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Preliminary report on best practice

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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 and Volkswagen AG as observers.

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The opinions, findings and conclusions expressed in this report are those of all partners, and do not necessarily reflect those of the European Commission.

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2 Introduction

In the Go4Hybrid project a first attempt has been made to address the key remaining problem facing hybrid RANS-LES methods, namely the Grey Area problem. Go4Hybrid is a pioneering project, in which novel methods are formulated and evaluated. Although promising initial results have been achieved, the inherent complexity of the problem and the short (2 year) project duration mean that definitive closure of the issue cannot be expected. This pioneering nature of Go4Hybrid is in contrast to "consolidation" projects concerned with more mature methods, such as the precursor project ATAAC.

As such, concrete best practice guidelines cannot be expected in relation to the Go4Hybrid methods. Nonetheless, this document aims to extract the state-of-art experiences gained by the contributing project partners and observers in terms of overall findings, lessons learned and initial best practice.

In Section 2, the overall findings of the project will be drawn together: an overview of the methods applied to each test case is given, followed by an evaluation of the strengths and weaknesses of each method observed in the studied test cases. In Section 3, lessons learned and best practice findings are reported. The document concludes with an assessment of direction and needs of future research.

The current deliverable D4.2-18 represents a preliminary status, to be updated and finalised in the deliverable D4.2-24. Hence, open questions and considerations are kept in red text in this deliverable for convenience.

3 Summary of findings from project

3.1 Application of GAM methods to test cases

In the following two subsections the application of non-zonal GAM and embedded approaches are reported, respectively.

Acronyms are used and the reader is referred to D2.1-06 for detailed descriptions of the non-zonal formulations and to D3.1-06 for the embedded approaches.

3.1.1 Non-zonal methods

The application of different non-zonal GAM approaches to the Go4Hybrid test cases are summarised in Table 1.

The following preliminary remarks can be made:

- All GAM methods have been tested on the mandatory shear layer case (F2)
- The most simulated complex case is the round jet (I5), with 8 simulations using GAM techniques and 2 reference simulations
- The delta wing (I2), 3-element airfoil (I3) and 2D hump (I4) have also been extensively tested, however the only one simulation with GAM approaches has been carried out on the helicopter fuselage case (I1)
- The most widely-tested GAM strategies are Δ_{SLA} and $\sigma + \widetilde{\Delta}_{\omega}$ (4 cases each), followed by HPF + stoch. BS and WALE $+\widetilde{\Delta}_{\omega}$ (3 cases each)
- Excluding the common assessment platform, four approaches have been implemented in two different codes, indicating strong collaboration between the partners. The approaches in question are WALE $+\widetilde{\Delta}_{\omega}$ (CFDB and NTS[1]) and σ (CFDB and NLR[2]) as well as the two vorticity-adaptive filter widths $\widetilde{\Delta}_{\omega}$ (CFDB and NTS) and Δ_{ω} (DLR and ONERA).

