aligned with \( z \), \( \tilde{\Delta}_\omega \) reduces to \( \mathcal{O}(\max\{\Delta_x, \Delta_y\}) \). This is the key difference to the formulation of Chauvet et al (2007), which would reduce to \( \sqrt{\Delta_x \Delta_y} \). The \( \tilde{\Delta}_\omega \) formulation hence returns a considerably lower value of \( \Delta \), as the dependency on the coarse \( z \) spacing is lifted compared to \( \Delta_{\text{max}} \). As the grid scale \( \Delta \) is directly linked to the local eddy viscosity, the intention of \( \tilde{\Delta}_\omega \) with regard to the RLT region is equivalent to the proposed model formulation, i.e. to strongly reduce \( \nu_{\text{SGS}} \) in this region.

The new \( \tilde{\Delta}_\omega \) was tested using the DIT case in conjunction with the Smagorinsky SGS model, where it adopted a spatially-averaged value of \( \approx 97.5\% \) relative to \( \Delta_{\text{max}} \). To balance that, the constant \( \alpha \) of Equation 2 was re-adjusted to \( \alpha = 1.025 \), although the effect of this is minor. Unlike the proposed DES-based model approach, the modified grid scale \( \tilde{\Delta}_\omega \) is active only on anisotropic grids, so its impact on RLT acceleration is smaller for more isotropic grid shapes.

3 Numerical methodology

A customised version of the open source CFD environment OpenFOAM® was used in this work, which is a cell-centred, unstructured, finite-volume based code of second order accuracy in space and time. All applied solvers utilise a pressure correction algorithm (SIMPLE) to couple velocity and pressure. Relevant customised features include standardised implementations of DDES and the underlying SA model as well as the hybrid convection scheme of Travin et al (2000). The latter applies a localised blending between low-dissipation second order central differences in well-resolved turbulent regions and a robust second order accurate upwind scheme in coarse grid regions or regions of irrotational flow.

4 Spatially developing shear layer

As a fundamental test case to study the performance of the novel approach, an incompressible spatially-developing shear layer is considered, where two turbulent boundary layers of different speeds emanate from the trailing edge of a splitter plate. The test case has been studied in the past by e.g. Deck (2012) to demonstrate the effectiveness of the original \( \Delta_\omega \) formulation and by Kok & van der Ven (2009) to assess their high-pass filtering approach for RLT acceleration.

A coarse grid of some 1.3M cells was employed in this study, that has also been used in the work of Kok & van der Ven. The computational domain extends 2m downstream from the trailing edge of the plate and exhibits a height (measured between centreline and boundary) and spanwise extent of both 0.15m. In the region of interest that extends 1.0m downstream of the trailing edge, the grid resolution is 3.125mm in both streamwise and spanwise direction. Given that the initial shear layer thickness closely behind the plate is \( \delta_\omega \approx 7.5mm \), the early shear layer is clearly underresolved by the grid. Sufficient resolution is guaranteed in the lateral direction, where roughly 40 points per shear layer thickness are present. Inflow conditions at the trailing edge were generated by adjusting the running length of the incoming boundary layers, so that velocity profiles at the trailing edge match those measured in the experiment of Delville (1998).

![Figure 2: Comparison of instantaneous vortex structures visualised via the Q criterion for different DES models.](image-url)

A first impression of the performance of the new approach is given in Figure 2, where instantaneous vortex structures based on the Q criterion are portrayed for 6 cases (i.e. for standard DES and WALES DES employing either \( \Delta_{\text{max}} \) or \( \tilde{\Delta}_\omega \) ). Clearly, standard DES using either the \( \Delta_{\text{max}} \) or the new adaptive \( \tilde{\Delta}_\omega \) grid scale shows poor performance for this test case, where almost no turbulent structures can be identified. In contrast, both new WALES-DES and \( \sigma \)-DES models show much improved behaviour, although a region close to the trailing edge where flow structures are highly correlated and two-dimensional still persists.
5 Turbulent round jet

Turbulent jets at high Reynolds numbers constitute a great challenge for hybrid RANS-LES methods, as the rapid development of turbulence in the separating shear layers has a significant influence on the overall flow and sound prediction. As a first step towards more complex jet applications involving installation effects, an unheated, compressible, static round jet at $M = 0.9$ is investigated, with a Reynolds number of $Re_D = 1.1 \times 10^6$ based on the nozzle diameter. This case has been analysed in numerous CFD studies, e.g. by Shur et al (2011), where a coupled RANS (flow inside the nozzle) and implicit LES (for the jet plume) approach was successfully evaluated. Unfortunately, the approach of ILES is not feasible for cases featuring interaction of turbulence with solid walls, e.g. jet/wing interaction or bucket-type thrust reverser, so that a process chain based on hybrid RANS-LES modelling is envisioned. In Mockett et al (2014), first results of WALE-DDES generated by NTS\footnote{New Technologies and Services, St. Petersburg, Russian Federation} were published for this case, indicating that the new model can indeed compete with the ILES approach for this kind of application, both in terms of the predicted flow field and the computed farfield sound.

