Go4Hybrid

CFD Software GmbH

CFD Software Entwicklungs- und Forschungsgesellschaft mbH

Deliverable D1.1-18

"18-months Management report"

.

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The work described in this document was performed as part of the Go4Hybrid project (Grey Area Mitigation for Hybrid RANS-LES Methods) which is funded by the European Union under Grant Agreement No. 605361.

The project is a collaboration between CFDB, NTS, DLR; FOI, NLR, ONERA, and UniMAN, with Bombardier Transportation, GE Global Research, NUMECA, EDF, PSA Peugeot-Citroen, Rolls-Royce Deutschland, SAAB, ANSYS, Volkswagen AG, and EXA as observers.

EADS CASSIDIAN and Eurocopter Deutschland GmbH are associate partners, not belonging to the consortium directly.

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1 Introduction

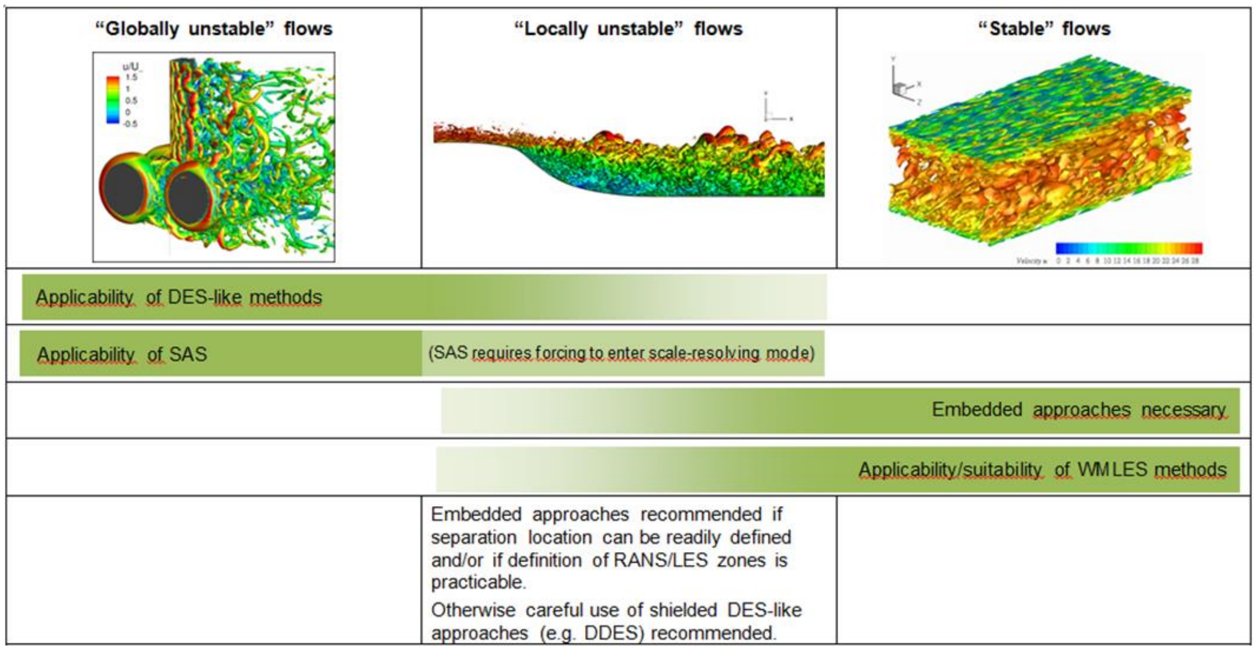
The present deliverable provides the summary of work carried out in the first 18 months of the (2-years) Go4Hybrid project and exhibits all relevant information on management activities and items.

2 Publishable Summary Report

2.1 State of the Art - Background

Computational Fluid Dynamics (CFD) has become a key technology in the rapid and cost-effective design of green aircraft with reduced fuel consumption and aero-acoustic noise emissions. The accurate and efficient prediction of turbulent flow, however, represents one of the central limitations of CFD, with precise methods requiring unfeasible computational resources and more efficient methods introducing approximations and inaccuracy. A new family of hybrid Reynolds Average Navier-Stokes - Large Eddy simulation (RANS-LES) methods have recently emerged, which offer a significant increase in accuracy whilst limiting expense to levels that are affordable with current and near-future computational capacity.

Despite excellent results by hybrid RANS-l.ES methods, a fundamental issue remains to be addressed. Known as the ‘Grey-Area Problem', this concerns the 'transition region' between the RANS and LES modes of such hybrid methods. The grey-area problem has a particularly detrimental impact on flows featuring shallow regions of boundary layer separation and re-attachment. In such cases, the accuracy of hybrid RANS-LES predictions can be inferior to the lower order RANS methods. Unfortunately, applications that tend to suffer from grey-area issues include some of the most important aerodynamic and aero-acoustic flows, such as wings near the borders of the flight envelope and jet noise.



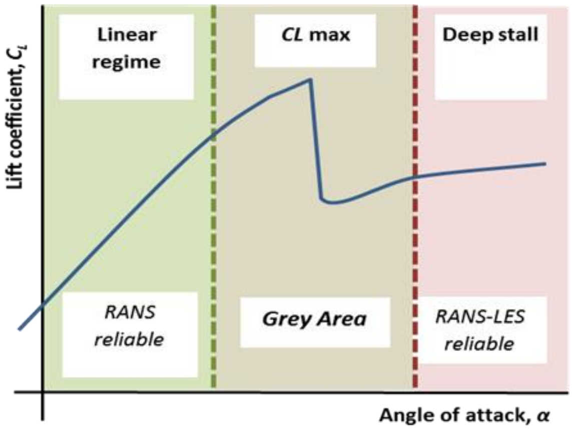
Summary of method applicability prior to Go4Hybrid; BPG from the ATAAC project - the acronym SAS refers to the hybrid method known as “scale-adaptive simulation”.

2.2 Objectives

The Go4Hybrid project will pursue the development and demonstration of improvements to hybrid RANS-LES methods to reduce the severity of the grey-area issue (or eliminate at entirely).

A range of approaches to reducing the grey-area severity will be developed and evaluated. The evaluation will take into account not only the predictive accuracy of the improved methods but also practical issues, such as computational expenses and user-friendliness. A balance will be struck between simple academic test cases (for reduced computational expense and more `pure' evaluation) and complex application test cases (for demonstrating applicability). More details are given in the next section.

The industrial relevance and exploitation of the project outcomes will be ensured by the consortium members, who are drawn from the aerospace, ground transportation and commercial CFD software sectors A midterm workshop (and its equivalent being the co-coordination of the 5th HRLM (Hybrid RANS-LES Methods) conference will provide strong means for disseminating the project findings. There are two small and medium-sized enterprises, SME, including the coordinator, and one SME observer involved in the project.



Schematic of Grey Area impact on aerodynamic wing simulations - the grey-area problem compromises predictive accuracy for the most important flow regimes.

2.3 Description of Work

Technically, a two-pronged strategy is adopted:

On the one hand, grey-area mitigation strategies for non-zonal hybrid approaches will be pursued. These methods are inherently more flexible and applicable to complex industrial geometries; but they also suffer the most strongly from grey-area effects. On the other hand, zonal or embedded strategies have the potential to eliminate the grey-area problem entirely. However, these are inherently more complicated to set up and are most readily applied only to simple configurations or a limited class of industrial problems. Improvements to the flexibility and applicability of embedded hybrid strategies therefore constitute the second aim of Go4Hybrids efforts.

All the development work will focus on just two academic test cases. The direct comparability and ranking of the methods will be facilitated by common grids and a common numerical assessment platform. These research and development and proof-of-concept test cases will be complemented by a range of complex industrial demonstration applications, including a delta wing, jet noise, a three-element airfoil, a shallow recirculating flow and the flow around a complex helicopter fuselage.

2.4 Expected Results

The expected direct outcome of the project will be a significant improvement in the predictive accuracy of hybrid RANS-LES methods for practical flows affected by the grey-area issue. Since this issue is typically strongly pronounced in flows representative of engineering performance limits, the practical impact is very significant. Industrial applications that will benefit from this include external aerodynamics of aircraft, automobiles and rail vehicles, gas turbines for propulsion and power generation, and aircraft noise sources such as yet and airframe noises.

By increasing the predictive accuracy and reducing the user burden of CFD for such key applications, the Go4Hybrid project will therefore enrich the increased adoption of simulation in contrast to expensive experiments (e.g. wind tunnel tests). The project therefore contributes to increased competitiveness and technical leadership of European industry. The transfer of the developed methods to industrial application is facilitated by the high-profile observer and associate partner group, as well as through public exploitation and dissemination activities.

3 General concept and objectives

The Go4Hybrid project, incorporating industry (SMEs), research institutes and one university focuses on the solution of accurate, reliable and robust computational fluid dynamics (CFD) applications in the general framework of hybrid RANS-LES methods.

The ***strategic goals*** have been defined as follows:

The Go4Hybrid project aims to foster aeronautics RTD work in Europe by recognising merits and achievements of previous and existing EU projects. The project follows the ACARE Vision-2020 and Flightpath-2050 future strategies, by contributing to "more affordable, safer, cleaner, quieter", hence greener aircraft. In particular in the field of computational fluid dynamics (CFD), nowadays applied extensively in all aerodynamic-based topics of aircraft design, the Go4Hybrid project supports the European research policy and contributes to improving the competitiveness of the European aeronautics industry. This will be achieved by a close collaboration between the partners of the project and by directing the proposed work to ensure a focus on industrial requirements. By means of improved scientific capabilities and prediction tools with a high Technology Readiness Level aiming at improved confidence when using hybrid RANS-LES methods, Go4Hybrid will allow for enhanced design processes by mitigating the "Grey Area" problem. Consequently, this will result in fewer design cycles, lower costs and reduced time-to-market of challenging future aircraft designs.

The ***concept*** in brief reads:

To speed up simulation processes, following Airbus's "***more simulation, less testing***" initiative, and to improve the current (numerical) situation, it is necessary to provide numerical tools offering advanced capabilities for ever increasing complexity of computed geometries and problem flow-types. Hybrid RANS-LES methods, successfully addressing this issue, still lack sufficient industrial suitability and confidence because of a severe problem, known as the Grey Area problem, in bridging the (U)RANS and LES domains. Hence, an improvement of hybrid RANS-LES methods for achieving accurate and reliable time-dependent flow solutions by the ***mitigation of the Grey Area*** - being the main objective of the Go4Hybrid project - is of utmost importance. As a result, more reliable and accurate hybrid methods will be available which will ensure a significant widening of applicability of these methods, particularly in off-design and maximum load situations, and will provide improved physical knowledge for all non-linear flows. These claims will be supported by demonstration on industrially relevant, hence complex test cases.

The ***objectives*** to be reached are:

- To develop generally-applicable extensions to non-zonal hybrid RANS-LES models for mitigation of the Grey Area problem;
- To improve the flexibility of embedded hybrid RANS-LES methods and hence their applicability to complex industrial problems;
- To select the most capable and flexible methods based on systematic evaluation in a directly comparable manner;
- To formulate Best Practice Guidelines (BPG) and maximise exploitation and dissemination of the improved methods;
- Preserve knowledge obtained in the project through the entry of selected test cases to a well-known long-term database, namely the ERCOFTAC[1] Knowledge Base Wiki – at the end of the project (exploitation issue).

[1] www.ercoftac.org

4 Work Progress and achievements during the first 18 months

4.1 CFDB

Technical activities

The technical activities of CFDB within the first 18 months of Go4Hybrid were:

- Formulation of novel non-zonal GAM approaches: WALE-DDES & σ-DDES
    - Alternative SGS forms in LES mode strongly reduce eddy viscosity in early shear layer
    - Generally-applicable formulation
- Implementation and testing of NTS $\tilde{\Delta}_\omega$ GAM approach in combination with the above
    - Adaptive definition of filter width, sensing alignment of vorticity vector with grid
    - Further reduces eddy viscosity on anisotropic grids without loss of generality
- Basic testing of above approaches:
    - Isotropic turbulence (calibration for equivalent behaviour in fully-developed turbulence)
    - Flat plate (test and recalibration of DDES shield function)
- Fundamental test case F2 (spatial shear layer)
    - Demonstration of strong acceleration of RANS-to-LES transition w.r.t. standard DDES
    - Best results achieved with σ-DDES + $\tilde{\Delta}_\omega$ approaches
    - Further improvement with redistribution of streamwise grid spacing achieved
- Complex demonstration case I5 (M = 0.9 round jet)
    - Comparison of models on coarse grid (strong improvement with new GAM formulation)
    - Grid refinement study with best model σ-DDES + $\tilde{\Delta}_\omega$
- Complex demonstration case I2 (delta wing)
    - Comparison of models on mandatory grid
    - σ-DDES gives much better results than WALE-DDES and standard DDES
    - Evidence of greater generality of σ-DDES over WALE-DDES approaches
- Compilation of D2.1-06, D2.1-12 and D2.1-15
- Definition of Common Assessment Platform (numerical approach, selection of GAM methods to be tested)
    - Implementation of 7 of 12 selected methods complete
    - Shear layer simulations underway

The results are highly encouraging for the improved methods proposed by CFDB: Strong reduction of the grey area problem has been achieved without loss of generality. The importance of testing for a wide range of different flow topologies is evident, since this gave rise to a strong preference for the σ-DDES over the WALE-DDES formulation. Technical work is on schedule. Some highlighted results are shown in the following figures.

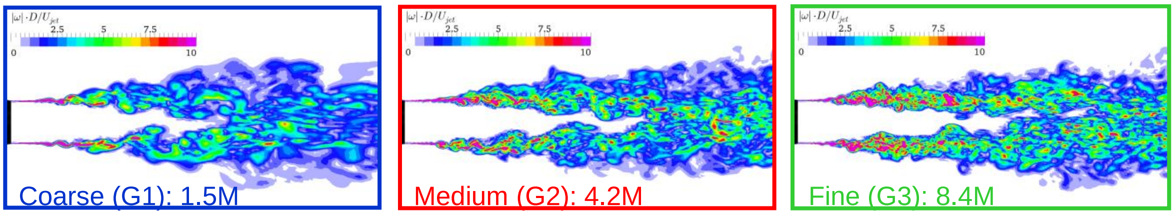


Figure 1: Effect of grid resolution on resolved structures for simulations of the jet test case I5 using the improved σ-DDES+ $\tilde{\Delta}_\omega$ model.

