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A QUICK OVERVIEW OF THE CAPABILITIES OF ZDES

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Abstract

This paper provides an up-to-date survey of the use of Zonal Detached Eddy Simulations (ZDES) in the frame of applied aerodynamics. The issue of zonal or non-zonal treatment of turbulent flows for engineering applications is discussed. The ZDES method used in this article and based on a fluid problem-dependent zonalization is briefly presented. Some recent landmark achievements featuring massively and thin-layer separated flows are presented. The remaining challenges including wall-turbulence simulation at high Reynolds number are also briefly discussed.

1 Introduction

The increasing demand for high-fidelity computational aerodynamics motivates more and more frequently unsteady turbulence modelling. Among the possible approaches, the hybrid RANS/LES paradigm is suited for the industrial needs since it combines a high degree of resolution in the zones of interest, which are treated in LES, with a cost-efficient RANS treatment of the other regions of the flow. The Zonal Detached Eddy Simulation technique (ZDES) [1] developed since 2002 enables a flexible definition of the zones of interest and has been widely validated and used for aerospace engineering applications (see e.g. [2]) as well as for academic research.

In this article, the issue for hybrid RANS-Large Eddy Simulation (LES) approaches to the zonal or non-zonal treatment of turbulent flows is first briefly discussed and the salient features of the Zonal Detached Eddy Simulation (ZDES) method are presented in §2. Some recent landmark achievements featuring massively separated flows are illustrated in §3 while some specific issues concerning the simulation of wall turbulence in the frame of Wall Modelled Large Eddy Simulation (WMLES) approaches are discussed in §4.

2 Turbulence modelling

2.1 Zonal or non-zonal treatment of turbulence?

As reminded in §1, it is now commonly acknowledged (see Haase *et al* [3]) that hybrid RANS/LES is the main strategy to drastically reduce computational cost (compared to standard WRLES) in a wide range of complex industrial applications. Despite a wide number of approaches (and acronyms!), these methods are close to one another and can often be rewritten as variants of a small group of generic approaches. In practice, these methods differ by their maturity in the sense that many have not been thoroughly validated or widely used on “real” three-dimensional configurations (see the

discussions in [4, 5]). At the same time, these methods raise the important question whether the treatment of turbulence has to be zonal or not.

Indeed, a fully automatic method (i.e. without user input) is desirable to reduce the decision load on the user but “utopian” in a near/mid-term future. In [1] Deck clearly advocates the use of a zonal treatment of turbulence to handle complex configurations, even if the decision load is increased, for several reasons:

- An automatic method (black-box push button) is not desirable (though very tempting!). Indeed, if the fully automatic model fails, the user is helpless (potential reasons for failures include complex geometries and physics on “real-life” grids).
- An automatic method can convey a misleading feeling of easiness. Even perfectly “idiot-proof” models require a significant level of expertise from the user which cannot be replaced by the computer so far (e.g. the design of an hybrid RANS/LES grid is far from being trivial).
- In the frame of wall-turbulence resolving simulations (e.g. on a whole aircraft), the activation of LES content in the TBL will be necessarily embedded in the computational domain (i.e. zonal!).
- A zonal non-automatic approach alleviates the user load during computation monitoring and post-processing since the behaviour of the model is known in advance.

It is worth stressing that a zonal approach also permits operation in an automatic mode (but the reverse is not true). Such a functionality is provided by ZDES mode 2 as will be detailed in the next section. It is worthwhile to notice that current best-practices within the hybrid RANS/LES community suggest the authors’ point of view is now increasingly shared by other teams (see for instance discussions by P. Tucker [6] and NASA [7] as well as the zonal RANS-IDDES technique [8]).

2.2 Zonal Detached Eddy Simulation (ZDES)

The Zonal Detached Eddy Simulation (ZDES) technique has been developed by Deck from 2002 onwards. It was first published in [9] and the complete formulation that proposes an efficient solution to prevent delay in the formation of instabilities has been more recently published in Ref. [1]. This approach takes full advantage of its zonal nature, not only to allow the user to specify RANS and LES regions, but also to make possible the use of various formulations within the same calculation (an example is provided in § 4.2).