Simulations on three different grids are conducted in this work, which are the grids used in Shur et al (2011). An overview of different grid and simulation parameters is given in Table 2. All grids are structured hexahedral grids, with an inner cartesian block in the jet core and an outer cylindrical block. The domain extents from $10D$ upstream of the nozzle to $70D$ downstream, where in the radial direction the outer radius of the domain varies from $15D$ at the nozzle exit to $30D$ at the domain outlet. As for the plane shear layer test case, the initial shear layers of the jet are underresolved and grid cells are highly anisotropic.

<table>
<thead>
<tr>
<th>grid G1</th>
<th>grid G2</th>
<th>grid G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>no. cells</td>
<td>1.6 M</td>
<td>4.2 M</td>
</tr>
<tr>
<td>$N_x$</td>
<td>308</td>
<td>515</td>
</tr>
<tr>
<td>$N_y$</td>
<td>81</td>
<td>101</td>
</tr>
<tr>
<td>$N_z$</td>
<td>64</td>
<td>80</td>
</tr>
<tr>
<td>$\Delta t U_{jet}/D$</td>
<td>$\approx 0.02$</td>
<td>$\approx 0.01$</td>
</tr>
<tr>
<td>$T_{avg U_{jet}}/D$</td>
<td>$\approx 240$</td>
<td>$\approx 192$</td>
</tr>
</tbody>
</table>

Table 2: Overview of grid and simulation parameters for round jet test case. $N_x$, $N_y$ and $N_z$ are grid sizes of the outer cylindrical block.

A variety of different experimental data sets is available for this case, which exhibit a somewhat high scatter. In this work, data from Lau et al (1979) and Lau (1981), Arakeri et al (2003), Simonich et al (2001) and Bridges & Werner (2010) is considered for comparison, where mean velocity and streamwise velocity fluctuations along the centre and lip line of the nozzle as well as radial velocity profiles are available. Although measured farfield sound spectra are available for the jet case, an aeroacoustic analysis is not conducted here, but is considered for future work.

The simulation strategy pursued is to first evaluate all approaches that were tested on the plane shear layer case on the coarsest grid G1, followed by a grid refinement study on grids G2 and G3 using the most promising approach.
In Figure 4, contours of instantaneous eddy viscosity ratio are shown for standard SA-DDES and the new SA-\(\sigma\)-DDES model on grid G1, both employing standard \(\Delta_{\text{max}}\). One feature that is visible in both simulations is the eddy viscosity that is convected from the RANS inlet profile, which appear to be roughly equivalent between both models (1). The area where an improvement of the model behaviour is envisioned is marked as (2) in Figure 4. In this region, standard SA-DDES produces significant amounts of “new” eddy viscosity driven by the strong shear. For the new \(\sigma\)-DDES, eddy viscosity is drastically reduced here, whereby eddy viscosity begins to slowly grow further downstream when flow structures become more three-dimensional.

The activity of the new LES length scale \(\tilde{\Delta}_w\) is depicted in Figure 5 relative to the standard formulation \(\Delta_{\text{max}}\). In the early shear layer where grid cells are highly anisotropic and the vorticity vector is aligned with the azimuthal direction, the new formulation returns significantly lower values than \(\Delta_{\text{max}}\), thus accelerate the formation of resolved turbulent scales. Inside the jet core and especially further downstream where three-dimensional turbulence is present, values of \(0.6 \leq \tilde{\Delta}_w/\Delta_{\text{max}} \leq 0.95\) are adopted.

The effect of eddy viscosity levels in the initial shear layer on the flow field is visualised in Figure 6, where the vorticity magnitude distribution is shown\(^2\). For standard SA-DDES, high values of eddy viscosity cause the shear layer to remain stable far downstream of the nozzle. Employing \(\tilde{\Delta}_w\) has a significant effect even for standard DES, leading to a more rapid development of flow unsteadiness and turbulence. This is even stronger pronounced for the new models WALE-DDES and \(\sigma\)-DDES, which both perform very similar.

In Figure 7 (a), velocity profiles for a radial slice at \(x/D = 8.0\) are shown. Due to the coarseness of grid G1, all improved models significantly under-estimate the potential core length, which leads to a decreased centreline velocity. For standard SA-DDES using \(\Delta_{\text{max}}\) however, the potential core width is strongly over-estimated. With regard to streamwise velocity fluctuations on the centreline displayed in Figure 7 (b), all improved formulations suffer from an overshoot in the range \(5 < x/D < 10\), although this is less pronounced for WALE- and \(\sigma\)-DDES. This again relates to the under-estimated potential core length on grid G1, which causes an upstream shift of the RMS-value peak in the streamwise \((x)\) direction.

