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HYBRID RANS-LES MODELLING: SOME RECENT DEVELOPMENT AND AERODYNAMIC APPLICATIONS

Shia-Hui Peng

Department of Aerospace Engineering, Swedish Defence Research Agency, FOI, Stockholm, Sweden

Abstract

Hybrid RANS-LES modelling exploits the merits of RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) approaches, enabling turbulence-resolving simulations with computing resources much less demanding than full LES. The present paper provides an overview of some research work on hybrid RANS-LES modelling methods, with a primary focus on CFD-based aerodynamic analysis targeting aeronautical applications. Along with progressive maturation in engineering practice of using hybrid RANS-LES methods, further development has been directed to enhancing simulation accuracy and improving modelling feasibility. Among others, the RANS-LES interface has attracted particular attention for Grey-Area Mitigation (GAM) in order to attain enhanced resolving capabilities in the grey area present in the LES region. In this work, following a highlight of the GAM methods, some application examples, where conventional RANS computations may become awkward, are presented with scale-resolving flow predictions in aerodynamic analysis.

Keywords: CFD (Computational Fluid Dynamics), Hybrid RANS-LES modelling, Grey-area mitigation, Turbulence-resolving simulation, Aerodynamic applications

1. Introduction

Hybrid RANS-LES modelling is an engineering modelling approach which provides a compromise between RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) computations of turbulent flows in terms of computational accuracy and efficiency. Pragmatically, hybrid RANS-LES models abandon a full LES resolution of wall turbulence, which is instead modelled in the context of (unsteady) RANS modelling. In the off-wall region and in regions where the flow undergoes massive separation, the capability of LES in resolving large-scale vortex motions is well exploited. Since the DES (Detached Eddy Simulation) modelling approach proposed by Spalart and co-workers [1-3], a large number of hybrid RANS-LES modelling methods have been reported. These include, among many others, Wall-Modelled LES (WMLES) [4-6], X-LES and improved variants by Kok et al. [7-9], zero- and one-equation based hybrid RANS-LES models (HYB0 and HYB1) by Peng [10-12], Zonal DES (ZDES) by Deck [13-15].

Nowadays, the development of hybrid RANS-LES methods has evolved with a rather wide range of modelling variants, being facilitated by industrial needs and by the rapid advancement of computing capabilities. Along with DES-type models, other scale-resolving modelling approaches have also been developed, which are categorized here in the general framework of hybrid RANS-LES modelling, including wall-modelled LES and embedded LES. Of many existing hybrid modelling methods, the RANS-LES interface has been regarded as being a major challenge in order to enable a feasible and physically profound RANS-to-LES transition in hybrid RANS-LES computations. Indeed, neighboring the RANS-LES interface, the initial part of the LES region is a typical grey-area, where turbulence is often insufficiently resolved and leading to a much delayed re-establishment towards fully developed turbulence. This is due to the fact that only modelled turbulent contents are fed into the LES region from the neighboring RANS region, which has consequently motivated intensive studies of relevant Grey-Area Mitigation (GAM) methods in order to enhancing turbulence-resolving capabilities in the grey area.

Over the recent years, a number of international and national initiatives have been undertaken to address scale-resolving modelling and simulation methodologies, with a primary focus on hybrid RANS-LES modelling and its aerodynamic applications to CFD-based analysis of aeronautical systems. This work provides an overview of some research activities on hybrid RANS-LES modelling and aerodynamic applications where turbulence-resolving simulations are desired to attain relevant analysis.

2. Grey-Area Mitigation

As mentioned, hybrid RANS-LES modelling is a pragmatic approach addressing turbulence effects on the flow field by hybridizing (unsteady) RANS and LES models to exploit the computational efficiency of the former and the scale-resolving capability of the latter. The hybridization of RANS mode and LES mode has attracted extensive attention in studies for advanced turbulence modelling. Due to the lack of relevant turbulent fluctuations at the interface from RANS to LES, the development of resolved turbulence is often delayed in the neighboring area accommodated by LES mode, which is termed a “grey area”.

Obviously, the presence of grey area degrades the advantage of deploying LES in hybrid modelling, which is exploited for improving modelling robustness in predictions of both the mean flow and the resolved turbulence. In order to alleviate, or even diminish, the grey-area problem and, consequently, to enable effective turbulence-resolving predictions, Grey-Area Mitigation (GAM) measures are desired. This can be done by either adding turbulent fluctuations to the RANS-modelled flow at the RANS-LES interface, or alternatively, enhancing the resolving capability of the LES mode itself. It is noted that the RANS-LES interface is equivalent to a boundary of the LES region in hybrid RANS-LES or embedded LES computations. With a prescribed interface location and imposing turbulent fluctuations on the RANS-computed mean flow at the interface, this type of modelling approaches is termed a **zonal** hybrid RANS-LES method (including embedded LES). Many hybrid RANS-LES modelling approaches have been formulated with seamless RANS-LES coupling by means of adaption of the RANS and LES length scales, typical examples include DES-type models [2, 3, 17, 18] and many other alternative hybrid RANS-LES methods, see e.g., Refs [7, 10, 13]. These methods are categorized as **non-zonal** hybrid RANS-LES modelling approaches, where the RANS-LES interface location is justified by means of inherent modelling formulation in terms of the local grid resolution and flow properties. In a series of collaborative initiatives in the framework of European and national research programs, we have involved actively in the development of hybrid RANS-LES modelling and related aeronautical applications, see e.g. in [19, 28, 29]. Some examples taken from these activities are briefly introduced in this work.