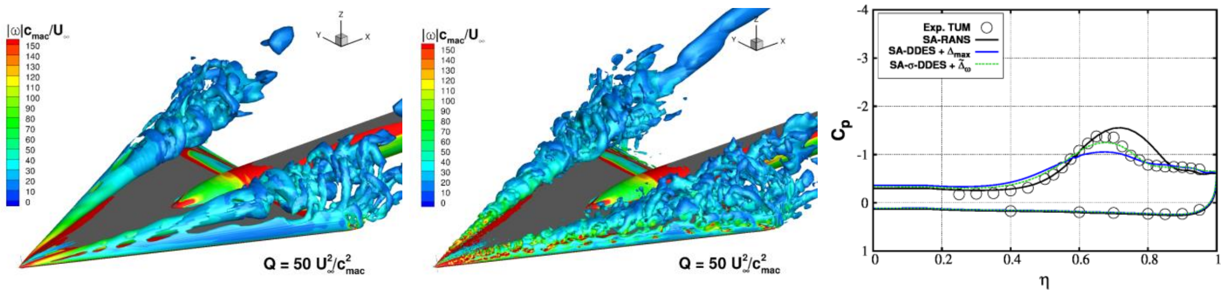


Figure 2: Snapshots of resolved turbulent structures compared between standard DDES (left) and the improved method σ-DDES+ $\tilde{\Delta}_{\omega}$ (centre). Comparison of mean pressure coefficient at $x/c_r = 0.8$ (right). Delta wing test case I2.

Exploitation and dissemination activities

CFDB have been heavily engaged in dissemination of project results among the academic research and industrial user communities, with presentations of Go4Hybrid project overviews and/or results at the following conferences:

- 5th Symposium on Hybrid RANS-LES Methods, Texas
    - Two papers and two presentations
- ECCOMAS-CFD Conference, Barcelona
    - Co-organisation of mini-symposium on Go4Hybrid topic
- 10th Symposium on Engineering Turbulence Modelling and Measurements (ETMM10), Marbella
    - Presentation and paper
- Presentations at meetings of the OpenFOAM user community:
    - 2nd North-German OpenFOAM User Network (Braunschweig)
    - 2nd OpenFOAM User Conference (Berlin)
- Presentation of project overview at the 4th EASN Workshop (Aachen)
- Presentation of project overview at a meeting of the linked TFAST project (Toulouse)

In addition, synergetic links to other EU and nationally funded projects have been established:

- AEROSTRUCT (funded in LuFo-IV by German BMWi)
    - Implementation of Go4Hybrid improved method in industrial solver and validation for jet noise applications
- JERONIMO (EU FP7)
    - Application of Go4Hybrid improved method and meshing best practice for simulation of jet-wing interaction noise
- HELIDES (CleanSky)
    - Mesh and results for the helicopter test case are drawn from CFDB activity in the (completed) HELIDES project

Furthermore, the expertise gained in Go4Hybrid are valuable in underscoring CFDB's activities as an SME engaged in technology transfer of cutting-edge CFD methods to industrial applications.

Outlook

CFDB will focus on the following activities in the final six months of Go4Hybrid:

- Preparation and hosting of the Go4Hybrid final workshop in Berlin (28th-29th September)
- Compilation of the Go4Hybrid book as a major contribution to dissemination and knowledge preservation
- Simulation of the I1 demonstration test case (helicopter fuselage) using the improved DES variant developed in Go4Hybrid

- Simulation of the jet test case (I05) with improved numerics and inlet boundary conditions, cross-plotting of partner contributions
- Further implementation of selected approaches in the Common Assessment Platform and execution of remaining comparative simulations for the shear layer test case
- Coordination of WP4: Compilation of best practice guidelines in collaboration with FOI, identification of conclusions and routes for future work

4.2 NTS

Task 1.1

NTS was coordinating the work on WP3.1 (Deliverables D31.12 and D31.12) and on the Test Case I.04 (2D hump). Other than that, assistance was provided to CFDB in coordination of the Test Case I05 (Round jet).

Task 1.2

NTS participated in preparing presentations and writing of 2 papers for HRLM-5 Symposium [1], [2]. Besides, a key lecture was delivered at FOR 1066 Symposium at DLR (Braunschweig) and a paper based on this lecture is written for the Symposium proceedings. Results of the work are already used in the NTS R&D projects and in lecture courses delivered by NTS employees at St.-Petersburg State Polytechnic University.

Task 2.1

In this Task a primary work of NTS was associated with development of an alternative definition of the subgrid length-scale ensuring GAM in DES. The new definition includes replacement of the conventional DES subgrid length-scale Δ_{max} with the modified length scale $\tilde{\Delta}_{\omega}$ which accounts for grid anisotropy and flow two-dimensionality. In addition, it includes a kinematic (grid-independent) measure of the local flow two-dimensionality called Vortex Tilting Measure or VTM (its detailed formulation is available in NTS input in the Deliverable D2.1-12). The modifications were implemented in the NTS code, applied to both generic flows (DIHT, BFS) and Fundamental Test Case of Go4Hybrid F02 and shown to be very successful (resulting in a virtually complete elimination of the grey area (see Figs.1, 2)).

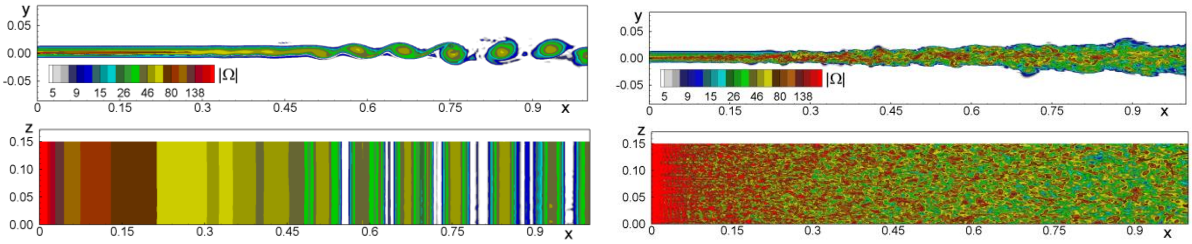


Fig.1. Snapshots of vorticity magnitude from the original DDES (left) and DDES with modified subgrid length-scale (right)

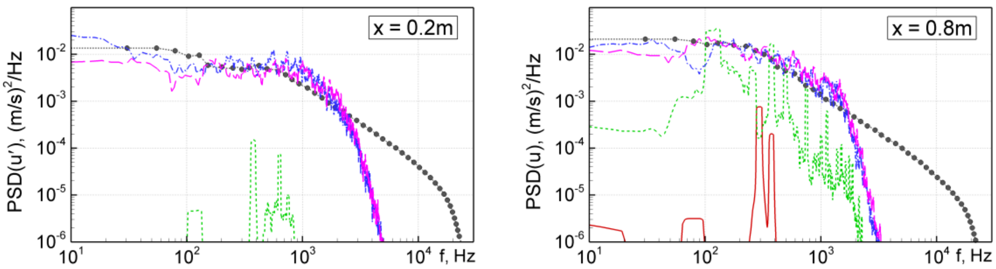


Fig.2. Computed (lines) and measured (symbols) power spectral density of streamwise velocity fluctuations in the shear layer predicted with the original DDES and DDES with new subgrid length-scale on coarse and mandatory grids

Task 2.2

This work had not been initially planned on but turned out to be necessary for evaluation of the newly developed non-zonal approach (see Task 2.1 above) on a complex test case. Hence, DDES of the M=0.9 jet (Test case I05) wall mounted 2D hump (Test Case I04) with the use of the new length-scale definition was carried out. Some results presented in Figs.3, 4 demonstrate a crucial improvement compared to the original DES (virtually complete elimination of the grey area and a very good agreement with the experiment and with the zonal RANS-ILES computations of this flow carried out by NTS previously).

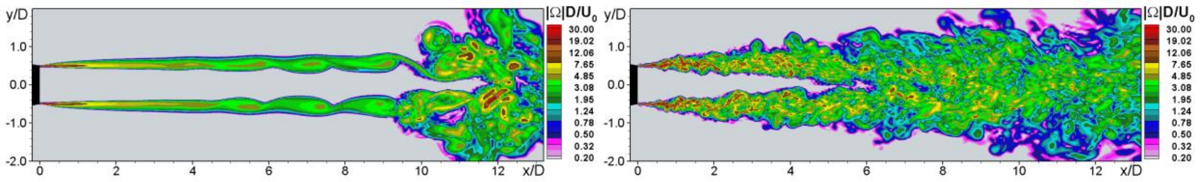


Fig.3. Snapshots of vorticity magnitude in jet meridian plane from the SA DES with $\Delta = \Delta_{\max}$ (left) and SA LES with $\Delta = \tilde{\Delta}_{\omega} F_{KH}$ (right)

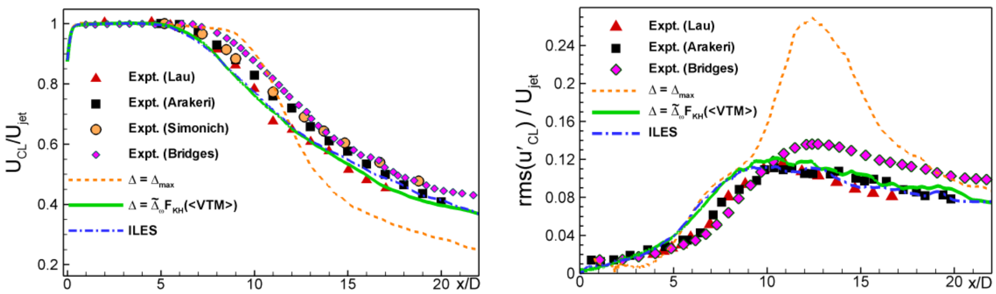


Fig.4. Comparison with experiments of centerline distributions of mean velocity and RMS of its fluctuations predicted with the use of $\Delta = \Delta_{\max}$, $\Delta = \tilde{\Delta}_{\omega} F_{KH}$, and with ILES

In addition, a similar comparison between the standard (with $\Delta_{\max}$) and modified (with $\tilde{\Delta}_{\omega} F_{KH}(<VTM>)$ carried out for the 3-element airfoil (Test Case I03) has shown that within IDDES, the replacement of $\Delta_{\max}$ with $\tilde{\Delta}_{\omega} F_{KH}(<VTM>)$ is neutral (doe not lead to any noticeable alteration of the solution.

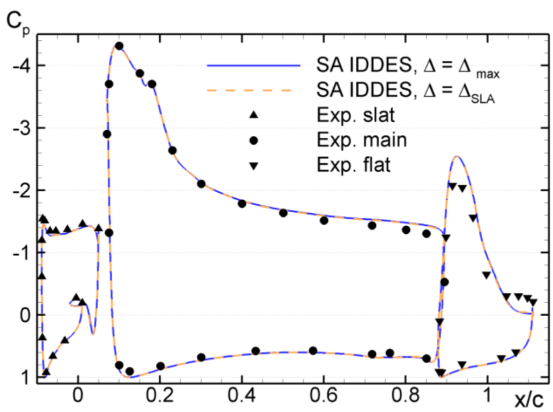


Fig.5. Comparison with experiments of pressure coefficient distribution over the 3-element airfoil predicted by the standard and modified IDDES

Other than that, in collaboration with BCFD, a WALE-Based DDES model coupled with the proposed SGS length-scale, $\tilde{\Delta}_{\omega}$ was implemented in the NTS code and shown to be competitive with the approach developed by NTS.

Task 3.1

A modified (more flexible and technologically convenient) version of the NTS Synthetic Turbulence Generator (STG) was developed based on volume source terms in the governing equations.

Computations of the TC F01 (flat plate boundary layer) with the use of embedded IDDES combined with the current and new versions of the NTS STG were performed. The results demonstrate a high efficiency of both versions and good overall accuracy of the approach. Other than that, embedded DDES was carried out of the TC F02 (plain mixing layer). Effects of the RANS-IDDES interface location and mean velocity profiles imposed at the interface were investigated. Results are generally encouraging (grey area is virtually eliminated - see sample results in Fig. 6).

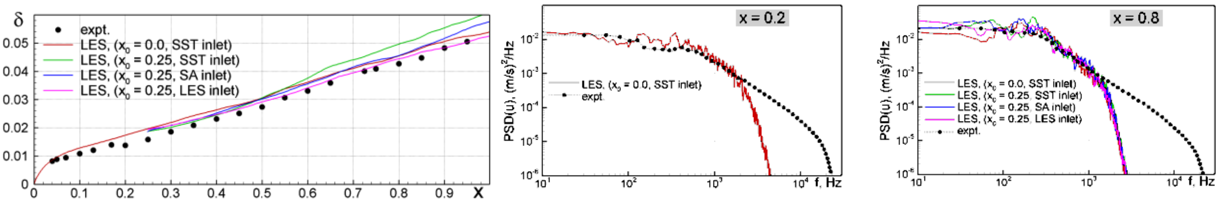


Fig.6. Streamwise distributions of the shear layer thickness and PSD of u' at x=0.2m and 0.8m from embedded SA-DES with different locations of the RANS-DES interface and inflow velocity profiles

Task 3.2

The TC I.04 (2D hump) description and guidelines for its computations (including mandatory grid) were provided to the Partners. Embedded IDDES of this TC with the use of the modified version of the NTS STG was carried out with two positions of the RANS-IDDES interface (-1.0 and 0.5). Sample results shown in Fig. 7 demonstrate quite accurate performance of the model and weak effect of the interface location.