Table 1: Application of non-zonal methods to test cases in Go4Hybrid

Partner	Underlying HRLM	Code	Non-zonal GAM approach	F1 Flat plate	F2 Shear layer	I1 Helicopter fuselage	I2 Delta wing	I3 3-element airfoil	I4 2D hump	I5 Round jet
			Σ =	0	19	4	6	8	6	10
FOI	HYB0	Edge	-		●				●	
FOI	HYB0	Edge	-		●			●		
Exa	RKE-proprietary	PowerFLOW	-		●	●				
CFDB	SA-DDES	OpenFOAM	-		●		●			●
NTS	SA-DDES	NTS	-					●	●	●
ONERA	SA-DDES	FLU3M	-		●					
UniMan	SA-DDES	Star-CCM+	-			●				
NTS	SA-IDDES	NTS	-					●	●	
CFDB	SST-DDES	OpenFOAM	-			●				
NLR	SST-DDES	ENSOLV	-				●			
DLR	SST-IDDES	TAU	-					●		
NTS	SST-IDDES	NTS	-					●		
NLR	DX-LES	ENSOLV	HPF		●		●			
NLR	DX-LES	ENSOLV	HPF + Stoch. BS		●		●			●
FOI	HYB0	Edge	Leonard BS		●					
CFDB	SA-DDES	OpenFOAM	WALE		●					●
CFDB	SA-DDES	OpenFOAM	WALE + Δ_ω~		●		●			●
NTS	SA-DDES	NTS	WALE + Δ_ω~							●
FOI	HYB0	Edge	Δ-based		●				●	
FOI	HYB0	Edge	Δ_{min}		●					
FOI	HYB0	Edge	Δ_{min} + Leonard BS		●			●		
NTS	SA-DDES	NTS	Δ_{SLA}		●			●	●	●
NTS	SA-IDDES	NTS	Δ_{SLA}					●		
DLR	SST-IDDES	TAU	Δ_ω						●	
ONERA	ZDES-M2	FLU3M	Δ_ω		●					
CFDB	SA-DDES	OpenFOAM	Δ_ω~		●					●
NLR	DX-LES	ENSOLV	σ		●					
CFDB	SA-DDES	OpenFOAM	σ		●					●
CFDB	SA-DDES	OpenFOAM	σ + Δ_ω~		●		●			●
CFDB	SST-DDES	OpenFOAM	σ + Δ_ω~			●				

3.1.2 Embedded approaches

In Go4Hybrid, predominantly RANS-to-LES interface conditions have been studied in the framework of embedded approaches. The embedded approaches are hence chiefly characterised by the choice of method applied to impose resolved turbulent fluctuations at the inlet to the scale-resolving region. The application of embedded approaches to the Go4Hybrid test cases is summarised in Table 2.

The following preliminary remarks can be made:

- All partners chose methods that can be categorised as synthetic turbulence approaches (as opposed to e.g. recycling/rescaling or database approaches)
- All synthetic turbulence generating methods were tested on the mandatory flat plate test case (F1)
- The test cases most studied with embedded approaches are the 3-element airfoil (I3) and the 2D hump (I4)
- Variants of the SEM are the most widespread approach, having been tested by 3 different partners (DLR, ONERA and UniMan)
- Imposition of fluctuations over a volume rather than a plane has been a widely pursued approach, tested by all partners involved in WP3

Table 2: Application of embedded approaches to test cases in Go4Hybrid

Partner	Underlying HRLM	Code	Turbulent fluct.	F1 Flat plate	F2 Shear layer	I1 Helicopter fuselage	I2 Delta wing	I3 3-element airfoil	I4 2D hump	I5 Round jet
			Σ =	5	1	0	0	4	3	0
DLR	SST-IDDES	TAU	-					●		
ONERA	ZDES-M0	FLU3M	-					●		
ONERA	ZDES-M3	FLU3M	DF					●		
ONERA	ZDES-M3	FLU3M	DF + WN					●		
ONERA	ZDES-M3	FLU3M	Mod. SEM (Pamiès)	●						
UniMan	SA-IDDES	OpenFOAM	DFSEM	●						
DLR	SA-IDDES	TAU	SEM (VF)	●					●	
DLR	SST-IDDES	TAU	SEM (VF)						●	
NTS	SA-IDDES	NTS	STG	●	●					
NTS	SST-IDDES	NTS	STG						●	
NTS	SST-IDDES	NTS	VSTG	●						

3.2 Review of methods

3.2.1 Non-zonal methods

3.2.1.1 Short description of the different approaches

- Δ_ω: ONERA, relax grid dependency in the direction of vorticity. Reduces to $\sqrt{\Delta_x \Delta_y}$ with vortices in z-direction.
- $\widetilde{\Delta}_\omega$:NTS, modification of Δ_ω to reduce influence of smallest grid size. Will approximately give $\max(\Delta_x, \Delta_y)$.
- Δ_{SLA}: NTS, further reduction of $\widetilde{\Delta}_\omega$ based on a "Kelvin-Helmholtz sensor" for detection of quasi 2D regions
- $\Delta_{\min}$: FOI, length scale based on minimum grid size $\min(\Delta_x, \Delta_y, \Delta_z)$
- σ: CFDB, sigma model reduces ν_{SGS} in 2D plane shear based on the eigenvalues of the resolved strain rate.
- HPF: NLR, high-pass filtered SGS model
- HPF + Stoch. BS: NLR, added stochastic backscatter to HPF
- Leonard BS: FOI, backscatter based on the Leonard term