Along with the development of modelling approaches, investigation of effective GAM methods has formed one of the main aspects in studies targeting improved turbulence-resolving capabilities [19]. For zonal methods, turbulent fluctuations generated from a precursor DNS or LES computation or from a synthetic turbulence generator (e.g. Ref. [20-23]) are imposed on the RANS-computed mean flow over the interface and being incorporated into the LES computation through the interface. Injection of turbulent fluctuations with reasonable re-adaption of flow physics on the RANS-LES interface has shown promising feasibility for grey-area mitigation [27, 28]. This is particularly the case when the LES mode serves to resolve turbulent mixing in the presence of shear layer immediately after the RANS-LES interface, for example, confluence of wall boundary layers detached from the trailing edge of a wing. In non-zonal methods, the development of GAM methods has usually been aiming to interfere directly the SGS modelling formulation so as to enhance resolved turbulent fluctuations in the grey area [28, 29]. In practice, injection of synthetic turbulence may also be used in conjunction with other GAM methods with, e.g., improved SGS modelling to achieve an effective re-establishment of LES-resolved turbulence in the grey area [30, 31].

2.1 Commutation term

Recognizing the commutation error between the hybrid filtering operation and the spatial derivative in hybrid RANS-LES computations, Arvidson et al. [30, 31] proposed an additional term stemmed from non-commutivity to enhance resolved turbulent fluctuations at the RANS-LES interface. The commutation term, stemmed from filtering a derivative of an arbitrary quantity, f, takes the form of the second term on the right-hand side of the expression below [32].

$$\overline{\frac{\partial f}{\partial x_i}} = \frac{\partial \bar{f}}{\partial x_i} - \frac{\partial \Delta}{\partial x_i}\frac{\partial \bar{f}}{\partial \Delta} \tag{1}$$

In the modelling of a zonal RANS-LES modelling based on a k-ω model, the commutation term for the convection terms in the k, ω and momentum equations, respectively, was deployed [30, 31]. The commutation terms, S_k^c and S_ω^c in the k and ω-equation, respectively, are related to each other in the following form.

$$S_\omega^c = \frac{\omega}{k} S_k^c = \frac{\omega}{k}\frac{\partial \Delta}{\partial x_i}\frac{\partial \overline{u_i} k}{\partial \Delta} \tag{2}$$

The addition of the commutation term in the k and ω equations on the RANS-to-LES interface tends to reduce the turbulent viscosity from RANS level down to SGS level in LES, as desired. In order to represent the instantaneous modelled-to-resolved energy transfer, a source term is further incorporated into the momentum equations in the form below [31].

$$S_{mom,i}^c = \mathrm{sign}(\bar{u}_i') \left| \langle S_k^c \rangle \frac{\bar{u}_i'}{\langle \bar{u}_m' \bar{u}_m' \rangle} \right| . \tag{3}$$

2.2 Vorticity-based LES length scale

The vorticity-based subgrid filter width, Δ_ω, proposed first by Chauvet et al. [16] has been examined in combination with non-zonal methods, for example, the HYB0 and HYB1 model [10] and the IDDES model [18], by a replacement of the original LES length scale, e.g., Δ_{max} in the HYB0 model. The implementation of the vorticity-based length scale on unstructured grid is based on a generalized form of Δ_ω, which is computed by projecting all dual-cell (control volume) faces $\vec{s}_l$ onto the normalized local vorticity vector $\mathbf{N}_\omega$ as:

$$\Delta_\omega = \left(\frac{1}{2} \sum_{l=1}^{m} \mathbf{N}_\omega \cdot S_l \mathbf{n}_l \right)^{1/2}, \tag{4}$$

where m is the number of control surfaces, S_l is the area of surface l with a normal direction $\mathbf{n}_l$, and $\mathbf{N}_\omega = \boldsymbol{\omega} / \Omega$, with $\Omega = (\omega_i\ \omega_i)^{1/2}$ being the vorticity magnitude, is the normalized vorticity vector (direction). It is noted here that, similar to the vorticity-based scale, a modified subgrid filter scale, termed the “shear-layer adapted” filter Δ_{SLA} was proposed by Shur et al. [33].

In general, the vorticity-based LES length scales have been proposed to induce a reduction in the modelled SGS turbulent eddy viscosity. This has often been achieved by adapting the SGS filter scale towards the local grid resolution that is particularly refined in directions perpendicular to the dominant vorticity orientation.