The ZDES method aims at treating in a single model all classes of flow problems indicated in Figure (1) and typical applications associated. A hybrid length scale d_{ZDES} entering the Spalart-Allmaras model [10] turbulence model is defined:

$$\tilde{d}_{ZDES} = \tilde{d}_{mode} \left(\tilde{\Delta}, d_w, U_{i,j}, \nu, \tilde{\nu}, \frac{\partial \tilde{\nu}}{\partial n}, \frac{\partial \|\omega\|}{\partial n} \right) \quad (1)$$

$$mode = 0, 1, 2, 3 \quad (2)$$

with $\tilde{\Delta}$ denoting the subgrid length scale entering \tilde{d}_{ZDES} that depends on the grid cell size, $U_{i,j}$ the velocity gradients, d_w the distance to the wall, $\|\omega\|$ the magnitude of vorticity, ν and $\tilde{\nu}$ the kinematic and pseudo eddy viscosity as well as $\partial/\partial n$ the derivative in the wall-normal direction. The definition of \tilde{d}_{ZDES} is not a minor adjustment in the DES framework since the modified lengthscales depend not only on the grid but also on the velocity and eddy viscosity fields and their wall-normal derivatives.

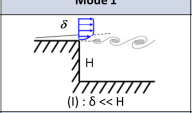
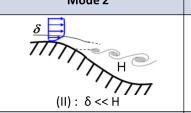
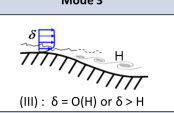
Zonal Detached Eddy Simulation (ZDES)			
	Mode 1	Mode 2	Mode 3
Flow category			
Applications	Base flow, free shear flows, spoilers, steps, slat/flap cove, etc.	Buffet, flaps, duct flows, nacelle intake, etc.	Corner flows, turbulent boundary layer, separation onset on high lift devices, shallow separations, etc.

Figure 1: Classification of typical flow problems, associated ZDES modes and examples of applications. *mode 1*: separation fixed by the geometry, *mode 2*: separation induced by a pressure gradient on a curved surface, *mode 3*: separation strongly influenced by the dynamics of the incoming boundary layer. RANS (*mode 0*) is the default mode (adapted from Deck[1]).

Thus, ZDES offers an attractive flexibility in the treatment of turbulent flows in technical applications and has been applied extensively with good results over a range of Mach numbers and configurations as will be illustrated in the following.

3 Simulation of massively separated flows

3.1 Mode 1

Many applications are concerned with massively separated flows as is the flow in the base region of a space launcher. ZDES is well adapted to simulate massively separated flows which rapidly develop strong instabilities overwhelming the turbulence inherited from upstream boundary layers. Within ZDES mode 1[1], the issue of slow delay in the formation of instabilities has been solved by using a subgrid length that depends not only on the grid but also on the velocity field (see [11]). As reminded earlier, a modern challenge lies in the taking into account of geometrical complexity without spoiling the quality of the results provided by a proven and effective numerical approach. To solve complex flows around realistic configurations in applied aerodynamics, a coupled approach between IBC (Immersed Boundary Conditions) and ZDES is proposed in [12]. This methodology is applied to a full space launcher configuration to assess its capability to return the interactions between the technological details, modeled with IBC, and the simplified afterbody, modeled with a body-fitted (BF) approach consisting in classical no-slip boundary conditions, in the turbulent flow field surrounding the main stage of

the space launcher afterbody. The considered configuration is a full Ariane 5 model with a 1:60 subscale ratio tested in NLR's DNW-HST facility ($M_0 = 0.8$; $Re_D = 1.18 \times 10^6$). The Z-shape sting holding the model in the wind tunnel is also taken into account in order for the simulation to be representative of the experiment [13].