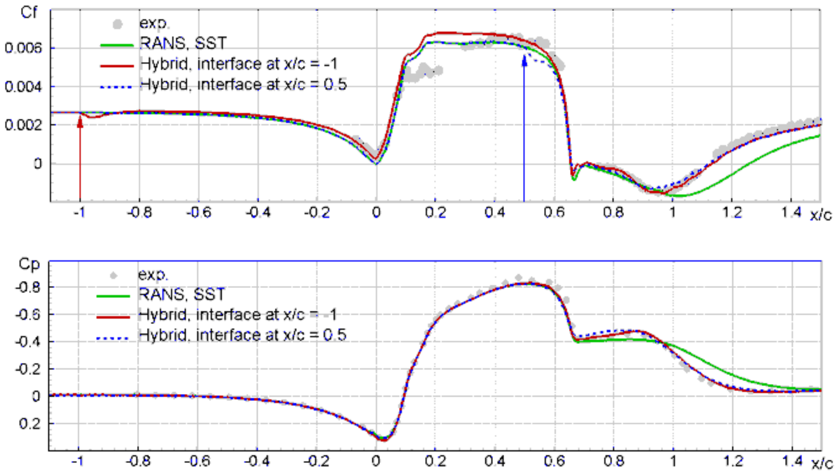


Fig. 7. Effect of RANS-IDDES interface location on distributions of skin-friction and pressure coefficients along 2D hump

References

[1] Prieto, A., Spalart, P.R., Shur, M., Strelets, M., Travin, A. (2015). Experimental and Numerical Studies of Flow in a Duct with a Diaphragm. Accepted for publication in Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer.

[2] Mockett, C., Fuchs, M., Garbaruk, A., Shur, M., Spalart, P, Strelets, M., Thiele, F., Travin, A. (2015). Two Non-Zonal Approaches to accelerate RANS to LES Transition of Free Shear Layers in DES. Accepted for publication in Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer.

4.3 DLR

DLR's contribution in ***WP 3.1*** started with preparatory work to establish the required capabilities of the unstructured compressible DLR-TAU solver for wall-modelled/embedded LES applications. For this purpose, a series of computations of the plane channel flow, using both wall-resolved LES and the Improved Delayed DES (IDDES) for wall-modelled LES, were validated against DNS reference data, while the solution sensitivity w.r.t. the numerical parameters of TAU's 2nd-order spatial discretization scheme was systematically analysed. Using a skew-symmetric central convection operator and a minimum amount of artificial matrix dissipation, a stable and energy-conserving low-dissipative scheme (LD) could be derived. Moreover, an additional gradient extrapolation of the central fluxes was implemented, which was shown to reduce the dispersion error in simple vortex-convection problems. The combination of the low-dissipation (LD) scheme with the low-dispersion extension, called "LD2 scheme", was tested in wall-resolved LES and IDDES computations of the plane channel flow, as well. While both LD and LD2 schemes clearly improve the simulation accuracy compared to TAU's "standard" scheme, only the LD2 scheme yields satisfying predictions of the mean velocity profile and the friction Reynolds number Re_τ in IDDES simulations (see Fig. 1, left).

Besides these basic numerical developments, a novel combination of Improved Delayed DES (IDDES) with the Jakirlic-Hanjalic-ε^h (JHh) Reynolds-stress model was derived and implemented in the DLR-TAU code. This allows to study the effects of the underlying RANS approach within hybrid/embedded LES in Task 3.1, and to benefit from the potential advantages of the second-moment closure in the RANS regions of more complex hybrid RANS/LES applications. As shown in Fig. 1 (left), convincing agreement with DNS data at $Re_\tau = 395$ is obtained for the new RSM-IDDES. Similar results were obtained at larger Reynolds numbers, i.e. $Re_\tau = 1100$ and $Re_\tau = 4200$.

In order to provide the required synthetic turbulent fluctuations at the interface of embedded approaches, different variants of the "Synthetic Eddy Method" (SEM) were implemented and verified in a TAU-development framework with both algebraic extensions for IDDES ("Algebraic IDDES" = AIDDES) and the new numerical schemes LD/LD2.

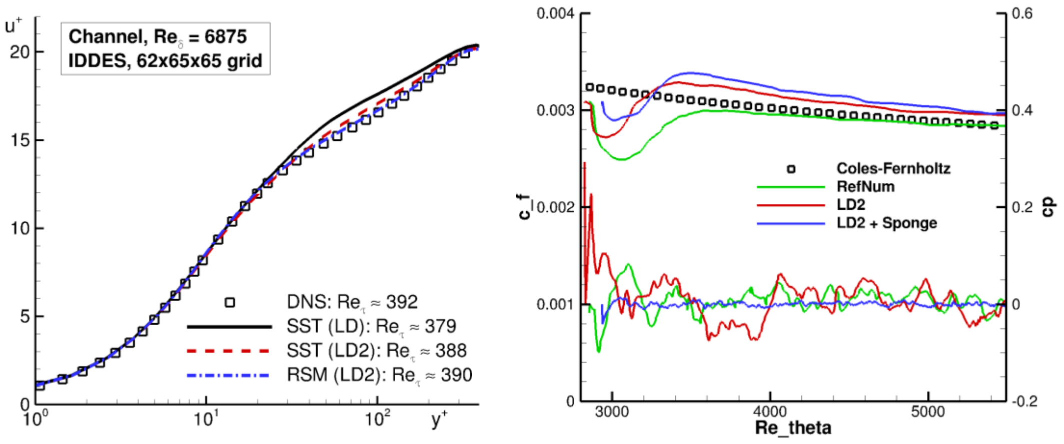


Figure 1: *Left:* Mean velocity profiles in the channel computed with TAU using the LD2 scheme and IDDES based on SST- and RSM-RANS modelling. *Right:* Mean skin friction and instantaneous pressure along the flat plate (TC.F1).

For the flat-plate test case TC.F1, a consolidated numerical setup was first derived using steady SA-RANS simulations, which also serve as initial and reference solutions for the assessment of SA-IDDES + SEM. Using a Dirichlet-type boundary condition for the original SEM at the inlet, rather strong pressure disturbances were observed, which are due to the (unphysical) divergence of the synthetic turbulence field and the compressible solution method.

After fixing a rarely occurring corruption of the initial computations of TC.F1, statistically converged results were so far obtained for SA-IDDES using the original spatial discretization scheme ("RefNum"), the newly-developed low-dissipation/low-dispersion scheme ("LD2"), and a combination of the latter with damping terms to reduce the inlet pressure disturbances ("LD2 + Sponge"). As visible in Fig. 1 (right), all computations yield a decent c_f-recovery to about the level of the reference solution ("Coles-Fernholtz"), but both LD2-results show a smaller initial c_f-drop near the inflow and a faster recovery to their final levels than the original scheme. While it is interesting to note, that the "RefNum" results matches the reference solution in the later part of the plate better than LD2, it should be pointed out that the LD2 results are overall in closer agreement with corresponding results of the project partners, e.g. NTS. For that reason, the LD2-scheme is considered the optimal choice and will be used in further investigations. Note that the "Sponge" terms in Fig. 1 (right) are helpful to reduce the unphysical pressure oscillations along the plate, but have only limited effect on the mean-flow solution (e.g. c_f).

In ***WP 3.2*** DLR performed work on embedded simulation of the 2D wall-mounted hump flow (TC.I4) and on the 3-element airfoil case (TC.I3).

To allow for inserting synthetic velocity fluctuations inside the flow domain, a local volume source term for the compressible momentum equations was formulated and implemented in the TAU code, which is an important prerequisite for computing the complex test cases TC.I03 (3-element airfoil) and TC.I04 (2D hump). The term is adjusted to the 2nd-order dual-timestepping scheme used in TAU and was first verified for simple test problems. The method was first applied to the 2D hump in its mandatory numerical setup, where the synthetic turbulence is to be inserted upstream of the hump at x/c = -1. As shown in Fig. 2 (left), a rapid development of resolved turbulent structures is obtained downstream of the interface plane, where the new source term for the SEM fluctuations is applied. The computation using SST-IDDES is currently running and will be assessed in detail, as soon as sufficient statistical averaging has been performed.

To enable such an embedded hybrid RANS/LES approach in an automatic manner, the algebraic boundary-layer and separation sensors within DLR's AIDDES approach are to be applied. They were shown to detect both the separation and reattachment locations with satisfying accuracy, thus forming a local LES region in the separation zone which is embedded within RANS modelling of the remaining (attached) flow field, see Fig. 2 (right). In the next steps, this approach is to be combined with the SEM at the RANS→LES interface. Moreover, the use of a sponge layer to better model the LES→RANS transition near reattachment is considered.

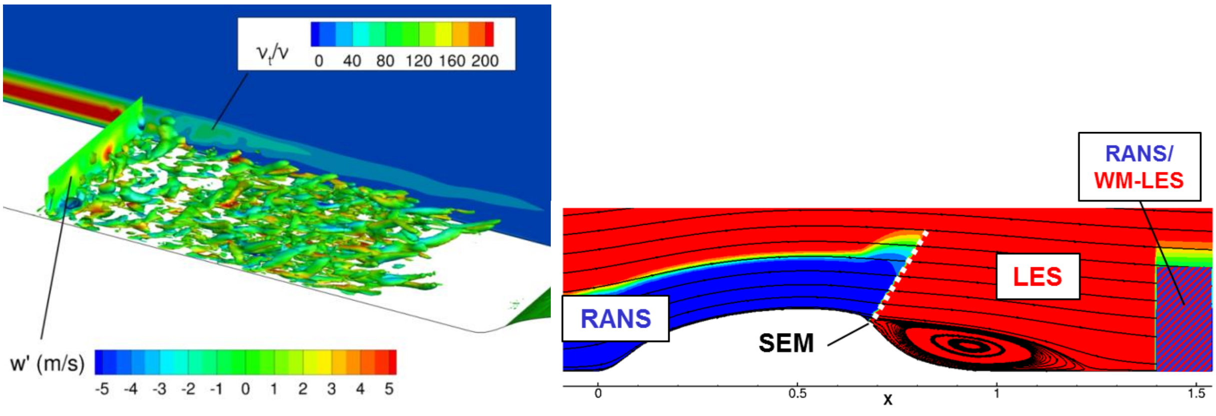


Figure 2: *Left:* Application of SEM with volume-source term at x/c = -1 in the 2D hump flow**,** TC.I4, (with iso-surfaces of Q-criterion). *Right*: Detected RANS and LES regions using AIDDES, which is to be used to demonstrate an "automatic embedded LES" without the need to predefine RANS and LES zones.

For the 3-element airfoil, a joint comparative study with the project partner NTS was conducted, were both partners used their own codes to compute the case at the same flow conditions, the same mesh and the same model, i.e. SST-based IDDES. Despite a different accuracy order of both codes (DLR-TAU: 2nd-order, NTS: 4th-order), good agreement of the mean-flow predictions was obtained. As the basic settings of this simulation correspond to the mandatory settings in Go4Hybrid, the results may serve as a reference solution for the intended simulations involving embedded-LES zones. Moreover, as coordinator for the 3-element airfoil case, DLR prepared the TC-definition documents and provided them to project partners

4.4 FOI

Over the 18-month period, the main effort of FOI technical work has been dedicated to WP 2, with a very small amount of work in WP 1 for project management. In **Task 1.1**, FOI has been the WP leader of WP 2, and coordinating test case F2 (mixing-layer). A part of work in this task concerns also FOI internal project plan and inspection of project work progress. In **Task 1.2**, FOI has involved as the symposium chair in the organizing work of the 5th Symposium on Hybrid RANS-LES Methods (Texas, USA, 18-20 March 2014). In collaboration with Saab and Chalmers, FOI participated in writing one paper on zonal hybrid RANS-LES modelling (in NFMM Vol. 130) and in collaboration with Texas A&M University a presentation on energy scale transfer for GAM. In part relation to the Go4Hybrid project work, FOI has in the ECCOMAS-CFD Conference made a presentation on airframe flow and noise generation, and further at the 10th Symposium on Engineering Turbulence Modelling and Measurements (ETMM10), Marbella, presented a paper on HYB0 computations for flow control of a backward-facing step flow. FOI hosted the 6-Month project meeting in Stockholm, April 2014.

FOI prepared Deliverable D4.2-03 with continuous updates and, together with other partners, made contributions to Deliverable D2.1-06, D2.1-12 and D2.1-15 coordinated by CFDB.

In **WP 2** FOI has been working on two different approaches aiming at alleviating the so-called “grey area” problem. The first formulates energy-backscatter function into the LES mode, in conjunction with the algebraic hybrid RANS-LES model (HYB0) and also being tested in a k-equation formulation (HYB1). This method targets to accelerate the development of resolved turbulence in the early separated shear layer. The second approach has been based on the PANS paradigm, for which additional terms quantifying the transfer of energy between resolved and modelled scales are derived. These terms, related to commutation error, arise when the PANS resolution parameter f_k varies rapidly.

The detailed formulation for the two FOI methods has been introduced in D2.1-06 and D2.1-12. The two FOI methods under investigation have very different theoretical argumentations, but targeting an improved enhancement of resolved turbulence through energy transfer between the resolved and the modelled turbulent structures. Some work conducted over the first half of the project period was dedicated to the implementation, calibration and verification of the methods. The energy backscatter function was incorporated in both HYB0 and HYB1 models in earlier calibration using turbulent channel flows. In the computations of test cases, TC-F2, TC-I3 and TC-I4, the HYB0 model has been taken as the base model for both FOI GAM methods.

To improve the prediction of resolved turbulence in the “grey area”, the energy-backscatter function aims to enhance the turbulence-resolving capabilities of the LES mode. The resulting SGS model is thus of mixed type, which was well demonstrated in full LES of turbulent channel flow, and further verified in hybrid RANS-LES computations using HYB0 model as the base model in previous work for turbulent hill flow and backward-facing step flow, which shows an effective re-establishment of resolved turbulent fluctuations in the “grey area”. The resulting model is termed the HYB0M model. With appropriate calibration and validation, the SGS model of mixed-type can be generalized in other hybrid RANS-LES formulation. The one-equation hybrid RANS-LES model (HYB1) was also taken as the base model with the energy-backscatter function incorporated (HYB1M model). The LES using the two-term formulation has shown very good results in the computation of a turbulent channel flow, whereas the HYB1M shows reasonable performance but needs to be further calibrated. These have been reported in the mid-term report. In the HYB0M computations of mixing layer (TC F2), furthermore, it was found that the energy-backscatter function alone plays only a marginal role in enhancing the initial shear-layer instabilities. It was found that a redefinition of the LES length scale, in terms of the minimum local cell size (to replace the max cell size in the original definition) and the conventional SGS scale (the cubic root of local control volume), may effectively enhance the resolved turbulent mixing in the initial stage, as shown in Figure 1. This needs to be further verified with a well-posed computational setup and appropriate grid resolution, however. The computation has shown that grid resolution may significantly affect the prediction as illustrated in Figure 1(e) in comparison with Figure 1(b) for the HYB0 computation with two grids.