2.3 Energy backscatter

The idea of using energy-backscatter function aims at enhancing the LES-resolved large-scale turbulence in the LES region, by deploying the instantaneous reverse transfer of turbulence energy from modelled to resolved scales. The formulation is based on an expansion (namely, the Leonard expansion) of the filtered stress residuals [24-26], which gives

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j = C_1 \Delta^2 \frac{\partial \overline{u_i}}{\partial x_k}\frac{\partial \overline{u_j}}{\partial x_k} + C_2 \Delta^4 \frac{\partial^2 \overline{u_i}}{\partial x_k \partial x_l}\frac{\partial^2 \overline{u_j}}{\partial x_k \partial x_l} + \cdots \tag{5}$$

The first term is an approximation of the conventional scale-similarity SGS model in terms of velocity gradients, which is able to induce instantaneous energy backscatter for $\varepsilon_L = -C_1 \Delta^2 \frac{\partial \overline{u_i}}{\partial x_k}\frac{\partial \overline{u_j}}{\partial x_k} \bar{S}_{ij} < 0$. The second term is related to the energy dissipation in the SGS modelling formulation [24]. This has thus led to a SGS model of mixed type in the following form.

$$\tau_{ij}^{LES} = (C_L \Delta)^2 f_L \frac{\partial \overline{u_i}}{\partial x_k}\frac{\partial \overline{u_j}}{\partial x_k} - 2 \upsilon_{sgs} f_D \bar{S}_{ij} . \tag{6}$$

As mentioned, the first term (the Leonard term) on the right-hand side of Eq. (6) is able to induce instantaneous energy backscatter from modelled small scales to resolved large scales. This function is then exploited in the LES mode of hybrid RANS-LES modelling. Using the *hybrid* eddy viscosity, ν_h, which is taken from the hybrid model, the modelled turbulent stress tensor in the hybrid model reads [25]

$$\tau_{ij} = -2\upsilon_h \bar{S}_{ij} + f_b (C_L \Delta)^2 f_L \frac{\partial \overline{u_i}}{\partial x_k} \frac{\partial \overline{u_j}}{\partial x_k}, \tag{7}$$

where the function f_b present in the second term on the right-hand side of Eq. (7) is to shield the Leonard term from the near-wall RANS layer with $f_b = 0.0$ there. The approximation of the scale-similarity model in terms of velocity gradients enables much less complicated computations than a second filtering operation as is otherwise in the conventional scale-similarity model. Equation (7) can be readily formulated in the turbulence production term for hybrid RANS-LES modelling involving turbulence transport equations (e.g. in the HYB1 and IDDES model). Kok and Van der Ven [8, 9] proposed a stochastic SGS model using a stochastic variable in the formulation of SGS eddy viscosity, which plays a role in turbulence energy backscatter and enhancing turbulent fluctuations in the development of LES-resolved turbulence [9]. It is noted that, with appropriate verification of consistent adaptation of flow physics, different GAM methods can be exploited in the context of a combination. Along with the energy-backscatter function, for example, a vorticity-based length scale may be invoked further in the SGS modelling.

3. Aerodynamic Applications

In this section, some examples are presented to highlight the use of hybrid RANS-LES modelling in aerodynamic applications. These include fundamental turbulent flows to demonstrate the verification of GAM methods and industry-relevant cases to shed light on the scale-resolving capability of the modelling approach.