Figure (2) displays the salient features of the turbulent field over the massively separated flow by showing an iso-surface of the Q criterion colored by the streamwise velocity. The several technological devices (DAAR ring, asymmetric struts, helium sphere, etc.) characterizing the afterbody of the Ariane 5 space launcher are taken into account *via* a zonal IBC approach. Indeed, the design of a classical body-fitted structured ZDES grid around such a complex configuration is quite impossible. Besides, this figure also shows that both mean and fluctuating pressure fields are well assessed with this methodology.

More generally, in [12] the authors argued that combining the IBC method in a zonal manner on a structured grid constitutes a serious and valuable alternative to unstructured mesh strategies in a hybrid RANS/LES framework since this preserves the robustness and accuracy of the time-honoured structured grid methods which are strongly validated.

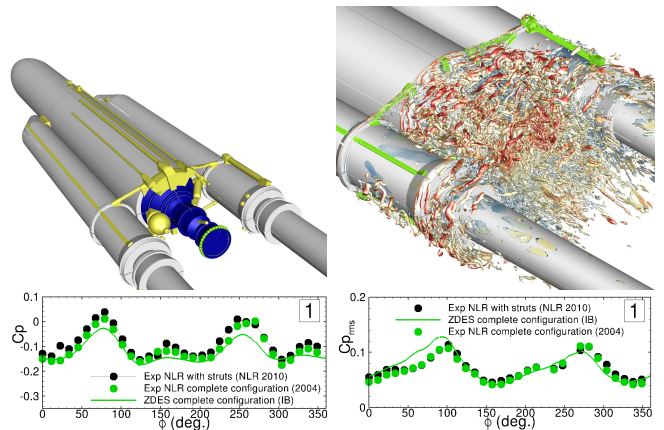


Figure 2: Comparison of the unsteady quantities of interest between NLR's experiments and ONERA's ZDES/IBC. **Top left:** Geometry of the full launcher with technological details (yellow), surface used for side-load integration (blue) and ring on the nozzle used to plot C_p and $C_{p_{rms}}$ evolutions (green). **Top right:** Visualization of Q criterion showing the coherent structures ($Q \cdot D^2 / U_\infty^2 = 200$) in the afterbody flow region. **Bottom left:** Azimuthal evolution of C_p at the end of the nozzle. **Bottom right:** Azimuthal evolution of $C_{p_{rms}}$ at the end of the nozzle. NLR's experiments on Ariane 5 complete configuration (green symbols), NLR's experiments on Ariane 5 with struts linking the main stage to the boosters only (black symbols), ONERA's ZDES/IBC on Ariane 5 complete configuration (green solid lines). Grid details: ($N_{xyz} = 75 \times 10^6$, azimuthal refinement: $\Delta\phi = 1^\circ$). Adapted from [12].

3.2 Mode 2

ZDES also provides an "automatic" operating option (referred to as mode 2 in the following) for which the switch between RANS and LES regions is dynamically set by the model itself. As an example, mode 2 is retained when the location of separation is not known in advance *i.e.* when it is induced by a pressure gradient.

In practice two main issues arise in any “DES-type” methods. The first one concerns an insufficient protection of the attached boundary layer region on fine grids (*i.e.* when $C_{DES}\Delta < \delta$), while the second one concerns a possible delay in the formation of “LES-content” in free shear layers. While the standard f_d function entering standard DDES [14] fails for fine meshes (typically when $C_{DES}\Delta < 0.3\delta$) and/or with adverse pressure gradients, the authors [15] have recently proposed a robust ZDES mode 2 mitigating the two aforementioned issues.