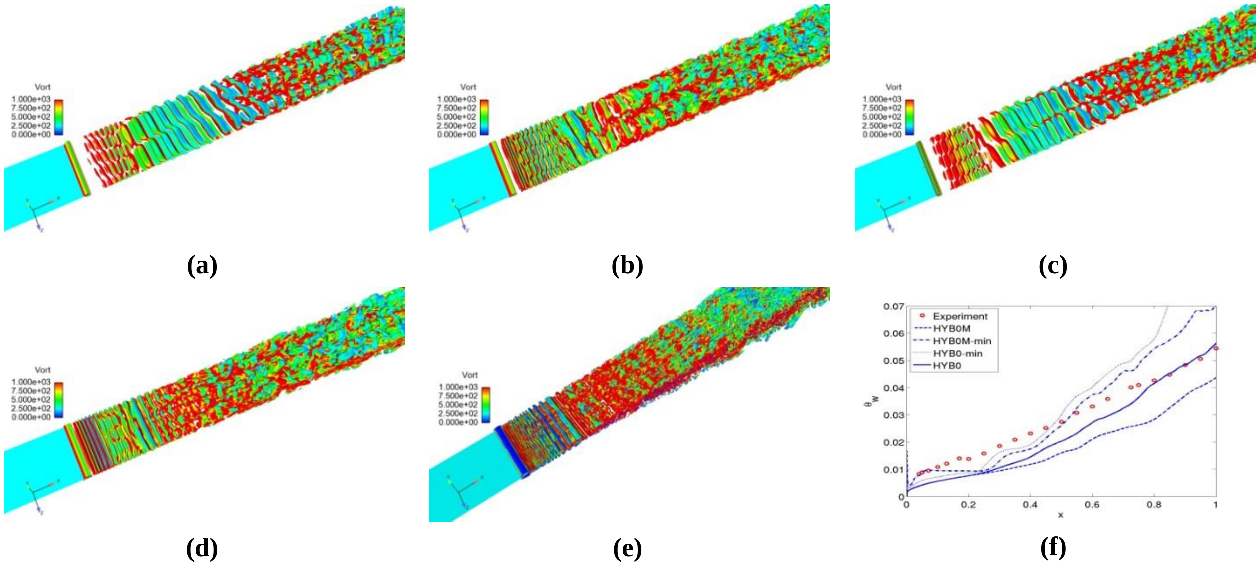


Figure 1: Mixing-layer flow (TC F2). Resolved turbulent structures (iso-surface of Q-criterion) by (a) HYB0, (b) HYB0 with Δ_{min}, (c) HYB0M and (d) HYB0M with Δ_{min}, with 4.4M nodes; and by (e) HYB0 with Δ_{min} with refined grid (7M nodes). In (f) the vorticity thickness of the mixing layer is shown.

Computation with the HYB0M model has also been conducted for TC I3 (LEISA HL flow). The HYB0M model shows sensible improvement in the prediction of surface pressure and the flap T.E. separation, as shown in Figure 2.

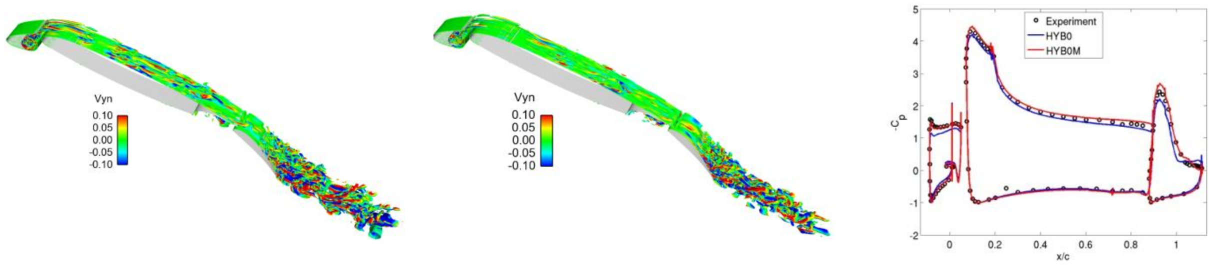


Figure 2: LEISA HL flow (TC I3). Resolved turbulent structures (iso-surface of Q-criterion) by HYB0 (left) and HYB0M (middle). In (c) the surface pressure C_p distributions are compared.

With the scale energy transfer in PANS methods, a series of calibration work has been done in computations of turbulent channel flows in the initial stage of the project work, as well as of the mixing-layer flow (TC F2). Two computations, shown in D2.1-12, using the original PANS without energy transfer terms, and PANS with the transfer production term, $\mathcal{P}_{Tr}$, but without the transfer eddy viscosity, were made for TC F2. It was shown that the PANS model suffers greatly from the transported RANS turbulence into the initial shear layer and the build-up of the resolved turbulence is strongly delayed. The $\mathcal{P}_{Tr}$ term is able to slightly reduce the modelled kinetic energy in the initial shear layer but insufficient in the present form.

Using the HYB0 model as the base model, the scale energy transfer is formulated in terms of a transport of the LES length scale, which is further adapted by a relaxation towards the baseline HYB0 model. In Figure 3, this formulation is tested in the computations of the hump flow (TC I4). It is shown that the modelled turbulent eddy viscosity in the shear layer has been largely reduced, as desired.

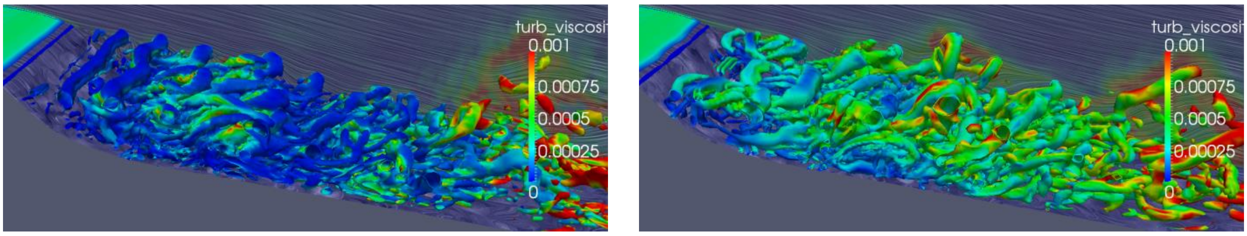


Figure 3: Hump flow (TC I4). Resolved turbulent structures (iso-surface of Q-criterion) by HYB0+Tr (left) and conventional HYB0 (left).

In summary, the FOI work over the reporting period has been placed on further refinement of the modelling formulation, dedicated to computations of fundamental flows and test cases defined in the project. The computations have been conducted for all the test cases in plan. FOI is currently working on the completion of these test cases, and examining further the effectiveness of the proposed GAM methods in these computations with different grid resolutions.

4.5 NLR

Two types of approaches are followed to mitigate the grey-area issue for the X-LES method:

- Reducing the level of SGS stresses in initial shear layers.
- Triggering instabilities by introducing a stochastic subgrid-scale (SGS) model.

For both types of approaches, a method had already been incorporated in X-LES prior to Go4Hybrid, and had been used with some success to improve the capturing of free shear layers. Within Go4Hybrid, a number of alternative methods are being investigated to see if further improvements can be made. Note that the approaches investigated can also be applied to other non-zonal DES methods.

Reducing the SGS stresses

As shear layers are initially very thin, they contain high gradients of the (mean) velocity, and therefore of the rate of strain, which leads to high values of the subgrid stresses. Any instability of the initial shear layer may then be damped by these high stresses, thus delaying the development of resolved turbulence.

The baseline method to reduce these high values of the stresses consists of a high-pass filtered (HPF) SGS model (Kok *et al.*, 2012). In this method, the SGS stresses are computed from a filtered velocity field defined as the instantaneous velocity minus the running time average of velocity. A disadvantage of this particular high-pass filter is that the running time average contains the complete time history, with equal weight, including the transient. Furthermore, it is also less suitable when the flow contains some non-turbulent unsteadiness at a low frequency that should also be filtered out.

Two alternative methods have been considered:

- Using a Butterworth-type recursive high-pass filter in the HPF SGS model.
- Replacing the HPF SGS model with an algebraic eddy-viscosity model.

The Butterworth-type recursive high-pass filter is less affected by the transient and may also filter out non-turbulent low-frequency unsteadiness. It has been tested for the spatial shear layer (test case F2) for which it gave very similar results as the baseline high-pass filter.

The Vreman model (Vreman, 2004) and the Nicoud σ-model (Nicoud *et al.*, 2011), are both local, algebraic models that have been designed to have zero eddy viscosity in the case of pure shear (Vreman) or, more general, for nominally two-dimensional flows (Nicoud). These models are incorporated in the SGS model in a similar manner as followed by CFDB. For the spatial shear layer, the Nicoud model turns out to be as effective in grey-area mitigation as the HPF SGS model, performing even slightly better in terms of the development of the momentum thickness. The Vreman model turns out to be ineffective.

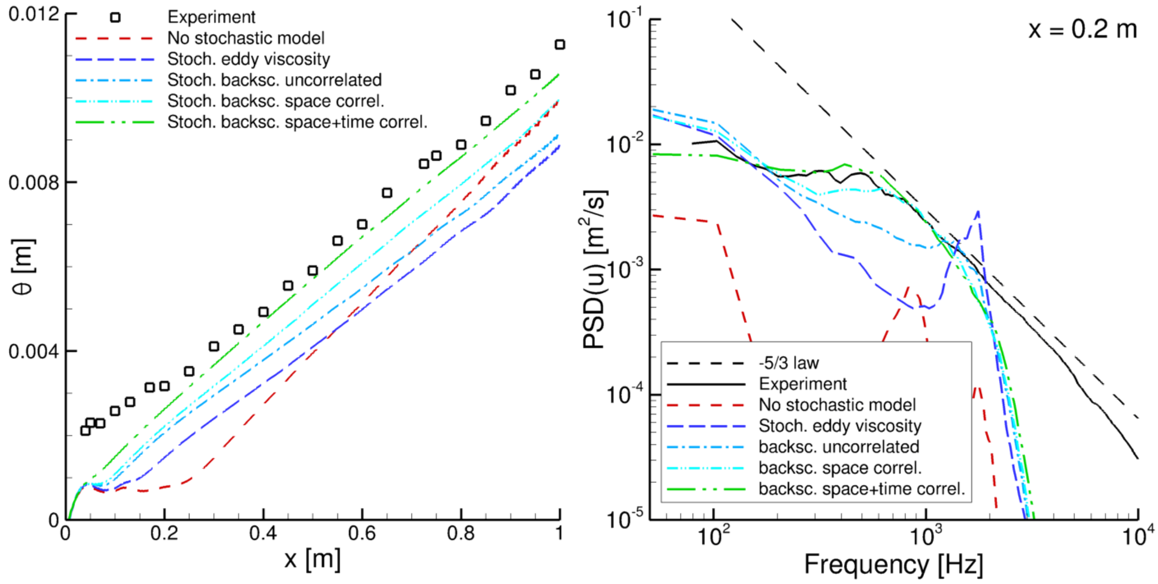
Triggering of instabilities

The baseline method to triggering instabilities in shear layers consists of a stochastic eddy-viscosity SGS model (Kok *et al.*, 2009) in which a stochastic variable is introduced in the expression for the eddy viscosity. This method becomes less effective when it is combined with the HPF SGS model, because the high-pass filtering effectively reduces the level of the complete subgrid stress which includes the stochastic term.

As alternative method, a stochastic SGS model that models energy backscatter has been considered. This model is based on the models of Leith (1990) and Schumann (1995). As in the Leith model, a random acceleration is added to the momentum equation, formulated as the rotation of a stochastic vector potential. The stochastic potential is correlated in space for distances smaller than the filter width by applying implicit spatial smoothing to a spatially uncorrelated stochastic variable. This is important when the mesh width is significantly smaller than the filter width, which is the case for grid cells with high aspect ratios as typically used in initial shear layers. The stochastic potential is also correlated in time over time intervals shorter than the subgrid time scale by solving a Langevin-type stochastic differential equation.

Employing this new stochastic backscatter SGS model gives a substantial improvement for the spatial shear layer over the baseline stochastic eddy-viscosity SGS model, in particular when the spatial and temporal correlation is included (see Figure 1). Development of 3D disturbance occurs much closer to the flat-plate trailing edge. The thickness of the shear layer approaches the experimental thickness. At the location $x = 0.2$ m, the energy spectra already show a broad spectrum, close to the experimental spectrum, for the stochastic backscatter SGS models. In contrast, with the baseline stochastic model, the spectrum is more narrow band (with a clear peak) and without a stochastic model, the energy level is much too low over the complete frequency range.

Note that these shear-layer computations have been performed on a coarse grid of 1.3 million cells (1/8th of the common grid) showing that the grey-area issue can be mitigated to a substantial extent on a relatively coarse grid.