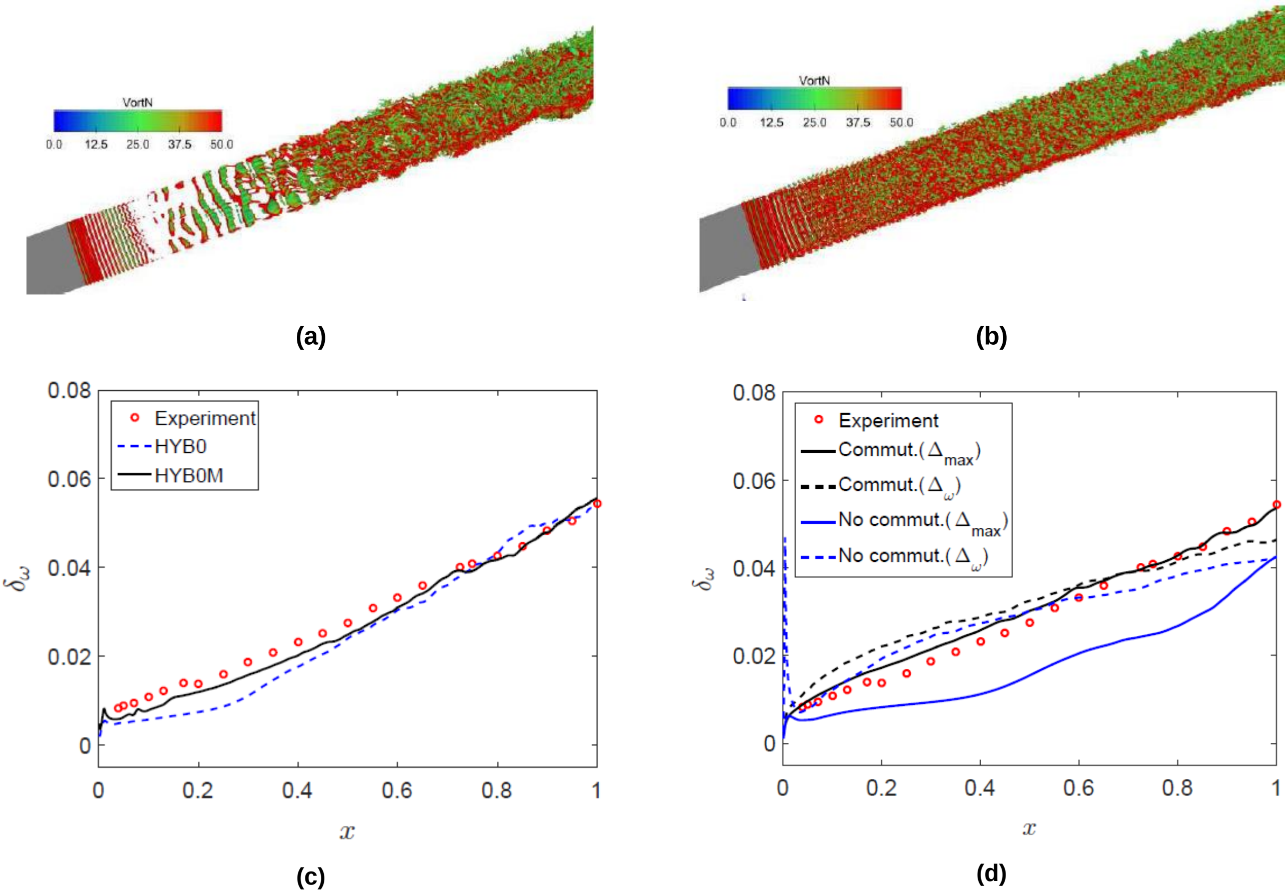
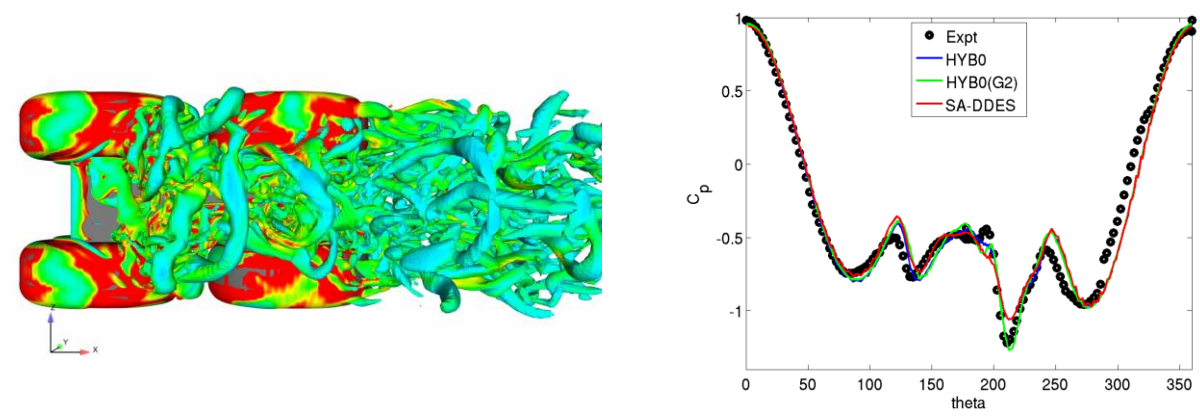


Figure 1 – Computations of turbulent mixing-layer flow. Resolved turbulent structures with the baseline HYB0 model in (a); and incorporating GAM with energy-backscatter function (HYB0M) in (b). Mixing-layer thickness with the HYB0 and HYB0M models in (c), and in (d) with a k-ω based hybrid model with and without commutation term using different LES length scales [31].

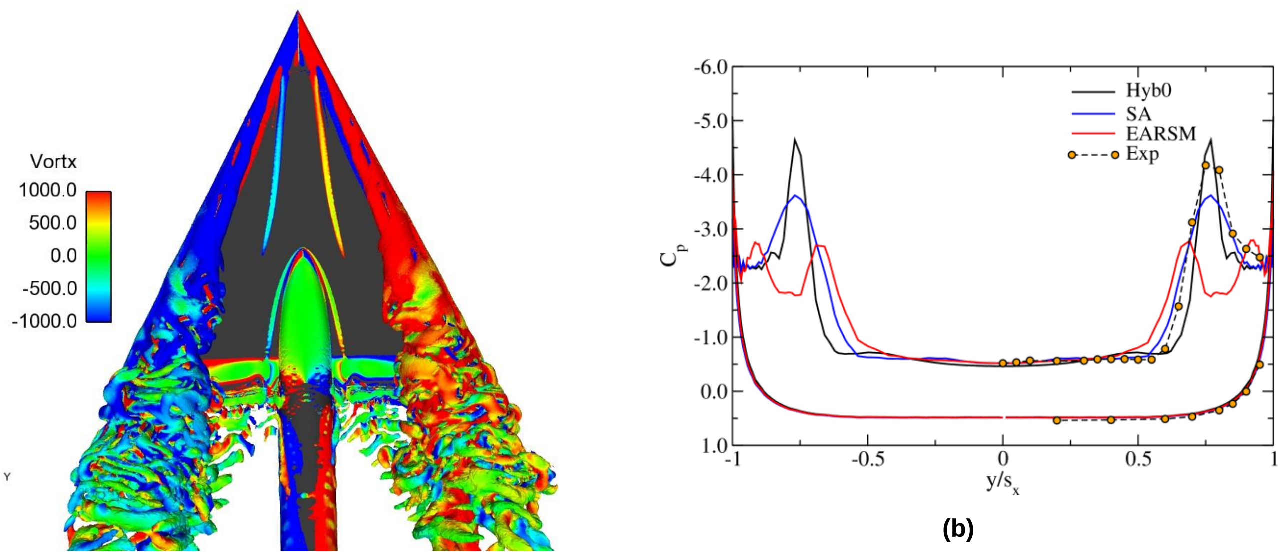
To demonstrate the function of GAM methods in enhancing turbulence-resolving capabilities, an example is first illustrated in Figure 1 for hybrid RANS-LES computations of a turbulent mixing-layer flow. The initial part of the mixing layer, formed by a confluence of the boundary layers on the upper and lower sides of a flat plate, is a typical grey area. As seen in Figures 1(a) and 1(b), much richer turbulent structures are resolved in the grey area with the GAM method incorporated comparing to the scale-resolving computation using the baseline HBY0 model. This is reflected further in the prediction of vorticity thickness of the mixing layer, as shown in Figures 1(c) and 1(d), in comparison with available experimental data.