A highly challenging and difficult case for hybrid RANS/LES methods is the numerical simulation of transonic buffet because it presents a thin-layer separation that moves significantly in time at a time-scale that is much much slower than the one of the wall-bounded turbulence. The test case retained here is the supercritical airfoil OAT15A in the same flow conditions as in the experiment of Jacquin *et al.* [16] ($Re_c = 3 \times 10^6$, $M_0 = 0.73$, $\alpha = 3.5^\circ$). The salient features of the instantaneous flow field are highlighted by figure 3(a), which shows the isosurface of the Q criterion coloured by the streamwise velocity magnitude and the $P/P_0 = 0.57$ isosurface to mark the shock location. The location of the shock is evidenced by plotting an iso-surface of pressure. One can first note that no resolved turbulent content can be seen in the flow upstream of the shock as this boundary layer is treated in URANS mode within ZDES mode 2. Downstream of separation, ZDES mode 2 switches rapidly in its scale resolving mode as no delay in the LES content formation can be depicted. The power spectral densities for two characteristic sensors located respectively on the lower and on the upper side of the airfoil are compared with the experiment in figure 3(b). The first sensor is located at the upper side close to the trailing edge at $x/c = 0.9$. The periodic nature of the large-scale self-sustained motion of the shock is evidenced by the strong harmonic peaks in the spectra. On the experimental side, the main peak is at 69 Hz (or $f_c/U_0 = 0.065$) and is very well reproduced by the present calculations together with the broad-banded spectral distribution at higher frequencies. The second sensor is located at the lower-side of the airfoil where ZDES mode 2 operates in URANS mode owing to its design so that only the high amplitude and low frequency fluctuations can be captured by the calculation.

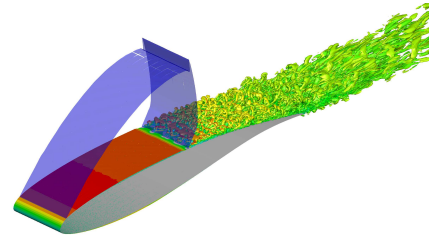
Another example is provided in Figure (4) where a complete aircraft at full scale 1:1 in true flight conditions ($Re_{AMC} = 50.10^6$) is simulated with a focus on the jet flow for an affordable CPU cost since the grid size could be limited to 200.10^6 points thanks to the skillful combination of ZDES together with the Chimera technique.

The new ZDES mode 2[15] can be considered as a case-independent answer to the demand for a general automatic and robust RANS/LES treatment of attached and massively separated flows.

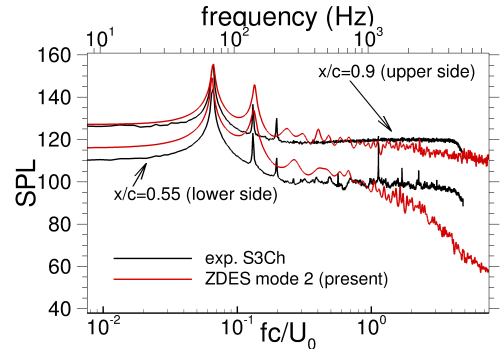
4 Towards wall turbulence simulation

4.1 High Reynolds number turbulent boundary layer

Boundary layers spatially developing at high Reynolds numbers are ubiquitous in engineering and geophysical flows. Consequently, wall-bounded turbulence plays a



(a) Isosurface of the Q criterion $Q = 40 \left(\frac{U_0}{c}\right)^2$ colored by the streamwise velocity component and $P/P_0 = 0.57$ isosurface to mark the shock location.



(b) PSD of pressure fluctuations at the lower and upper sides of the airfoil $SPL = 20 \log_{10} \left(\sqrt{G(f)} / 2.10^{-5} \right)$

Figure 3: ZDES mode 2 of the flow around the OAT15A airfoil in transonic buffet condition. Grid details: $N_{xyz} = 58 \times 10^6$, $N_z = 148$, $L_z/c = 0.2$. Adapted from [15].