3.2.1.2 Performance of non-zonal methods for the mandatory case (shear layer)

This section will be finalised following the CAP activity, in which selected methods will be compared directly using the same CFD code. Based on preliminary information, it looks as if the following tentative statements can be made:

- All studied GAM strategies have achieved significant acceleration of RANS to LES transition compared to the baseline hybrid models
- The approaches that seek to strongly reduce eddy viscosity in the early shear layer achieve a roughly similar effect. It appears from the current CAP status as if the Δ_{SLA} approach has a slightly stronger effect than the $\sigma + \widetilde{\Delta}_\omega$ method, which is roughly similar to the Δ_ω approach (HPF has not yet been tested)
- From NLR's simulations it appears as if the excitement of small scales via stochastic backscatter achieves a further degree of improvement on coarse meshes, with the gap to pure eddy-viscosity reduction closing on a finer grid. A corresponding assessment of the Leonard backscatter approach cannot be made due to the suspected contamination of results by strong numerical dissipation

3.2.1.3 Overall evaluation of strengths and weaknesses of non-zonal methods

Alongside the performance of the improved methods for accelerating RANS-LES transition in a pure planar shear case, it is essential to conduct an overall evaluation from the information available from the broader selection of test cases and from a critical analysis of the model formulations.

Implementation and usability issues

The most straightforward implementations are the vorticity-adaptive grid scales Δ_ω and $\widetilde{\Delta}_\omega$ and the eddy-viscosity reducing formulations Δ_{SLA}, WALE and σ, since these are explicit and local formulations. These furthermore introduce no additional user parameters. The HPF approach requires some kind of temporal filter to be implemented – the option of a running time-average leads to a non-local formulation in time and in all cases the specification of the temporal filter width introduces an additional user parameter. The Δ-based energy transfer approach requires the implementation of an additional transport equation, which represents a minor increase in implementation inconvenience. For the stochastic backscatter approach to be effective, it was shown that spatial and temporal correlations need to be imposed involving the solution of three additional transport equations. The Leonard backscatter term is local and explicit but the dissipative part should be limited to keep total $\nu_{SGS} > 0$.

Generality

It is conceivable that some approaches may give very good performance in terms of RANS to LES acceleration in the particular case of the planar shear layer, but introduce disadvantages in more general situations. Any such known limitations to generality are discussed here.

Beginning with the grid scale definitions, a regular topic for heated discussions in the Go4Hybrid consortium is the validity of measures involving the minimum grid cell edge length (and it should be stated that no unanimous agreement on this topic has been reached). There are well-founded concerns that such formulations (i.e. Δ_{min} and Δ_ω) will strongly under-predict eddy viscosity in situations such as isotropic turbulence on an anisotropic grid. The $\widetilde{\Delta}_\omega$ approach in contrast was formulated specifically to avoid reliance on the minimum grid dimension and is hence considered by its proponents as more general.

All GAM approaches seeking to exploit anisotropy of the grid (i.e. Δ_{min}, Δ_ω and $\widetilde{\Delta}_\omega$) will of course be ineffectual on isotropic grids. They are hence useful in situations such as jets or airfoil wakes, where prior knowledge of the shear layer location is combined with carefully designed structured grids. Unstructured grids by contrast tend to be isotropic except for the near-wall prism layers.

It appears as if all non-zonal GAM approaches pursued in Go4Hybrid are in principle applicable to unstructured meshes, however only the $\sigma + \widetilde{\Delta}_\omega$ approach has actually been tested on an unstructured grid (for the helicopter fuselage case I1). Results pending.

Question (@NLR): Is the stochastic backscatter approach with the transport equations for correlations applicable to unstructured grids?