The application of hybrid RANS-LES computations aims at resolving unsteady aerodynamic flow properties to support improved industrial designs and analysis, where conventional (unsteady) RANS computations are inaccurate or even incapable. Indeed, it is commonly recognized that hybrid RANS-LES modelling is much desirable in resolving massive turbulent flow separation and vortex motions that are triggered by geometries of system configuration. In earlier applications of hybrid RANS-LES methods, DES-type and other hybrid RANS-LES methods have undergone intensive verification, showing in many cases good agreement with experimental measurements.



(a) (b)

Figure 2 – Computations for turbulent flow over a rudimentary landing gear (RLG). (a) Snapshot of resolved instantaneous turbulent structures over the RLG wheels. (b) Time-averaged surface pressure, C_p, distribution around the LG front wheel. G2 indicates an unstructured grid alternative to the structured grid used in the other two computations with HYB0 and SA-DDES model.

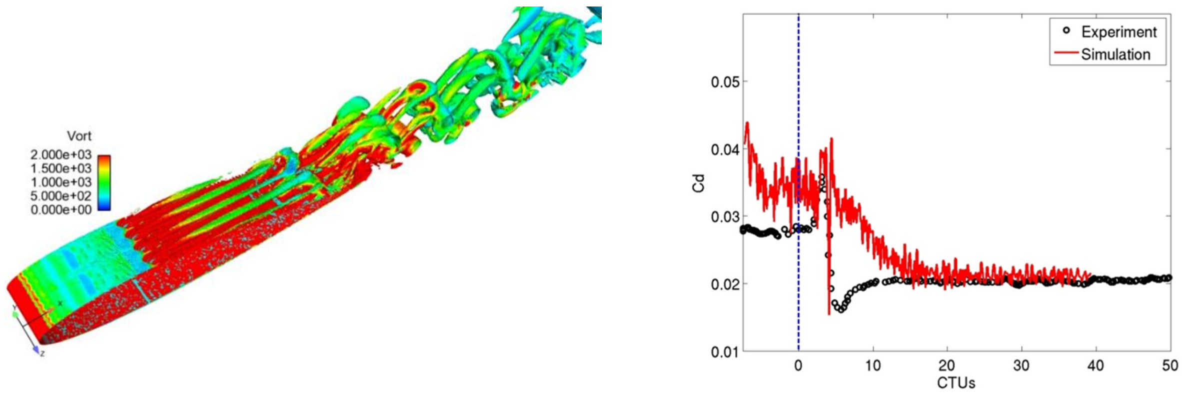


(a) (b)

Figure 3 – Computations of flow over a Delta wing. (a) Illustration of resolved structures, Q_{cr}-isosurface colored with streamwise vorticity ω_x; (b) Time-averaged surface pressure coefficient, C_p, at position, x = 0.2C, in comparison with experimental data.

Figure 2 and Figure 3 present two examples, respectively, highlighting the predictions of the flow past a rudimentary landing gear [34] and over a Delta wing [35]. These examples have clearly shown that hybrid RANS-LES modelling is able to resolve large-scale turbulent motions and provide reasonable (and improved) predictions of flow properties characterized by massive flow separation and intensive vortex motions, as desired, in comparison with RANS computations.