An analysis of velocity signals inside the shear layer located on different positions downstream of the nozzle are visualised in Figure 8. For the location closely behind the nozzle, i.e. \(x/D = 1.0\), the turbulence is not yet fully developed, but is still at least in part two-dimensional and affected by the Kelvin-Helmholtz instability. In line with expectation, the simulations using both means to counter the RLT issue, i.e. the new turbulence model approach and new grid scale, show enhanced and richer spectral content than the models using the standard \(\Delta_{\text{max}}\) formulation. The delay in RANS to LES transition for standard SA-DDES is clearly visible. For the location further downstream, i.e. \(x/D = 5.0\), all simulations except for standard SA-DDES using \(\Delta_{\text{max}}\) show sufficient turbulent content and a spectrum matching the \(St^{-5/3}\) slope in the inertial subrange.

Based on the presented results on grid G1, two ad-

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\(^2\)where \(U_{jet}\) is the fully expanded jet velocity
Figure 7: Comparison of different approaches on grid G1.

Figure 8: Power spectral densities of streamwise velocity for different probe locations inside the shear layer on grid G1.

Figure 9: Effect of grid refinement on aerodynamic quantities of jet for SA-σ-DDES model with $\Delta_\omega$.

Additional simulations on grids G2 and G3 were conducted, for which the SA-σ-DDES with $\Delta_\omega$ was employed. Figure 10 shows instantaneous vorticity magnitude on all grids, thus given an impression of the increased resolution of structures achieved through grid refinement. As one of the main aerodynamic quantities of interest, profiles of centreline velocity are plotted in Figure 9 (c), giving also an impression of the potential core length of the jet. An improvement of prediction relative to the experimental data is observed with grid refinement, although no grid-independent solution could be achieved. Agreement also improves for the radial velocity profile and velocity fluctuations on the centreline shown in Figures 9 (a) and (b). Compared to results published in Mockett et al (2014) which were generated on identical grids but using the WALE-DDES model and the CFD solver of
NTS, the predicted core length is about 20% lower at each grid level. Given that WALE and σ-DDES performed equivalent in this study on the coarsest grid G1, a model influence is disregarded as an explanation for the discrepancy. We suspect the second order code used here rather than the higher order NTS code to be responsible for this.

Nevertheless, a satisfying prediction of the mean aerodynamic quantities of the jet could be achieved, where both WALE and σ-DDES in conjunction with the \( \hat{\Delta}_n \) formulation seem to be suitable candidates to cover this or even more complex jet applications.

Figure 10: Comparison of instantaneous vorticity magnitude for SA-σ-DDES using \( \hat{\Delta}_n \) on grids G1-G3. (region between 0 < x/D < 10 is shown)

6 Conclusions and outlook

A new approach based on modification of the SGS formulation of DES has been proposed, which targets acceleration of RANS to LES transition in free shear layers. The main concept is based on aggressively reducing eddy viscosity in this 2D flow region. Two alternative SGS formulations have been tested, i.e. the WALE and σ models of Nicoud and co-workers, which offer a better treatment of planar shear than the Smagorinsky-like form that standard DES adopts in LES-mode. The new formulation has been successfully tested for predicting the energy cascade using the DIT case (including calibration of model constants), thus verifying that the modifications made to the behaviour of DES in early shear layers do not compromise SGS functionality in fully three-dimensional turbulent flow. Encouraging results could be achieved for both the planar shear layer case as well as for the more complex round jet case, which both feature pronounced RLT regions. Between both WALE and σ model, no clear favourite could be identified, where σ-DDES seems to perform marginally better for the plane shear layer case. In addition, a new formulation of the grid scale has been assessed, i.e. \( \hat{\Delta}_n \), which further improves RLT acceleration.

Future work on the plane shear layer test case will include a comprehensive grid study, where both different coarsening and refinement strategies will be employed. As for the round jet case, work will continue in the direction of extracting far field sound information, including correct acoustic treatment of boundary conditions and analysis of suitable Ffowcs Williams and Hawkings (FWH) surface data. To obtain more information about the behaviour of WALE and σ-DDES, the flow over an inclined delta wing including vortex breakdown will be computed, which also features an RLT-dominated situation, as demonstrated in Kok & van der Ven (2012). Unlike the shear layer and jet test case, the delta wing flow shows a significant topological departure from planar shear, thus delivering more evidence over the generality of new DES-based approach.

Acknowledgments

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