Another generality issue has been seen to arise in the form of sensitivity to the flow topology. CFDB showed that the WALE approach was effective in situations of approximately planar shear (shear layer and round jet test cases), however performed very poorly for the vorticity-dominated delta wing case. Similar findings were reported by NLR for an equivalent approach based on the Vreman sub-grid scale model. In contrast, the σ approach was found to perform well in all cases owing to increased generality of the underlying formulation. CFDB conducted an equivalent test of the Δ_{SLA} formulation on the delta wing case and found that it too gave strong GAM performance.

Robustness

Reducing eddy viscosity to promote the development of resolved turbulence can be expected to bring an overall trend to reduced numerical stability, particularly when the early shear layer is coarsely resolved. Strongly related is the amount of dissipation introduced by the numerics. This should be as low as possible to avoid damping the insipid resolved turbulence, which may make the solution less robust. It has generally been observed that the development of the early shear layer region, particularly on a coarse grid, is extremely sensitive to fine differences in the turbulence modelling and numerics.

Anecdotal evidence indeed indicated that the GAM approaches that produce the most sudden drop in eddy viscosity exhibited lower numerical robustness. Although all simulations could be successfully run without serious difficulties, the strong interplay between numerics, turbulence modelling and mesh resolution should be studied more closely in the future. Optimal approaches are very likely to be code-specific.

Another key robustness issue relates to proper shielding of attached boundary layers (e.g. as addressed by the DDES approach). CFDB reported a degradation of the DDES shielding performance when combined with the σ and WALE GAM approaches. A similar effect should be expected with other GAM approaches. A recalibration of the DDES shield function was needed to restore the shield functionality. Not taking into account such secondary modelling effects would lead to an increased likelihood of spurious "grid-induced separation" in practical simulations.

Question: has shielding influence of GAM approaches been studied by other partners? It is highly likely that recalibration would be also needed for (at least) the HPF and Δ_{SLA} approaches.

3.2.2 Embedded approaches

3.2.2.1 Short description of the different approaches

- Mod. SEM (Pamiés): ONERA Synthetic-Eddy Method. Injection of random coherent structures at the interface. The structures are based on real boundary layer turbulence.
- SEM-DF: ONERA As above, including Dynamic Forcing downstream of the SEM plane to match target Reynolds normal stress.
- SEM-DF+WN: ONERA As above, with additional White Noise to speed up turbulence development.
- DFSEM: UniMan Divergence-Free Synthetic-Eddy Method. Injection of random vortices in a local volume around the interface. Global (correlations) in space and time including running averages.
- SEM (VF): DLR Synthetic-Eddy Method. Injection of random vortices in a local volume around the interface. Global (correlations) in space and time. Automatic determination of the RANS-LES interface requires local BL properties (wall-normal integration).
- STG: NTS Synthetic Turbulence Generator. Injection of random Fourier modes at the interface plane. Global (correlations) in space and time.
- VSTG: NTS Volume distributed STG. Distributed source term in the momentum equation with a related sink term in the k–equation. Non-forced RANS solution needed requires a two-stage procedure or overset grids in the interface zone.

3.2.2.2 Performance of embedded approaches for the mandatory case (flat plate boundary layer)

This section will be finalised following the CAP activity. Also here, selected methods will be compared directly using the same CFD code. The following tentative/preliminary statements can be made:

- For high-Re boundary layers, there are two difficulties associated with embedded approaches in general and the mandatory flat plate case in particular. These are (i) the under resolved LES region that requires a well working WMLES method and (ii) the RANS–LES interface that requires injection of turbulent structures.
- The WMLES method within the LES region is assumed to be sufficiently well known and has been studied elsewhere. This is not of primary concern in this project, although some sensitivity of different approaches has been studied.
- Different methods of injecting turbulent structures are tested. The transition phase for the turbulence to rebuild is found to be 5–10 δ, which can be seen as acceptable and a rather unavoidable consequence of the turbulence cascade.