In some aerodynamic applications, conventional RANS modelling may produce reasonable predictions of mean flows, but is unable to resolve any turbulent fluctuations that are required for comprehensive analysis of, for example, physic mechanisms of flow-control devices, aerodynamic loads and noise generation associated to instantaneous vortex motions and temporal-spatial correlations. Due to its turbulence-resolving capabilities, hybrid RANS-LES modelling has often been employed to resolve unsteady aerodynamic features for which full LES computations may become computationally too costly. In Figure 4, an example is illustrated with the hybrid RANS-LES method adopted in analysis of active flow-control mechanisms, where an array of micro jets are deployed to suppress the flow separation over the NACA0015 airfoil [36]. The SA-IDDES model was used in the computation. The transient process in response to the jet actuators was explored in terms of the drag evolution with time. A study as such has aimed at attaining an improved understanding on the flow control mechanism, where jet-induced large-scale vortex motions energize the momentum of the boundary layer to overcome the adverse pressure gradient and, consequently, diminishing boundary layer separation. As shown in Figure 4(b), the drag was over-predicted before the micro jets were activated (at CTU = 0). This has been caused by an early onset of separation in the IDDES prediction. Both the simulation and the experiment have claimed a lagged drag evolution in response to the actuation. The measured drag evolution shows a rapid drop after a peak, which is reduced to a very small value and then increasing continuously to the value converged for the fully controlled state. The numerical simulation presents a very similar drag reduction but arising sharply again to large values prior to a continuous reduction, showing a slower transitional stage towards the fully controlled flow. In the simulation, the micro-jets were simulated by a mass-flow boundary condition at the jet exit, which should otherwise be resolved with injection from an embedded cavity. This has led to the inconsistent response after switching on the jets, as compared to the experiment [37]. The transient response is associated to the evolution of coherent structures in the wake and those generated by the jet injection from the embedded cavity. The jet flow was however not fully resolved in the simulation, by imposing a mass-flow boundary condition at the jet exit on the airfoil upper surface.

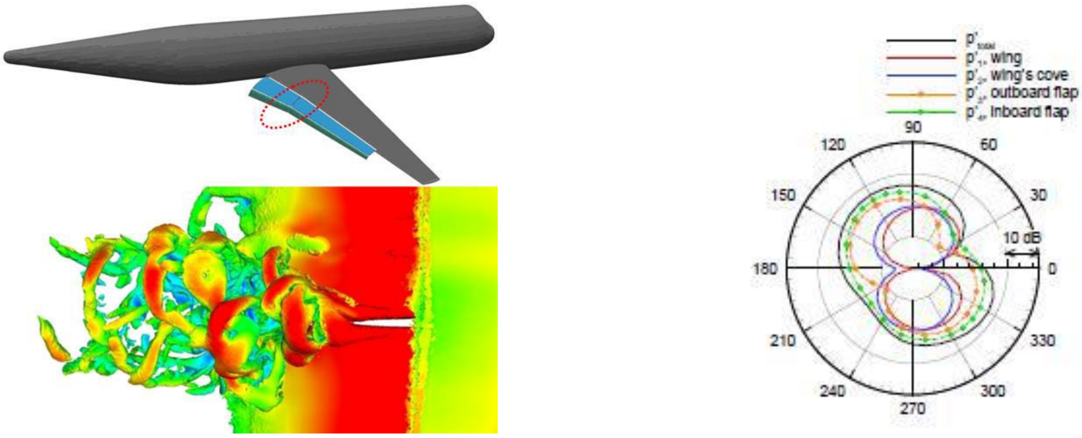


(a) **(b)**

Figure 4 – Active flow control with micro jets to suppress airfoil trailing-edge flow separation. (a) Resolved flow structures with micro jets. (b). Effect of flow control for drag reduction.

In simulations of aeroacoustic noise generation and propagation, hybrid RANS-LES modelling has become one of the most popular scale-resolving methods to address aerodynamic flow-induced noise sources. Aerodynamic noise generation is essentially related to unsteady flow phenomena with inherent turbulent fluctuations or flow oscillations. The formulation of aeroacoustic noise sources takes terms of spatio-temporal variation and correlations of flow and pressure fluctuations.

For improved predictions in Computational Aero-Acoustics (CAA), hybrid RANS-LES modelling, for its computational effectiveness, has been used to characterize noise generation in analysis of acoustic noise propagation [38, 39]. In Figure 5, a hybrid CFD/CAA analysis of a multi-element highlift-configuration is given as an example to highlight the feasibility of hybrid RANS-LES modelling in formulating noise generation of airframe configurations. In the computation, particular attention was paid to the flow over the flaps [38], particularly, on the aerodynamic flow features with extensive flow deformation over the flap side-edge in relation to noise generation. As shown in Figure 5(a), extensive vortex motions are present over the flap side gap and forming potent noise sources. In Figure 5(b), the contribution of different highlift-configuration elements to the far-field overall SPL (OASPL) is illustrated, in which the Curl method was used for far-field noise propagation.