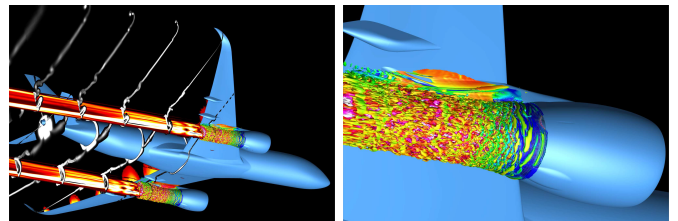


Figure 4: ZDES of the flow around a complete aircraft at scale 1:1 in true flight conditions, with focus on the jet development ($Re_{AMC} = 50.10^6$, $M = 0.8$, 200.10^6 points). Mode 2 is used for the whole computational domain. The grid size has been limited to 200.10^6 points thanks to the Chimera technique which allows the use of a fine mesh only where it is necessary, namely in the jet development area. Adapted from [2].

key role in many applications, especially because of its impact on friction drag, adverse-pressure-gradient response and incipient flow separation. A RANS averaged description may be insufficient in such cases because of the influence of the turbulent fluctuations from an incoming thick boundary layer on the dynamics of a mild flow separation, but also because of the RANS modelling limitations in presence of strong pressure gradients. Besides, some applications such as aeroacoustic or unsteady load predictions require the explicit resolution of turbulent fluctuations. ZDES mode 3 is devoted to zones where turbulence should be resolved inside attached boundary layers. Turbulence in the outer layer is LES-resolved whereas a near-wall RANS zone plays the role of wall model. With a recommended RANS/LES

interface location near $d_w = 0.1 \delta_{99}$, mode 3 becomes the Wall-Modelled LES branch of ZDES [17] with a significant computational cost saving at high Reynolds numbers compared with a Wall-Resolved LES as illustrated in Figure (5). Furthermore, the capacity of ZDES mode 3 to perform as WRLES has also been validated [18, 19]. The resolved fields in WRLES (fine mesh) and WMLES (coarser mesh) are compared in Figure (6) together with the interpolation of the WRLES field on the WMLES grid (showing the best that may be expected from the WMLES simulation). This illustrates the overall good performance of the WMLES use of ZDES.

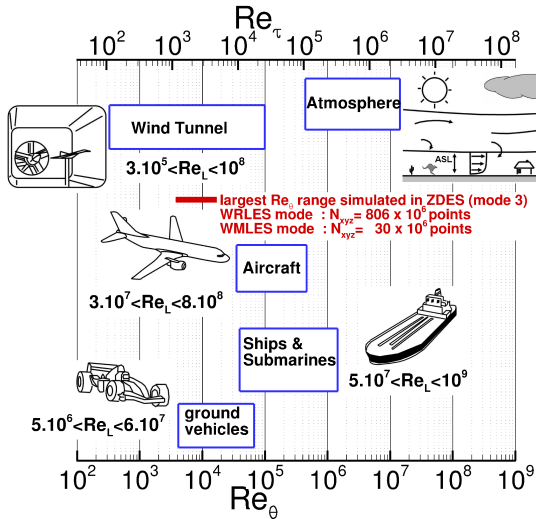


Figure 5: Typical Reynolds numbers in boundary layer applications. Re_L and Re_τ denote the Reynolds numbers based on the streamwise characteristic length and momentum thickness, respectively. Re_τ denotes the friction Reynolds number. ASL: Atmospheric Surface Layer; PBL: Planetary Boundary Layer. The largest wall turbulence simulation performed with ZDES (both in WMLES [17] and WRLES[19] operating modes) to date is emphasized along with the corresponding grid size. Note that the Reynolds number range achieved corresponds to the one commonly observed in sub-scale wind tunnels and that the use of WMLES allows a CPU cost reduction factor close to 30 compared to a complete WRLES simulation. Adapted from Deck *et al* [19].