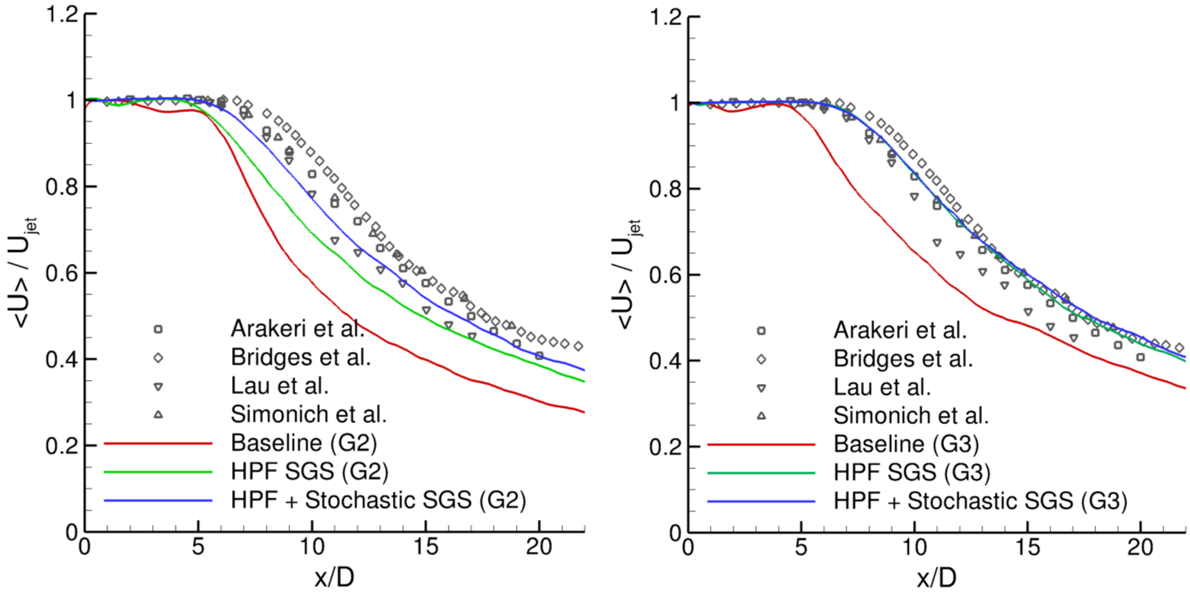


a) Momentum thickness with different stochastic SGS models

b) Energy spectrum at x = 0.2 m with different stochastic SGS models

Figure 1 Spatial shear layer (test case F2) with different stochastic SGS models

As the stochastic backscatter model was the most successful approach of NLR for grey area mitigation, it was further tested for the Mach 0.9 jet test case (see Figure 2). Computations have been performed on three grid levels (G1 to G3, with G3 the mandatory grid) and using three models: baseline X-LES without grey-area mitigation, X-LES with only the HPF SGS model, and X-LES with the HPF model and the stochastic backscatter model. As expected, the HPF model gave a substantial improvement over the basic model, with a much earlier instability of the jet shear layer closer to the nozzle exhaust. On the finest grid (G3), this resulted in a solution close to the experimental data. Including the stochastic backscatter model gave a further significant improvement on the two coarse grids. On the finest grid, the impact of the backscatter model was limited to the very initial shear layer and the results remained in close agreement with the experimental data. Thus, the stochastic backscatter model reduced grid dependence.



a) Coarse grid G2 b) Fine grid G3

Figure 2 Centreline velocity of round jet at Mach 0.9 (test case I5) for X-LES with different SGS models

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4.6 ONERA

Overview of ONERA contribution

In the framework of Go4Hybrid, ONERA assesses the capability of ZDES to simulate the turbulent flow on several test cases defined within the project.

The ZDES was first proposed by Deck [**1**][**2**] and the complete formulation has been recently published in Ref []. The method is based on a fluid problem-dependent zonalisation and makes possible the use of various formulations within the same calculation.

In the framework of ZDES, three specific hybrid length scale formulations, also called modes, are optimized to be employed on three typical flow field topologies as illustrated in **Figure** . Though the method can be adapted to any turbulence model, in the framework of the underlying SA model [3], d_w is replaced with $\tilde{d}_{ZDES}$ in the model. Mode 1 concerns flows where the separation is triggered by a relatively abrupt variation in the geometry; mode 2 is retained when the location of separation is induced by a pressure gradient on a gently curved surface, and mode 3 for flows where the separation is strongly influenced by the dynamics of the incoming boundary layer (see Figure 1). All these flow cases may be treated by the same ZDES technique in its different modes and are assessed in WP2 (task 1) and WP3 (task 1 and 2) of the project (see 1).

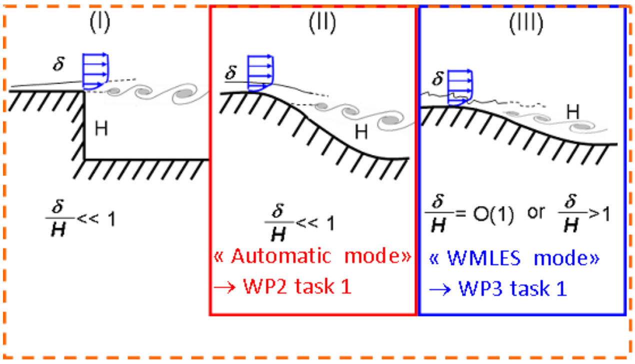

Figure 1 Classification of typical flow problems. I: separation fixed by the geometry, II:separation induced by a pressure gradient on a gently-curved surface, III: separation strongly influenced by the dynamics of the incoming boundary layer.

WP2-ZDES mode 2 of the plane mixing layer

ONERA contributed to the definition of the numerical setup (size of the domain) and performed ZDES (mode 2) calculations of the mixing layer. Let us be reminded that mode 2 of ZDES is the "automatic" operating mode of ZDES similar to DDES. Turbulent structures educed in Figure 2 highlight the very important delay in the formation of instabilities obtained with standard DDES as well as the significant improvement brought by ZDES mode 2. Both DDES and ZDES mode 2 calculations are compared with the experiment in Figure 3. This figure highlights the significant improvement obtained with ZDES mode 2 as regards the assessment of Reynolds stresses compared with standard DDES.

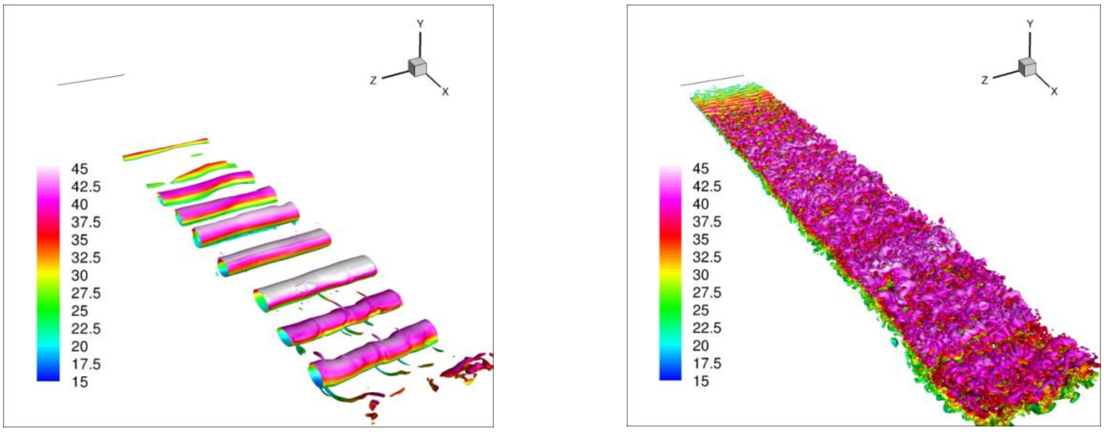

Figure 2 Turbulent structures educed by the Q criterion. Left: DDES; Right: ZDES mode 2.

WP3-ZDES mode 3 of the spatially developing turbulent flat plate boundary layer

ONERA coordinates test case F1 "Turbulent Flat Plate Boundary Layer" (flow conditions, expected results) and prepared a thorough description for this test case, the grid as well as inlet files. This information is gathered in [**4**].

ZDES (mode 3) calculations on TCF1 have been then conducted on the mandatory grid with an interface fixed at 0.125δ where δ is the local boundary layer thickness. Turbulence content is generated with the modified Synthetic Eddy Method adapted to ZDES. As shown in Figure 4, turbulent content is generated quickly downstream from the inlet. Another interface proposed by Renard & Deck [**5**] has also been assessed.

A first cross-plot and synthesis of results obtained by the different partners has been presented at the mid-term meeting held in Manchester on 23 and 24 October 2014.

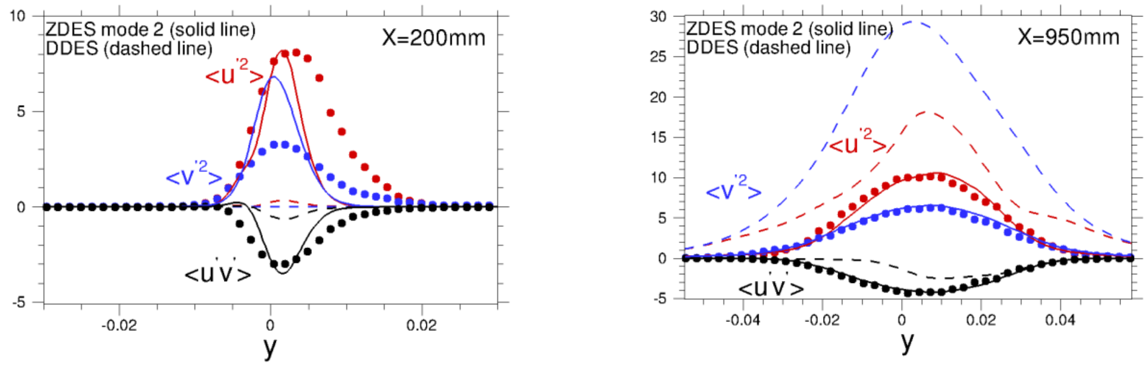

Figure 3 Comparison with experiment of Reynolds stresses obtained by DDES and ZDES mode 2

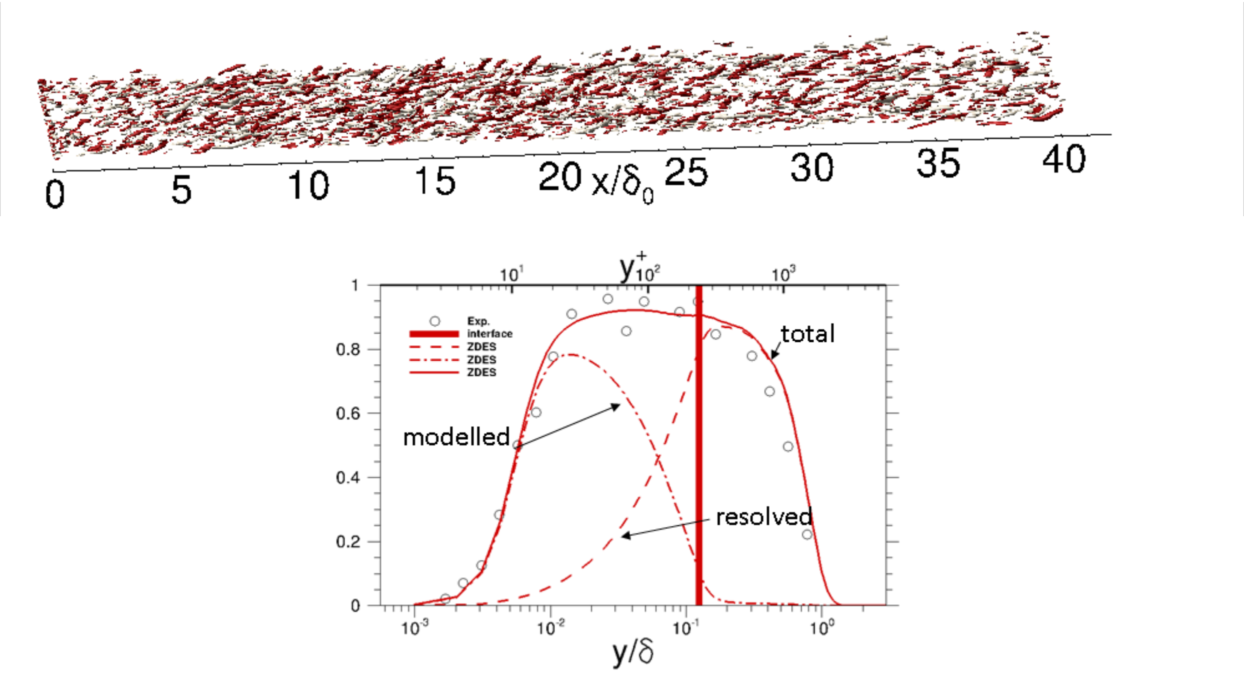

Figure 4 Top: Turbulent structures educed by the Q criterion. Bottom: Shear stress (resolved-modelled-total) profiles at Re_θ=5 200.

References

[1] S. Deck. Numerical simulation of transonic buffet over a supercritical airfoil. AIAA J. 43(7), 1556-1566, 2005.

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4.7 UniMAN

Summary

UniMAN have thus far focussed most of their effort on WP3.1, towards a generalisation of the synthetic eddy method, (SEM) [1], and the divergence free variant, DFSEM [2]. The obligations in WP1.2 have been met in setting up the website, and activities are underway in WP3.1/2 in the evaluation of various different methodologies. Work has now commenced on the Common Assessment Platform (CAP) WP4.1.

WP1.2: Website

The project website has been set-up and all partners/observers have been registered. User documentation has been prepared and all parts of the site are now being populated with results, meeting documents and progress reports.

WP3.1: Development of Embedded Methods

The bulk of the effort thus far has been concentrated in this task. The original formulations were not strictly valid for inhomogeneous eddy sizes or distributions. If the methods are employed under inhomogeneous conditions (as is typically the case), there are resulting errors in the reproduction of second order statistics. For example, see Figure 1. Here, the eddy lengthscale, σ, is set to vary according to the position that the eddy is injected as $\sigma = k^{3/2}/\mathcal{E}$, where k and $\mathcal{E}$ are taken from a pre-cursor RANS calculation of plane channel flow. For simplicity, the target stress is set to 1 everywhere. It can be seen that the resulting stress deviates significantly from the target in places.

This error arises as a result of the normalisation to account for the concentration of eddies. The value $\frac{N_e V_e}{V_b}$ (where N_e is the number of eddies, V_e is the volume of the eddies and Vb is the volume of the box in which the eddies reside) is used to normalise for this concentration. For inhomogeneous eddy situations, the actual concentration would be greater than would be realised from this simple analysis in regions where the non-local contributions of large eddies overlap smaller ones (and vice-versa for regions where contributions from small eddies “do not reach” the area of interest).

There are further motives for generalising the (DF)SEM beyond improved reproduction of the second order statistics. One significant issue of Lagrangian synthetic turbulence generators is that computational costs can be high if the number of eddies becomes excessive. Costs are of the order $O(N_f N_e)$, (where N_f is the number of faces comprising the inlet). In the original (DF)SEM, the number of eddies is chosen so as to achieve statistical coverage of the eddies. To be sure of global statistical coverage, the number of eddies used should be based on the volume of the smallest eddy, V_{e_small}, according to $N_e = \frac{V_b}{V_{e\_small}}$. Meanwhile, the volume of the box containing the eddies is related to the size of the largest eddies.