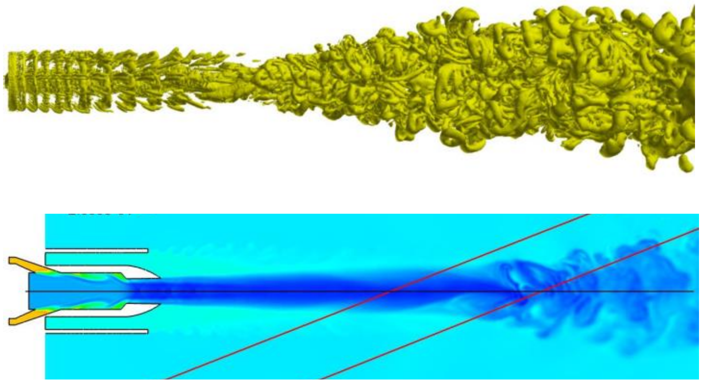


(a) **(b)**

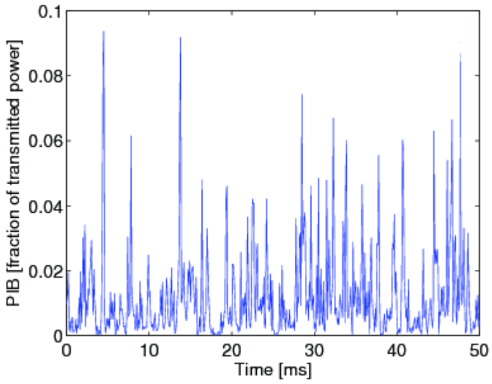
Figure 5 – Aero-acoustic analysis with hybrid CFD/CAA simulations. (a) The configuration (upper) and resolved instantaneous structures over the wing kink (lower). (b) Far-field OASPL using acoustic analogy method based on the hybrid RANS-LES computation of the near-field flow for noise-generation analysis.

Aero-optics analysis of Airborne Optical Systems (AOS) is another topic, where hybrid RANS-LES modelling can be well deployed. In analysis of, for example, optical Missile Approach Warning Systems (MAWS) and laser Directed Infrared Countermeasures (DIRCM), optical turbulence is an important issue that may affect the system performance, particularly, the engine plume turbulence, which may create strong disturbances to the optic beam. The engine plume turbulent flow lies in the supersonic flow regime and is characterized by large gradients and fluctuations in flow properties and composition mass fractions from the combustion process. Variations in density (or temperature) and gas species fractions affect the speed of light in the air, as described by the refractive index. Variations of spatial scales larger than the cross section of the laser beam act as a wedge, causing the beam to refract away from areas where the refractive index is low. Smaller vortices will produce variation of the refractive index on spatial scales smaller than the beam cross section, leading to significant aberrations of the laser beam. The aberrations as such will cause beam broadening and break-up of the beam profile into beamlets. In the DIRCM case an important parameter is the power entering the aperture of the seeker that needs to be defeated. The simulation of temporal and spatial variation of the power relies on unsteady scale-resolving computations.

In the example illustrated in Figure 6, the optical analysis has been performed for a laser beam path crossing the engine plume at an angle of 21^o to the engine axis, which was chosen for computational convenience but not a realistic scenario [40]. The jet plume exhausts at a Mach number of $M = 1.4$, triggering complicated vortex motions in the form of toroidal-shape vortices in the initial part and hairpin-like structures after the jet breaks up, see Figure 6(a). The variation in density (as illustrated in Figure 6(b)) is then used to determine the refractive index, which is integrated into the optical path length and further to obtain the phase screen representing the aberration that affects the laser beam. The phase screen impact can then be analyzed on the beam profile to calculate the laser intensity distribution in the far field. For the application to DIRCM, the far field intensity distribution is used to calculate the power entering the aperture of the seeker or the Power-In-Bucket (PIB). Without any aberration, 55 % of the power passes within a 10 cm diameter aperture at 1 km. With the aberration from the plume, the beam is severely distorted and the PIB is reduced significantly, with large temporal variation as shown in Figure 6(b).



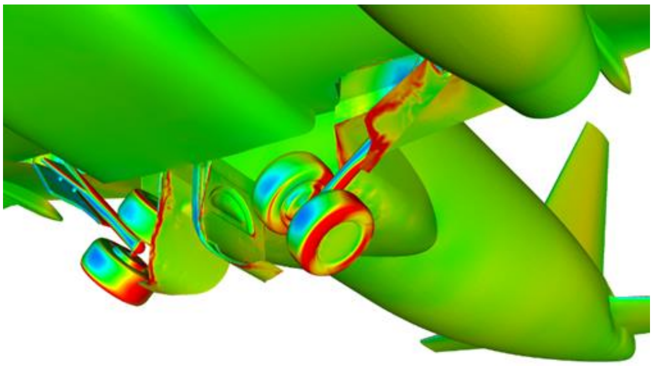
(a)



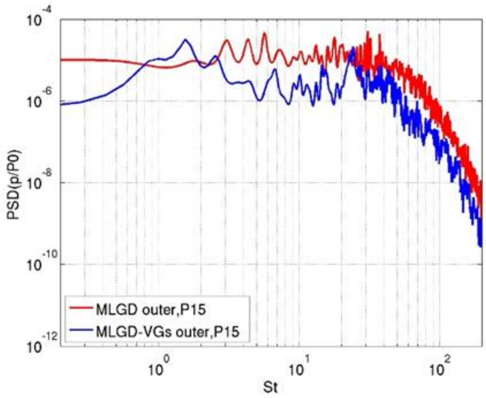
(b)

Figure 6 – Simulation of engine-jet plume for aero-optic analysis of laser beam passing through engine exhausted plume. (a) Resolved flow structure (upper) and instantaneous contour of density (lower). (b) Time variation of PIB for aperture centered at nominal pointing position at 1 km.