- The error level in the transition region is dependent on the quality and physicality of the injected turbulence. All methods show good behaviour. Concluding remarks will be added for the final version of this deliverable. The ONERA SEM and NTS STG produce similar resolved turbulence. DLR SEM produces some quite large structures in comparison which, however, have no large impact on the down-stream turbulence. Also, the NTS VSTG with the distributed forcing is consistent with the local STG approach.
- The sudden introduction of turbulence structures at the interface will generate spurious noise emanating from the interface contaminating aero-acoustic predictions. A distributed volume forcing will mitigate the spurious noise and was adopted by DLR SEM and NTS VSTG. Also, NTS IDL STG is particularly developed for eliminating spurious noise by blending RANS and LES pressure in an overlap region (the NTS implementation strategy uses overset grids).

3.2.2.3 Overall evaluation of strengths and weaknesses of embedded approaches

Let us first briefly discuss the underlying WMLES approaches and their relevance for comparison of the different turbulence generators. The length of the flat plate was chosen to be sufficient for obtaining a reasonable fully developed boundary layer without major effects from the inlet procedure. In particular when plotted v.s. Re_θ. The primary observation from the different computations is that the different WMLES approaches used (IDDES S-A, IDDES SST and ZDES) are accurate within 5% for mean quantities like skin friction and mean velocity. The requirements and best practice for WMLES has been covered elsewhere and will not be further considered herein. The following discussion will be focused on the different methods of generating turbulence at the LES zone inflow.

Implementation and usability issues

Obviously, embedded approaches are much more complex to implement compared with the non-zonal approaches. Also the user input concerning the setup of the case and choices of parameters require significantly more effort. All methods require the setup and meshing of an explicitly user defined LES region or zone embedded in a RANS environment. Inflow and outflow interfaces or zones must be defined by the user. The only exception here is the DLR approach which will be discussed later.

For most methods (ONERA and UniMan SEM and NTS STG) a RANS–LES interface must be defined which will act as a RANS outflow BC and a LES inflow BC where fluctuations are added to the RANS mean velocity profile. The procedure for generating the fluctuations is non-local[3] (parallelisation issues), might need running averaging (UniMan DFSEM) or applicable only on structured meshes (NTS STG[4]). Moreover, the RANS solution is used for defining the fluctuating velocity amplitudes and scales.

For the NTS VSTG and DLR SEM the interface is replaced by a zone extended in the stream-wise direction where volume forcing is utilised for building up the turbulence structures. Volume forcing will relax the grid requirements compared with an interface plane enabling e.g. unstructured grids. Here, the RANS solution needed for deriving the fluctuations cannot just be sampled within the interface. DLR (SEM) samples the RANS solution “somewhat upstream of the interface”, which will be another used input to setup. It also requires solutions only slowly varying in the stream-wise direction. NTS VSTG, on the other hand, utilises their possibility of overlapping grids and the RANS and LES regions then overlap in the interface zone.

An interesting method to define the LES zone has been investigated by DLR. Here, the LES zone is automatically defined within the running computation as the region of the flow with separated boundary layer identified by the boundary layer shape factor. The boundary layer properties must then be integrated through the boundary layer along all grid lines emanating from the wall nodes and DLR is presenting a methodology also for unstructured grids.

Generality

[3] CM: I don’t believe the NTS STG method is non-local. Misha?

[4] CM: Again, I don’t think this is true for NTS STG. Misha?

All methods need information about the length and velocity scales of the injected turbulence structures. The length scale is related to the wall distance and RANS integral length scale. The time scale requires a "convective velocity" to be specified by the user as a single constant value. Interfaces located in three-dimensional mean flows might have different length and time scales at different parts of the interface which cannot easily be accounted for. Is this the case for all methods, or can some use locally-varying scale values without problems?

The ONERA SEM method introduces real boundary-layer turbulence structures which might need to be adapted when used for an interface within a free shear flow like jets, wakes or mixing layers. The NTS STG method on the other hand uses only information from the RANS anisotropy when generating the structures. This approach is more general which was proven for the mixing layer case with the interface at different down-stream positions. What is the case concerning the DLR and UniMan methods?

All methods can be transformed to work with an arbitrary direction of the interface plane. More general geometries with curved interface surfaces or oblique flow relative the interface cannot easily be considered within the present formulations. Moreover, a mixed in and outflow interface, such as putting the interface within a region of recirculating flow, is out of the scope and not recommended for the embedded approaches.