Where there is significant variation between large and small eddy sizes, the number of eddies can easily become excessive. Since the eddies are placed randomly (so as to maintain the uniform distribution that was required in the original (DF)SEM), the majority of eddies tend to be inactive on the inlet for most of their lives (small eddies in a large box), or tend to be contributing to a concentration that is much larger than strictly required by statistical coverage (larger eddies). This brute-force approach is wasteful.

In the generalised (DF)SEM, there is no need for an eddy box. Instead, eddies are generated 1σ upstream of the inlet, and convected through. This way, all eddies are active at all times, thereby significantly reducing the number of eddies required for statistical coverage (see Figure 2; Level of coverage on the inlet plane (red) is greater for the generalised formulation with the same number of eddies since all eddies are active at all times.). Furthermore, in the generalised (DF)SEM, eddies are introduced randomly, but with a bias towards regions where the concentration is locally low. This is achieved by generating a random number on the interval (0,1], which is then squared to give bias to lower values. When regenerating an eddy (after being convected 1σ downstream of the inlet), the eddy will only be accepted if the local lengthscale is below this randomly drawn value.

The generalised DFSEM has shown good development for plane channel flow. See, for example, Figure 3 in which the skin friction evolution for the original DFSEM is compared with the general formulation.

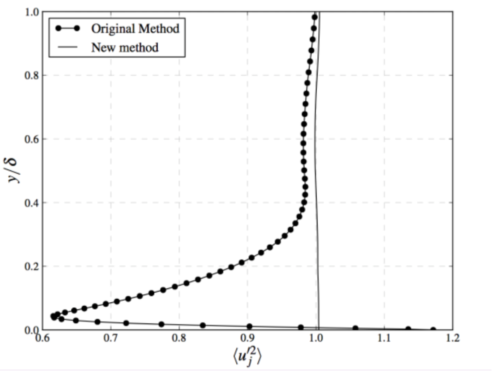

Figure 3 Resulting stresses for the original SEM and the generalised SEM.
Target stress is 1

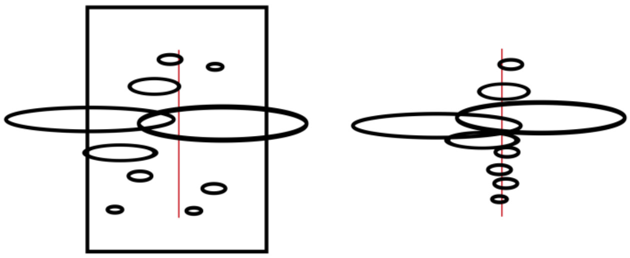

Figure 4 Eddy arrangement in original SEM (left) and generalised SEM (right)

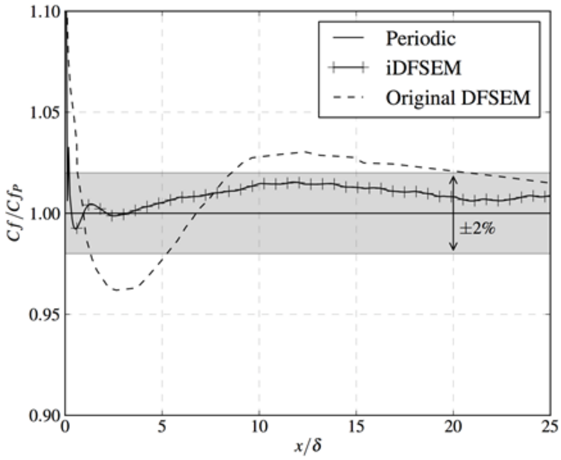

Figure 5 Development length in channel flow

WP2.2/3.2: Assessment of methods

Work has commenced on the assessment of embedded methods for the flat plate and the mixing layer, while DDES-type methods are being evaluated for the 3-element airfoil and the helicopter cases.

WP4.1: Common Assessment Platform

Our work in this task is now well underway after having completed a survey of all methods to be included in this platform.

Publications

Mockett, C., Fuchs, M., Garbaruk, A., Shur, M., Spalart, P, Strelets, M., Thiele, F., Travin, A. (2015). Two Non-Zonal Approaches to accelerate RANS to LES Transition of Free Shear Layers in DES. Accepted for publication in Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Springer.

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Probst, A., Garbaruk, A., Schwamborn, D., Shur, M., and Strelets, M., “Hybrid RANS/LES Simulations of Multi-Element Airfoil Stall Using Different Flow Solvers,” 6th European Conference on Computational Fluid Dynamics, Barcelona, 20-25 July, 2014.

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5 Exploitation activities

The research organisations taking part in Go4Hybrid will directly exploit the knowledge gained in the project by improving their tools for further use in other projects and at the same time contribute to the dissemination by providing these improved tools to their current and future partners in industry and academia.

The big "group of observers", Bombardier, GE, NUMECA, EDF, PSA, RRD, Saab, ANSYS and VW will have access to technical information and will be allowed to provide own results. Evidently, the observer group opens another important door to dissemination and even exploitation.

During run-time, a ***tenth observer was accepted by the consortium. This is EXA***, a company working in particular on Lattice Boltzmann approaches. Their interest goes beyond being a "passive" observer, they promised to work on a few test cases themselves and to provide openly their results for comparison with the consortium partners' results. This is a clear "added value" and will help to establish a better understanding f the EXA approach for the consortium as well as in turn improved knowledge for EXA with respect to handling of turbulence, extended wall models in PowerFLOW and improvements in accuracy and reduction of numerical dissipation.

In addition, there are two so-called "Associate Partners", CASSIDIAN and EUROCOPTER, who have provided test cases – but are not allowed to participate in technical meeting and don't have access to the technical outcome. They will solely receive a report with summarised results on their test case – and did not sign any cooperation agreement. Nevertheless they belong to the area for dissemination and exploitation although in a somewhat limited sense. Both "associated partners" were invited to the kick-off meeting in order get a more precise overview about the Go4Hybrid project. Unfortunately, only EUROCOPTER participated.

5.1 Links to other projects

5.1.1 A link to ERCOFTAC

As concerns further dissemination and, moreover, exploitation, UniMAN is hosting the ERCOFTAC database of test cases. It is foreseen by the Go4Hybrid consortium that a selection of most interesting test cases will be reviewed by the consortium at the end of the project and then added to the database which is freely accessible and frequently used by the CFD community, see www.ercoftac.org

5.1.2 A link to GARTEUR

Not yet decided, but discussed already, another link will/can be established with the GARTEUR Action Group AG54. The question arose whether the TC F1 test case set-up should be released to GARTEUR. The reason would be straightforward as the GARTEUR action group is almost identical with the Go4Hybrid consortium. Nevertheless, it was decided to wait for an official letter from GARTEUR, because such action is seen to be a clear exploitation issue. At time of writing such letter has not been sent by GARTEUR.

5.1.3 A link to other running EU Projects

It has been noted in the DoW that links to other EU projects should be established. The current status reads:

TFAST: This project is near to the final meeting, which means that no further help concerning grey area problems is likely needed. CFD work is quite advanced. However, at the time of writing (the draft) of this report we received the information that TFAST will be prolonged by one year.

Therefore, a direct contact was established via the coordinator, CFDB, in particular by Marian Fuchs, who presented Go4Hybrid at the TFAST meeting in Toulouse on 16-18 March 2015. The Go4Hybrid consortium agreed on an upload of the presentation file to the (private) TFAST Web site.

Go4Hybrid is making use of baseline results and a computational grid from the CleanSky project **HELIDES**, which was coordinated by CFDB with the role of Topic Manager played by the Go4Hybrid

Associate Partner Airbus Helicopters. From the exploitation of this synergy, the efficiency of the Go4Hybrid project is increased.

JERONIMO: Models going to be developed in Go4Hybrid will be applied to jet-wing interaction noise. Moreover, in the German LuFo-IV project, AEROSTRUCT, models will be implemented which will be derived in Go4Hybrid. One of the Go4Hybrid project observers, Rolls-Royce, is guiding this issue.

5.2 Publication of final results

A first discussion has been taken place at the 6-month meeting on final publication of results. It was not yet decided on a “final” procedure, however, the coordinator provided reasons for “keeping the final results together”. This means in turn that the consortium partners will try to write reports on test cases and methods in a way that can finally be integrated into a book – to be published by Springer in the NNFM series. Of course this provides the need to set up a structure for the book.

The main reason for such a book publication is exploit all results in a way which ensures the corporate identity of the project and to present it as a European initiative on collaborative effort on hybrid RANS-LES methods and approaches.

At the time of writing, Springer agreed on the publication of the Go4Hybrid results in the NNFM series in 2016.

5.3 The 5th Hybrid RANS-LES Conference

Go4Hybrid was the co-coordinator of the 5th conference/symposium on Hybrid RANS-LES Methods (HRLM-5, www.hrlm-symposium.org), that took place in College Station (near Houston), Texas, USA, from 19 to 21 March 2014. Coordinators are S. Peng, FOI, D. Schwamborn, DLR, and W. Haase, WHAC/CFDB. The fourth coordinator and at the same time the local organiser was Prof. Sharath Girimaji from A&M university.

All in all, 52 participants from 7 countries (Austria, China, France, Germany, Sweden, UK, USA) have registered with 44 presentations including 4 invited speakers (Basara (AVL), Hanjalic (Deft University and Novosibirsk State University), Spalart (Boeing), and Yakhot (Boston University)).

It should be mentioned that this conference was taking place rather early compared to the outcome of the Go4Hybrid project, however, however the project was presented by the technical coordinator of the project and accompanied by a few (early) papers with respect to work about hybrid RANS-LES modelling:

C. Mockett[1], W. Haase[2] and F. Thiele[1] ([1]CFD Software E+F GmbH, Germany; [2]WHAC, Germany) Go4Hybrid: A European initiative for improved hybrid RANS-LES modelling
N. Ashton and A. Revell (U. of Manchester, UK) Grey-area mitigation for the Ahmed car body using embedded DDES
C. Mockett[1], M. Fuchs[1], A. Garbaruk[2], M. Shur[2], P. Spalart[3], M. Strelets[2], F. Thiele[1] and A. Travin[3] ([1]CFD Software E+F GmbH, Germany; [2]NTS, Russia; [3]Boeing Commercial Airplanes, USA) Two non-zonal approaches to accelerate RANS to LES transition of free shear layer in DES
N. Renard and S. Deck (ONERA, France) On the interface positioning in a zonal detached eddy simulation (ZDES) of a spatially developing flat plate turbulent boundary layer

The conference, despite the big work effort (as usual higher than expected (!)), was and still is seen to be of utmost importance for the Go4Hybrid project as the conference offered a unique platform for technical discussions and an exchange of knowledge and expertise at the same time. The consortium considers the ***co-coordination of the conference being equivalent to a mid-term workshop,*** which was offered in the original DoW – see list of deliverable in the following chapter, too

The conference results, i.e. all papers (that have been reviewed before publication) will be published in a separate volume of Springer's NNFM book series – ***NNFM, Vol. 130, 2015***.

5.4 The final workshop and the 6th HRLM Symposium

Secondly, at the end of the Go4Hybrid project, a final *open workshop* was envisaged as part of the DoW - to offer again a much broader platform for technical discussions. This workshop has to take place at the end of September 2015, in conjunction with to the final meeting. It should allow for participation of external people interested in the field of hybrid RANS-LES methods and related modelling aspects.

However, there is one major drawback as far as the crowded meeting/conference schedules are concerned. The latter concerns the European Rotorcraft Forum (1-4 September 2014), the 5th CEAS Air- and Space Conference (7-11 September), the Turbulent Heat- ad Mass Transfer conference, THMT-15 (15-18 September) and - last but least - the DGLR Congress (22-24 September). Hence, at time of writing of this deliverable, the ***final workshop plus the final consortium meeting will take place in Berlin, hosted by CFDB in the last week of September, 28-30***).

The Go4Hybrid consortium offers in addition to join the ***6th Hybrid RANS-LES (HRLM) conference***, and present the results obtained in a separate session of this HRLM conference, as an added value with respect to the exploitation policy adopted for the project.

For additional information on the project's exploitation/dissemination policy, please refer to deliverable D1.2-12.

6 Meeting schedule

- The kick-off meeting took place ***in Berlin***, hosted by ***CFDB*** on 10/11 October 2013. It was attended by all partners, all observers and Eurocopter as one of the associate partners.
- The first consortium meeting took place in ***Stockholm***, hosted by ***FOI*** on 10/11 April 2014. It was attended by all partners and by the observers Saab, EDF, RRD, Bombardier and GE, as well as EXA.
- The third consortium meeting was held in ***Manchester***, hosted by ***UniMAN*** on 23/24 October 2014. It was attended by all partners, and the GE, ANSYS, EXA, EDF, SAAB and PSA.
- The fourth consortium meeting was held in ***Amsterdam***, hosted by ***NLR*** and took place ***on 19/20 March 2015***.
- The final meeting, together with the final workshop will be hosted by ***CFDB in Berlin*** on 28-30 September 2015. The workshop will take place from 28 (likely noon) until 29 (noon), followed by the final consortium meeting.

7 List of deliverables

The table to follow provides the list of deliverables as defined in the DoW. Those marked in green are available, those possibly marked in light red are not yet available (only in a draft version), all others to be issued later in the project are left unmarked.

Please note that according to the co-coordination of the 5th HRLM conference, see above, deliverables D1.2-15, D1.2-17 and D4.2-16 do not apply any more.