Similar to its deployment in computational analysis of aerodynamic flow- and noise control, hybrid RANS-LES modelling may play a unique role in analysis of aerodynamic flow-induced vibration control [41, 42]. Aerodynamic vibration is often triggered by unsteady aerodynamic loads generated by extensive pressure oscillations (fluctuations). Conventional RANS computations are not able to resolved instantaneous pressure fluctuations, and thus unable to produce necessary inputs in flow-structure coupling analysis. Figure 7 shows an example of hybrid RANS-LES computations to support the design and analysis of different vibration control measures for aircraft Main Landing Gear Doors (MLGD). When the landing gears are deployed in takeoff or landing, the MLGD is exposed to the vortex flow generated from upstream Nose Landing Gear (NLG) system and is subjected to severe vibrations. In Figure 7(a) the resolved instantaneous surface pressure is illustrated, which was then used in analysis of structure deformation in cases with and without vibration control devices. In one of the vibration-control designs addressed, a set of vortex generators (VGs) was mounted on the door surface in accordance with the numerical simulation at locations to alleviate local pressure variations and fluctuations. Figure 7(b) presents an example at a location on the MLGD to highlight the pressure fluctuation (in terms of its power spectral density, PSD), which has been appreciably alleviated by means of VGs in comparison with the baseline case (red line in Figure 7(b)) [41] by suppressing the local flow separation on the MLG-door outer surface.



(a)



(b)

Figure 7 – Simulation for aero-vibration control analysis to mitigate the vibration of MLG-bay door with VGs. (a) Resolved surface pressure around the door surfaces. (b) PSD of surface pressure fluctuations at an exampled location on the MLG-door surface with/without VGs.

4. Summary and Outlook

With the rapid evolution of digitalization in aviation industries and to comply with the engineering need, scale-resolving simulations have been increasingly implemented to attain reliable predictions to support realistic CFD-based aerodynamic design and analysis. For complicated aeronautical systems operating at high Reynolds numbers, it is recognized that flow simulations with hybrid RANS-LES methods are becoming computationally affordable, as compared to full LES. Hybrid RANS-LES modelling has been exploited as a popular approach to deal with turbulence effects in computational aerodynamics, aero-acoustics and aero-optics, where scale-resolving simulations of turbulent flow properties are desired.

This paper provides an overview of some recent development and aerodynamic applications. In the development of hybrid RANS-LES modelling approaches, RANS-LES coupling remains an important and challenging issue to address in order to enhance turbulence-resolving capabilities in the grey area. Indeed, a hybridization of a scale-modelled RANS mode with a scale-resolved LES mode must be established on a physics-profound basis for grey-area mitigation. Some GAM methods have been highlighted in this work. Turbulence (synthetic or from a pre-cursor scale-resolving simulation) injection at the RANS-LES interface has been often used for zonal hybrid methods, which is able to support an effective re-establishment of resolved turbulence in the grey area. Other GAM methods have aimed at enhancing the resolving capability of the LES mode, by means of triggering (usually) a physically-consistent reduction of modelled SGS eddy viscosity and thus enhancing resolved turbulent fluctuations. As highlighted in this work, these include an exploitation of commutation terms incorporated in the modelling equations, the vorticity-based length scale and the energy-backscatter function in the formulation of eddy viscosity and/or in the modelling of the SGS turbulent stress tensor.

Aerodynamic applications of hybrid RANS-LES methods are often directed to addressing unsteady flow problems, particularly, when resolved time-dependent aerodynamic properties and/or flow fluctuations are required in the analysis. Typical examples include analysis of bluff-body flows characterized by massive flow separation and intensive vortex motions, computational analysis of aeroacoustic noise generation and propagation, aero-optic analysis of laser beam intensity distribution, as well as in CFD-based design and analysis of flow-, noise- and vibration control devices. In these applications, conventional RANS computations are unable to produce resolved turbulent fluctuations, while LES and/or DNS is too costly or even unaffordable, leaving the hybrid RANS-LES method the best choice for turbulence-resolving simulations.

There is no universal modelling approach. Like RANS and SGS modelling in LES, the feasibility of hybrid RANS-LES modelling is closely associated to the physic argumentation incorporated in the modelling formulation. For massive flow separation and/or vortex motions induced by bluff-body geometries of flow configuration with most turbulence being generated in the detached vortex motions, hybrid RANS-LES computations should be expected to produce results comparable to LES. For aerodynamic flows with wall boundary layer separation, the modelling may become rather demanding to the performance of the RANS mode hybridized in predicting the onset of near-wall boundary layer separation and in interacting with the LES mode. In addition to the robustness of the RANS and LES modes and their coupling, low-dissipative and low dispersive numerical schemes should also be invoked particularly in the LES region with necessary grid refinement, where too a large numerical dissipation renders usually less-resolved, or even unphysically dampened, turbulent fluctuations.

Facilitated by aeronautical applications, development of advanced hybrid RANS-LES modelling approaches remains one of the most important, yet very challenging, topics in engineering turbulence modelling, particularly, on the RANS-LES coupling, and furthermore, for CFD-based analysis of high-speed flows accompanied with laminar-turbulent transition, shock interaction and chemistry reactions. Hybrid RANS-LES modelling is becoming, and will be, one of the mainstays for flow-physics modelling in the next-generation CFD platform, combining further with a wide spectrum of functionalities addressing different aerodynamic applications, as well as with new and emerging methodologies, such as machine learning and big-data analytics.

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Contact Author Email Address

Shia-Hui Peng, FOI, Sweden. mailto: peng@foi.se

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