Robustness

The turbulence structures are injected either as a boundary condition at the internal interface or as a volume forcing in a local volume in the interface region. Both boundary conditions and volume forcing can be made preserving numerical stability with well-known considerations. Some of available methods are not divergence free, meaning that the generated structures are not fulfilling the divergence or incompressibility criteria. For some incompressible solvers this could lead to numerical problems since no mechanism is present for damping strong divergence. For compressible solvers the non-zero divergence will lead to local compression and related pressure waves with might cause numerical issues and spurious generation of noise.

4 Lessons learned and best practice findings

Before adopting the different improvements for GAM proposed in this project, the baseline hybrid RANS-LES method must be well tested, understood and tuned. The particular GAM methods cannot overcome problems such as excessive numerical dissipation or poor resolution in time and space. This is valid for both non-zonal and embedded methods.

The implementation and use of non-zonal GAM methods is, in general, not much different from the base-line hybrid RANS-LES methods with formulations local in time and space. The amount of complexity and computational overhead is limited. However, the non-zonal methods are limited when it comes to the ability to quickly switch from RANS to LES. The methods presented show great improvements but they are still far from completely eliminating the grey area.

Embedded methods require much more from the user in terms of setting up the case and providing parameter input. Also the implementation issues are non-trivial involving new data structures and treatment of non-local relations. However, with a well working generation of turbulence structures at the RANS-LES interface the transition region can be kept to a minimum of a few large-eddy turn over times (or distances).

Embedded approaches might lead to spurious noise which could contaminate aero-acoustic analyses. Some of the methods presented were shown to overcome this problem.

As was written in the introduction, the field of GAM with non-zonal as well as embedded methods are still progressing. Nonetheless, the final version of this document will be completed with the aid of the contributing project partners and observers in terms of overall findings, lessons learned and initial best practice.

5 Conclusion

The Go4Hybrid project has gathered some of the groups that are active in the further development of hybrid RANS-LES methods resulting in novel developments and increased experience and knowledge related to the grey area problem. The lessons learned and initial best practice is collected in this document.

Obviously, there are additional activities outside of this group that have not been considered which makes the best practice incomplete for obvious reasons. Moreover, there are other urgent problems related to hybrid RANS-LES which have not been addressed in this study.

Non-zonal and embedded methods are conceptually very different but one interesting attempt has been made to adopt the embedded method by an automatic procedure of identifying the embedded LES region. Hence, much of the user interaction is eliminated and the embedded computation will virtually be similar to a non-zonal approach.

5.1 Future trends and needs

The most promising of the newly developed methods and model extensions must now be carefully assessed and tested on a variety of flow cases in order to gain experience and, most importantly, to capture any inconsistencies and degenerated behaviour in more general conditions. These are e.g. the boundary layer shielding capabilities. It is essential to ensure that we don’t improve RANS-LES transition at the expense of other important properties.

These investigations together with careful improvements and further calibrations will then be the basis for a more complete and rigorous best practise guide.

Based on this experience and on the needs of engineers and researchers without in-depth, “developer” knowledge, the need for generalisation and automation is obvious. Here, the Go4Hybrid project findings can be an important support for software vendors and engineering development departments.

Looking forward then, a clear need is for improved **industrialisation** of the improved methods generating within this pioneering project. Topics that need to be studied further include:

- Assessment of performance for more complex cases and mixed flow types (as mentioned above).
- Resolution of numerical issues, relating to the high sensitivity of the typically poorly-resolved early shear layer. The balance between low-dissipation and robustness is key here.
- A more detailed study of the influence of grid resolution, targeting more concrete best practice guidelines and potentially informing automatic grid adaptation algorithms.
- An assessment of the impact of grey-area improved hybrid methods on grid resolution requirements: For example, do the improved methods exhibit relaxed grid requirements relative to standard methods?
- Further improvement to the flexibility of embedded approaches, including LES-to-RANS conditions, mixed inlet-outlet conditions to the LES region, automatic detection of resolved and modelled zones.