Deliverable Code [1]	Deliverable Title	Task no.	Responsible Partner (short name)	Nature[2]	Deliv. level [3]	Dissem. date[4]
D1.1-01	Provision of forms needed for monitoring the project	1.1	CFDB	R	CO	01
D1.1-13	Mid-term report	1.1	CFDB	R	CO	13
D1.1-18	18-months Management Report	1.1	CFDB	R	CO	18
D1.1-24a	Final technical report split into three parts: 1. General management issues, 2. description of methods and 3. TC related final presentations	1.1	CFDB & TC coordinators	R	CO	24
D1.1-24b	Publishable summary report	1.1	CFDB	R	PU	24
D1.1-24c	Final exploitation report	1.1	CFDB	R	PU	24
D1.2-01	Set-up of project Web site; report on use of Web site	1.2	UniMAN	R	CO	01
D1.2-03	Preliminary exploitation report describing means and procedures	1.2	CFDB	*R*	CO	03
D1.2-12	Revised version of D1.2-03	1.2	CFDB	R	CO	12
D1.2-15	15-month open workshop	1.2	CFDB	O	PU	15
D1.2-17	Report on workshop month 15	1.2	CFDB	R	CO	17
D1.2-24	Final open Workshop	1.2	CFDB	O	PU	24
D2.1-03	Report on the ***test case (F.2)*** including issues of result comparison (mandatory grids, output formats etc.)	2.1	FOI	R	CO	03
D2.1-06	Detailed (sufficient for implementation) formulation of different techniques applied to non-zonal methods and description of their incorporation into CFD codes – including output formats, mandatory grids, etc.	2.1	CFDB	R	CO	06
D2.1-12	Report on performance of GAM methods for non-zonal approaches on fundamental test cases	2.1	CFDB	R	CO	12
D2.1-15	Provision of methods for implementation into common assessment platform - and revised performance report	2.1	ALL WP2 Partners	R	CO	15
D2.2-10	Test case definitions available on Web site, including issues of result comparison, e.g. mandatory grids, output formats, etc.; no written report foreseen – connected with task 3.2	2.2	NLR	O	CO	10
D2.2-21	Preliminary report on performance of non-zonal methods on complex (I.x) test cases (report compiled from all partners involved); final version will be part of deliverable D1.1-24a	2.2	NLR	R	CO	21

D3.1-03	Report on the ***test case (F.1)*** including issues of result comparison (mandatory grids, output formats etc.)	3.1	ONERA	R	CO	03
D3.1-06	Detailed (sufficient for implementation) formulation of different techniques for generation of inflow turbulent content for Embedded methods and description of their incorporation into CFD codes	3.1	NTS	R	CO	06
D3.1-12	Report on performance of Embedded methods on fundamental test cases	3.1	NTS	R	CO	12
D3.1-15	Provision of methods for implementation into common assessment platform - and revised performance report	3.1	ALL WP3 Partners	R	CO	15
D3.2-10	Test case definitions available on Web site, including issues of result comparison, e.g. mandatory grids, output formats, etc.; no written report foreseen – connected with task 2.2	3.2	DLR	O	CO	10
D3.2-21	Preliminary report on performance of embedded methods on complex (I.x) test cases (report compiled from all partners involved); final version will be part of deliverable D1.1-24a	3.2	DLR	R	CO	21
D4.1-15	Report on status of implementation of GAM methods in use by partners (in dedication to workshop month 15)	4.1	UniMAN	R	CO	15
D4.1-22	Report on comparison of methods based on common code assessment platform	4.1	UniMAN	R	CO	22
D4.1-24	Revised final report on comparison of methods based on common code assessment platform	4.1	UniMAN	R	CO	24
D4.2-16	Brief report on Workshop month 15 and recommendations for final workshop (month 24) *– connected with Milestone M5*	4.2	FOI	R	CO	16
D4.2-18	Preliminary report on best practice	4.2	FOI	R	CO	18
D4.2-24	Final best practice report (in cooperation with all partners)	4.2	FOI	R	CO	24

1 Deliverable numbers ordered task wise. Last two digits, e.g. D1.1-**13**, define the date of delivery.
2 Nature of the deliverable:
R = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other
3 Dissemination level:
PU = Public; **PP** = Restricted to other programme participants (including the Commission Services); **RE** = Restricted to a group specified by the consortium (including the Commission Services); **CO** = Confidential, only for members of the consortium (including the Commission Services).
4 Measured in months from the project start date (month 1).

8 List of Milestones

The table to follow provides the list of deliverables as defined in the DoW. Those marked in green are available, those possibly marked in light red are not yet available (or only in a draft version), any others to be issued later in the project are left unmarked. All deliverables in Milestone M5 that are related to the mid-term workshop and its equivalent, the co-coordination of the 5th HRLM conference, are marked as green, i.e. “fulfilled”.

Milestone no. / Name	WPs/Tasks involved	Expected Date [month][1]	Means of verification / Title
M1	1.1 1.2 1.2	01 01 03	Provision of management means (D1.1-01) Set-up of project Web site; report on use of Web site (D.1.2-01) Preliminary exploitation procedure (D1.2-03)
M2	2.1 3.1	06 06	Detailed formulation of different techniques for non-zonal approaches (D2.1-06) Detailed formulation of different techniques for embedded approaches (D3.1-06)
M3	---	---	Not needed, hence not set
M4	1.1 1.2	13 12	Mid-term assessment report (D1.1-13) Revised version of exploitation report (D1.2-12)
M5	1.2 2.1 2.2 3.1 3.2 4.1 4.2	15 15 15 15 15 15 16	15-month open workshop (D.1.2-15) Provision of methods for implementation into common assessment platform (D2.1-15) Workshop month 15: Presentation of test cases from task 2.2 and first preliminary results (no specific deliverable needed, just collection of data) Provision of methods for implementation into common assessment platform (D3.1-15) Workshop month 15: Presentation of test cases from task 3.2 and first preliminary results (no specific deliverable needed, just collection of data) Short list of final candidate approaches for common assessment platform (D4.1-15) Workshop month 15 organised and successfully held (connected to D4.2-16) to be issued after the workshop) (D4.2-16)
M6	4.2	18	Preliminary report on best practice (D4.2-18)
M7	2.2 3.2 4.1	21 21 22	First report on performance on non-zonal methods on complex (I.x) test cases (D2.2-21) First report on performance on embedded methods on complex (I.x) test cases (D3.2-21) Completion of implementation and testing of candidate approaches (D.4.1-22)
M8	1.1 1.2 2.2 3.2 4.1 4.2	24 24 24 24 24 24	Final Reporting (D1.1-24a, D1.1-24b, D1.1-24c) Final report on exploitation and feedback from open workshop on Go4Hybrid outcome (D1.2-24) Workshop month 24: Presentation of final results from all task 2.2 test cases and their assessment (connected to D1.1-24a) Workshop month 24: Presentation of final results from all task 3.2 test cases and their assessment (connected to D1.1-24a) Revised final report on comparison of methods (D4.1-24) Best practice guidelines report available (D4.2-24)

1 Measured in months from the project start date (month 1).

9 Observers' Forum – selected at mid-term meeting

9.1 GE

GE is very much impressed by the quality of the work and the progress realized. Improved methodologies contributed to mitigate the grey areas of the RANS-LES transition, which was clearly demonstrated with the fundamental test cases. We appreciate the fact that both zonal and non-zonal methods are being investigated, so that their relative strengths and weaknesses can be compared.

We look forward to seeing how the selected models will perform on the Common Assessment Platform, which will be an important element to define some best practices. As a tighter collaboration will be required in the final half of the project.

GE would encourage all the partners to have regular updates via virtual meetings (teleconferences, etc.)

9.2 ANSYS

Overall Impression

I took with me a very favorable impression of the project. The consortium is well balanced, the subject area is well defined and of high relevance and the contributors are very active in their respective areas. I also had the impression that the discussions within the team are constructive and there is a fair discussion of overall merits and potential shortcomings of the different methods (in that respect, the consortium seems more open than in some previous RANS based projects).

Many of my comments results from my position in the CFD software industry. They are motivated by avoiding a proliferation of models, as such proliferation has very severe downsides/cost:

- Cost of understanding the models in detail
- Cost of implementation
- Cost of providing user documentation and user guidance
- Cost of updating the model to newer versions (including going through the above steps again)
- Cost of training support staff so that they can provide guidance to their users
- Confusion in the user community
- Difficulty in comparing different simulations

Specific Comments

By the very nature of the project, there are different groups with a range of different/competing methods both in the area of hybrid models as well as synthetic turbulence generation. This is fine, and in a way also a motivation to succeed.

For a non-expert, I am afraid it is very difficult to discern the pros and cons of the different approaches as well as their level of maturity and generality. Our 'general-purpose' CFD users are already fairly confused by the different already existing forms of the DES family of models (DES, DDES, IDDES). In addition, the consortium works on PANS as well as zonal formulations, where the user needs to interact with the definition of the RANS and LES zones. It will therefore by very important (as well as difficult) to provide a readable and overarching documentation of the different approaches, beyond the typical 'developer' publications which typically concentrate only on the merits of the approach.

From an industrial CFD perspective, I would see the DDES model (not IDDES) as the industrial standard. This is the hybrid model, most widely used in industrial/commercial CFD. It would therefore be desirable, if all methods in the project would be described in relation to at least this formulation. This would require giving the pros- and cons of each approach relative to DDES at least. In a way, any challenger needs to be superior (or at least offer elements of superiority) to the reigning champion for justifying its existence (at least from an industrial standpoint). I would also like to see for model developments like the new version of DDES coming from this project a clear statement like 'This formulation supersedes the existing DDES formulations and should replace the current DES, DDES and IDDES versions in industrial CFD codes'.

Another example in need of discussion relative to DDES is PANS. My impression from the meeting is that PANS seems to more and more converge towards DDES by:

- Including the grid spacing (or ratio Lt/Delta) into the formulation to switch between RANS and 'LES'
- The need for shielding once this ratio is introduced

The remaining difference between PANS and DDES is therefore only in the 'LES' formulation, which is not based on conventional LES models, but maintains a RANS-like formulation. However, in that form (fk ne 1) the RANS model does not retain any of its calibrated properties. I am somewhat skeptical that PANS-LES for a given time and space resolution is generally superior to a conventional LES model. This would really need to be demonstrated, both for the RANS-LES transition as well as for LES stand-alone for a range of test cases. Of course this is an industrial comment – the justification can also be given from an academic perspective (e.g. PANS has a more mathematical foundation and therefore warrants further development …), but then it would be desirable to also state the current development status relative to DDES.

There are other items to be considered for cross-comparison/documentation, e.g. that any model using disturbance inside the domain will have to be treated with caution when applied to acoustics simulations, … finally, it needs to be stressed that zonal formulations, or formulations needing very specific flow dependent information or non-local operations, are much less attractive than global models (there is a clear need for 'global' and 'zonal' method, but this distinction needs to be stressed).

As proposed at the meeting, the current consortium has the critical mass to define 'standards' for the evaluation of hybrid RANS-LES methods. In a first step one should probably distinguish between 'zonal' and 'global'. As 'global' is obviously much harder to formulate than 'zonal', it might be sufficient to then concentrate on the 'global' formulations. I could anticipate a nice publication 'Categorization and Evaluation Procedures for Hybrid RANS-LES Turbulence Models'. As stressed at the meeting, the emphasis has to be divided equally between 'proper' shielding as well as RANS-LES transition fidelity. Especially on the shielding side, formalized procedures would help the developers to understand the requirements, and the end-users to assess the safety of these models. Shielding evluation should include adverse pressure gradient flows, not only flat plates. It should also be kept in mind that 'shielding' has mostly been based on argumenst for aeronautics-type flows, where certain assumptions about sensible streamwise-normal-spanwise grid resolution can be made. In general flows (the majority of flows where DDES is applied) this is much less obvious.

Summary

This is a very good project. Success will crucially depend on ability of the consortium to provide an overarching documentation.

9.3 EXA

General Overview

New zonal and embedded hybrid RANS/LES methods have been presented and tested on fundamental test cases (Boundary Layer & Shear layer) and to a lesser extent on complex test cases (Helicopter, Delta-Wing, 3-Element Airfoil, 2D Hump, Jet).

Concerning the shear layer, improved results have been achieved using the Delta_Omega length scale as a DES input because it detects the two-dimensionality of turbulence which can be resolved on stretched grids. A new model by Kok (NLR) gave satisfying results, even on a very coarse grid. Concerning the flat plate boundary layer, different zonal methods have been introduced based on synthetic eddy methods. The resulting wall-modelled LES achieves good results concerning skin friction and recovery length of the boundary layer after injecting turbulence (< 10 delta_0). Concerning the complex test cases, few results have been presented so far. Most successful simulations were shown for the zonal formulation of NTS for the 2D-Hump and the jet.

Technical Comments and Recommendations

The current status of the project is very satisfying. A lot of improvement has been shown for the fundamental test cases after only one year. It is now important to finalize the turbulence model development and to move on to the industrial test cases during the second year of the project. So far the work has been achieved rather independently by each partner. I would encourage more exchange between the partners for the industrial cases.

During the course of presentations it became obvious that some partners have issues with the underlying code. It remains hard to distinguish what is the influence of the turbulence model and what can be attributed to each solver's numerics. The idea of the "Common Assessment Platform" is therefore very helpful if the quality of the new approaches is to be assessed independently from the underlying solver. The work to be done is ambitious but great added value can be expected.

The shear layer test case is crucial for many real world applications. Since the mandatory grid has a zero-thickness flat plate, the focus lies solely on the shear layer instabilities. This is legitimate but the finite thickness of the flat plate plays an important role as well. If we consider the Reynolds number based on the trailing edge thickness and a characteristic velocity equal to (U_a+U_b)/2, a vortex shedding should be expected. However, none of the partners' simulation were able to show this flow feature identified in experiments. Therefore, the recommendation was given by Exa to investigate the influence of the flat plate thickness by the partners.

For each test case a mandatory mesh has been provided by the test case owner. The owner most likely has a lot of experience with his test case and therefore knows how a suitable mesh should look like. This is often not the case in an industrial context. I therefore encourage reporting an a posteriori criterion like the ratio of resolved to total kinetic energy for all cases and subsequently establishing some kind of best practices from the results of this project. Even if this ratio is not always sufficient to judge mesh quality, it will definitely help industrial users.

This finally ties up to the proposed book: The best practices and expertise of each partner should be summarized for the individual test case. There should be some kind of recommendation for future users explaining the weaknesses and strengths of the new models/approaches.

Summary

This is an important project to pave the way for high fidelity unsteady CFD methods towards industrial usage. The progress so far is very good with open discussions among the partners. The overall success will rely on a good documentation of guidelines and lessons learned as well as on applying the new methods to the complex test cases.

9.4 EDF

The objective of Go4Hybrid project program is clear; dealing with the grey area between RANS and LES approaches. The topic is very hot and challenging and needs tremendous efforts (18 months are not sufficient of course to deal with the present topic).

The steps followed to reach the objective, at least for the two academic cases, are scientifically speaking relevant. Although the approaches differs from a participant to another (DES, PANS, ...), (SEM, new STG, ...), the work done is of high quality. There is perhaps a need to reduce the number of models (and acronyms!). For one of two academic cases, CFDB and NTS seem to use almost the same method but obtain totally different results. The observer can't believe that only the higher order numerical scheme used by NTS explains such differences! This has to be clarified.

The project is somewhat innovative but rather for LES approaches (Delta_omega formulations by ONERA and NTS) than for RANS. This is surprising as the reviewer felt at the beginning that the project was rather a RANS oriented one. This is a very good thing for an industrial researcher like the observed who chose to keep the two approaches (RANS and LES) separately as an option, depending on the industrial configuration. Some of the LES outcomes of the present project, if published, could be used in other industries, such as nuclear or by industrial, open-source or commercial CFD codes. The target group is clearly the aeronautic industry but the present work can have outcomes in other industrial fields.

The symposium (5th HRLM) co-organized by some of the participants is to the observer opinion one of the best ways to evaluate/demonstrate their knowledge of the international state-of-the-art and to disseminate the findings. There will be also probably high quality journal communications at the end of the project.

The observer wonders whether there will be enough time to deal with the proposed industrial test-cases by the end of the project (at least with the same quality performed for the academic test-cases).

9.5 SAAB

Overall impression

The consortium has had a good progress during the first half of the project. Many interesting and promising ideas have been developed and explored so far. Furthermore, the collaboration between the consortium partners seems to work out very well. Ideas are exchanged between the partners and fruitful discussions seem to take place also outside the official project meetings, which is very much appreciated.

For a project as Go4Hybrid where a very specific problem (Grey-Area Mitigation, GAM) is studied, the concept of a small core team of partners seems to be advantageous as compared to e.g. the ATAAC project where many more partners were involved. However, with a small core team, it is important to have a wide range of observers from industry, which the project has, in order to get feedback and to be able to disseminate the project achievements and conclusions.

Specific comments

Many different GAM methods have been proposed by the project partners. Moreover, the GAM ideas are implemented into different simulation frameworks such as DDES, IDDES, ZDES, PANS etc. From an academic and research point of view it is important to explore these GAM methods in different frameworks in order to know their versatility. However, for industry it is important that the consortium at the end of the project delivers one or at most a few common methods which are concluded to be the best and most applicable to industrial applications.

For industry both non-zonal and zonal approaches applies and is therefore encouraged. The non-zonal approaches must be of such a kind that the GAM methods developed in this project are effective but the simulation approaches must at the same time keep the boundary layers safe with respect MSD/GIS. The zonal approaches are advantageous since one can specify zones of URANS, LES, DES/DDES/IDDES, etc. and therefore concentrate the computational effort where it is most needed. From an industrial perspective, the zonal approaches should, if possible, not trust in prescribed wall-parallel RANS-LES switches or other prescribed turbulent quantities at the RANS-LES interfaces which heavily loads the users and can contribute to large error sources in the turbulence resolving flow.

Many GAM approaches use synthetic turbulent fluctuations on the RANS-LES interface. It is important that the consortium highlights the effect of these added fluctuations on e.g. aero-acoustic analysis. Moreover, it is important that the project communicates guidelines and recommendations for how to use these approaches and which approaches that are recommended for industrial applications.

Expectations at the end of the project

The various GAM methods presented at the mid-term meeting should have been further explored and tested on the advanced test cases included in the project. It is expected that the consortium presents thorough comparisons of the different GAM methods developed in the project and clearly highlights the pros and cons of these methods. Moreover, recommendations of a few GAM approaches with respect to robustness and accuracy for industrial applications are very important.

The work presented on the mid-term meeting by the partners was made using different solvers with different numerical schemes. Therefore, the work package dedicated to the common assessment platform (CAP, in this case OpenFOAM) is of high importance and a key factor for a project success since this is the only way the community can be able to compare the different GAM methods using the same platform.

The GAM methods developed and recommended by the consortium should be well documented and described in a way so that industry can implement and use the methods in their own flow solvers. The documentation should also include the comparisons made in CAP to give a clear view on the differences between the chosen GAM methods. Since many industrial flow solvers use second order numerical schemes, it is expected that results presented for the recommended GAM methods in the final project report also use second order schemes as a comparison to the higher order numerical schemes used by many of the Go4Hybrid partners. Moreover, it is important that the numerical schemes used in CAP and in the project partners' flow solvers are presented together with the results in the final project report.

9.6 PSA

According to our latest Go4Hybrid meeting, significant results were shown to confirm the relevance of the project on an industrial point-of-view. Particularly, the comparison of different turbulence models for the same test case represents a real improvement in the hybrid models development for an industrial request. However for an application of flow computation around a complete vehicle, it is essential not only to compare different models on the same test case but also to compare the same models on different tests cases. Indeed, the simulation of the flow around the car is an accumulation of different flow components: mixing layer type for the interaction between the underbody flow and the wake, vortices generation at the rear top of the car, etc.

This is the reason why, for PSA Peugeot-Citroën interest, we recommend to confront each of the most promising models with different test cases in order to validate not only successful models but also models with the best compromise for the consideration of different types of flows.

10 Quarterly Progress Report

In the following please find the summary of the quarterly progress reports per 6th quarter, hence the sheet exhibits the status of man-months per partner and per task at the end of month 18.

It has to be noted that the partner ***NTS*** has already used the man-months allocated, and is continuing work on own funds; see total values given in the last matrix.

Go4Hybrid

WORK SUMMARY - RISK MONITORING
According to Quarterly Progress Reports
QPR 01 - QPR 06
1 October 2013 to 31 March 2015

The table is considered to be (more or less) self-explanatory. However, a few remarks might be necessary:

1. All given figures are in **person-months**.
2. In the second column, "A" stands for "Actual" man-days used in the relevant quarter,
   "P" stands for the "Planned" effort in the relevant quarter, again in man-months.
3. The "Actual" figures are given per quarter and they are summed up per year and - in the last column - for the whole project working period.
4. The "Planned" man-days are specified according to the original values provided in the Technical Annex where they had been given as man-months per quarter.
5. Task-wise highlighted, written in Italic and underlined, partners are responsible for coordinating the corresponding task.
6. M1 to M6 are abbreviations for the Milestones defined in the Technical Annex.
7. The last page provides the total working days per partner - actual and planned
8. Coloring of the table has the following meaning:

Action item reached/fulfilled	(green)
Work on action item has started	(orange)
Action item not yet started	(pink)
Work load changes requested	(cyan)
Active period of task	(light cyan)

Task 1.1	Coordination of the project															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES	M1				M4						M8					
CFDB	0,25	0,20	0,45	0,15	0,15	0,30	0,25	0,25	0,50			0,00	1,25	3,00	1,75	
NTS	0,05	0,05	0,10	0,05	0,05	0,10	0,02	0,01	0,03			0,00	0,23	0,25	0,02	
DLR	0,05	0,00	0,05	0,00	0,05	0,05	0,00	0,00	0,00				0,10	0,25	0,15	
FOI	0,05	0,00	0,05	0,05	0,00	0,05	0,05	0,00	0,05				0,15	0,25	0,10	
NLR	0,06	0,00	0,06	0,06	0,00	0,06	0,06	0,06	0,12				0,24	0,25	0,01	
ONERA	0,00	0,05	0,05	0,00	0,00	0,00	0,00	0,05	0,05				0,10	0,25	0,15	
UniMAN	0,05	0,05	0,10	0,00	0,05	0,05	0,00	0,00	0,00			0,00	0,15	0,25	0,10	
TOTAL	0,51	0,35	0,86	0,31	0,30	0,61	0,38	0,37	0,75	0,00	0,00	0,00	2,22	4,50	2,28	

Task 1.2	Web site / Dissemination / Exploitation															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES	M1				M4						M8					
CFDB	0,10	0,40	0,50	0,10	0,25	0,35	0,25	0,15	0,40			0,00	1,25	1,00	-0,25	
NTS	0,00	0,15	0,15	0,05	0,00	0,05	0,00	0,00	0,00			0,00	0,20	0,25	0,05	
DLR	0,00	0,00	0,00	0,00	0,15	0,15	0,15	0,00	0,15			0,00	0,30	0,25	-0,05	
FOI	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,05	0,05			0,00	0,05	0,25	0,20	
NLR	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			0,00	0,00	0,25	0,25	
ONERA	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00			0,00	0,00	0,25	0,25	
UniMAN	0,80	0,40	1,20	0,10	0,05	0,15	0,10	0,05	0,15			0,00	1,50	1,50	0,00	
TOTAL	0,90	0,95	1,85	0,25	0,45	0,70	0,50	0,25	0,75	0,00	0,00	0,00	3,30	3,75	0,45	

Task 2.1	Non-zonal Methods: Development and evaluation for mandatory fundamental test cases															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES		M2					M5									
CFDB	0,65	2,00	2,65	1,50	0,50	2,00	0,10	0,25	0,35				5,00	4,50	-0,50	
NTS	1,50	0,50	2,00	0,00	2,00	2,00	0,50	0,50	1,00				5,00	3,00	-2,00	
FOI	0,45	0,75	1,20	0,50	0,50	1,00	2,00	0,80	2,80				5,00	6,00	1,00	
NLR	0,43	0,69	1,12	1,25	0,70	1,95	0,00	0,00	0,00				3,07	3,00	-0,07	
ONERA	0,00	0,25	0,25	0,75	0,75	1,50	1,00	0,20	1,20				2,95	3,00	0,05	
TOTAL	3,03	4,19	7,22	4,00	4,45	8,45	3,60		5,35				21,02	19,50	-1,52	

Task 2.2	Non-zonal Methods: Demonstration of improvements based on complex test cases															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES							M5				M8					
CFDB				0,50	1,25	1,75	0,20	0,80	1,00			0,00	2,75	3,00	0,25	
NTS		1,20	1,20		1,30	1,30	1,50	1,30	2,80			0,00	5,30	0,00	-5,30	
FOI					0,00	0,00	0,05	2,05	2,10			0,00	2,10	4,00	1,90	
NLR					0,50	0,50	1,50	1,10	2,60			0,00	3,10	4,00	0,90	
TOTAL		1,20	1,20	0,50	3,05	3,55	3,25	5,25	8,50	0,00	0,00	0,00	13,25	11,00	-2,25	

Task 3.1	Embedded Methods: Development and evaluation for mandatory fundamental test cases															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES		M2					M5									
NTS	1,50	1,00	2,50	2,00	0,20	2,20	0,00	1,00	1,00				5,70	6,00	0,30	
DLR	0,25	1,50	1,75	1,50	2,00	3,50	1,25	0,75	2,00				7,25	7,50	0,25	
ONERA	0,50	1,50	2,00	0,50	1,00	1,50	0,50	0,50	1,00				4,50	5,00	0,50	
UniMAN	0,20	1,00	1,20	1,00	0,50	1,50	1,00	0,10	1,10				3,80	6,00	2,20	
TOTAL	2,45	5,00	7,45	5,00	3,70	8,70	2,75	2,35	5,10				21,25	24,50	3,25	

Task 3.2	Embedded Methods: Demonstration of improvements based on complex test cases															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES							M5				M8					
NTS	1,00		1,00	2,00	0,00	2,00	0,00	0,00	0,00			0,00	3,00	8,00	5,00	
DLR				0,25	0,25	0,50	0,75	1,25	2,00			0,00	2,50	5,00	2,50	
ONERA				0,50	0,00	0,50	0,50	1,25	1,75			0,00	2,25	5,00	2,75	
UniMAN				0,10	0,10	0,20	0,10	0,20	0,30			0,00	0,50	2,00	1,50	
TOTAL	1,00		1,00	2,85	0,35	3,20	1,35	2,70	4,05	0,00	0,00	0,00	8,25	20,00	11,75	

Task 4.1	Common Assessment Platform															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES							M5			M7						
CFDB					0,25	0,25	0,40	1,00	1,40			0,00	1,65	3,00	1,35	
UniMAN					0,25	0,25	0,60	2,40	3,00			0,00	3,25	2,50	-0,75	
TOTAL					0,50	0,50	1,00	3,40	4,40	0,00	0,00	0,00	4,90	5,50	0,60	

Task 4.2	Best-practice, knowledge preservation, and workshop preparation															
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
MILESTONES							M5	M6			M8					
CFDB							0,10	0,25	0,35			0,00	0,35	1,50	1,15	
NTS							0,00	0,00	0,00			0,00	0,00	0,50	0,50	
DLR							0,00	0,00	0,00			0,00	0,00	1,00	1,00	
FOI							0,00	0,00	0,00			0,00	0,00	0,50	0,50	
NLR							0,00	0,00	0,00			0,00	0,00	0,50	0,50	
ONERA							0,00	0,00	0,00			0,00	0,00	0,50	0,50	
UniMAN							0,00	0,00	0,00			0,00	0,00	1,00	1,00	
TOTAL							0,10	0,25	0,35	0,00	0,00	0,00	0,35	5,50	5,15	

TOTAL																
Quarter	1	2	1/2Y	3	4	1Y	5	6	3/2Y	7	8	2Y	Used Total	Planned	Rest	Remarks
CFDB	1,00	2,60	3,60	2,25	2,40	4,65	1,30	2,70	4,00	0,00	0,00	0,00	12,25	16,00	3,75	
NTS	4,05	2,90	6,95	4,10	3,55	7,65	2,02	2,81	4,83	0,00	0,00	0,00	19,43	18,00	-1,43	
DLR	0,30	1,50	1,80	1,75	2,45	4,20	2,15	2,00	4,15	0,00	0,00	0,00	10,15	14,00	3,85	
FOI	0,50	0,75	1,25	0,55	0,50	1,05	2,10	2,90	5,00	0,00	0,00	0,00	7,30	11,00	3,70	
NLR	0,49	0,69	1,18	1,31	1,20	2,51	1,56	1,16	2,72	0,00	0,00	0,00	6,41	8,00	1,59	
ONERA	0,50	1,80	2,30	1,75	1,75	3,50	2,00	2,00	4,00	0,00	0,00	0,00	9,80	14,00	4,20	
UniMAN	1,05	1,45	2,50	1,20	0,95	2,15	1,80	2,75	4,55	0,00	0,00	0,00	9,20	13,25	4,05	
TOTAL	7,89	11,69	19,58	12,91	12,80	25,71	12,93	14,57	29,25	0,00	0,00	0,00	74,54	94,25	19,71	