The last evolutions of the RANS/LES interface treatment (outer-scaled positioning and smooth interface function) enable an accurate prediction of mean skin friction within a 5 % error margin [17, 20]. The ZDES technique has been used together with theoretical developments in order to better understand the dynamics of wall-bounded turbulence at high Reynolds numbers, which is an active field of academic research with a wide scope of practical applications (Figure (5)) and relatively recent discoveries such as superstructures [21]. The respective contributions of resolved and modelled turbulence to mean skin friction have been investigated with a focus on the role of the largest scales, leading to a new physical decomposition [19, 22]. Further refinements of the physical analysis have been introduced focusing on the scale dependence of the convection velocity of the velocity fluctuations [23]. These studies have confirmed the dominant role played by the production of turbulent kinetic energy in the logarithmic layer at high Reynolds numbers which ZDES mode 3 aims to resolve (at least partially) in order to attain a higher degree of universality than provided by RANS modelling.

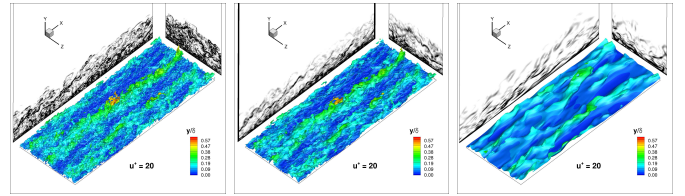
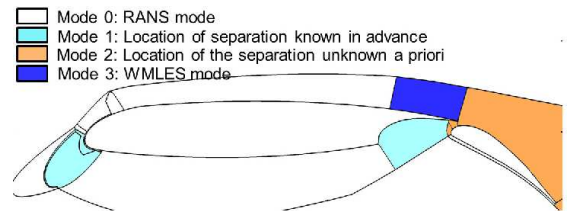
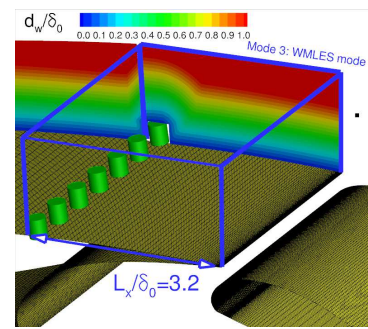


Figure 6: ZDES mode 3 simulations of a zero pressure gradient flat plate turbulent boundary layer. Iso-surface of the streamwise velocity $u^+ = 20$ coloured by the wall distance y/δ , near $Re_\theta = 13\,000$, and numerical Schlieren (density gradient magnitude). Left: fine mesh ($\Delta x = 50^+/\Delta z = 12^+$) WRLES ZDES; Center: Fine mesh ($50^+/12^+$) WRLES ZDES interpolated on the WMLES ($200^+/100^+$) mesh; Right: WMLES mesh ($200^+/100^+$) ZDES, $y_{\text{interface}} = 0.1\delta$.



(a) ZDES zones for the calculation of the three-element airfoil



(b) Roughness elements in the WMLES domain.

Figure 7: Computational description. d_w/δ_0 is the normalized distance to the wall where δ_0 is the boundary thickness at the inlet domain. Adapted from [24].

4.2 Low noise turbulent generation

For WMLES of fully turbulent boundary layers, resolved turbulence must be injected into the flow. This means that the ZDES mode 3 technique is used in conjunction with a turbulent injection method. However, in many applications involving compressible flows, the acoustic footprint of this injection may be problematic since the acoustic waves are important and must be predicted accurately at the boundaries and in the interior, especially for aeroacoustic studies.

In [24], the authors present a turbulent inflow for a rapid and low noise switch from RANS to Wall-Modelled LES on curvilinear grids with compressible flow solvers. The new approach relies on roughness elements described as immersed boundaries (ZIBC, Zonal Immersed Boundary Conditions as described in [12]) whose length scales are selected in order to disturb the boundary layer profile and generate large scale vorticity. The fluctuations are then enhanced by a dynamic forcing approach (inspired by Spille-Kohoff & Kaltenbach [25] and adapted to ZDES by [26, 27]), enabling a quick transition from the vorticity generated by the roughness to fully devel-

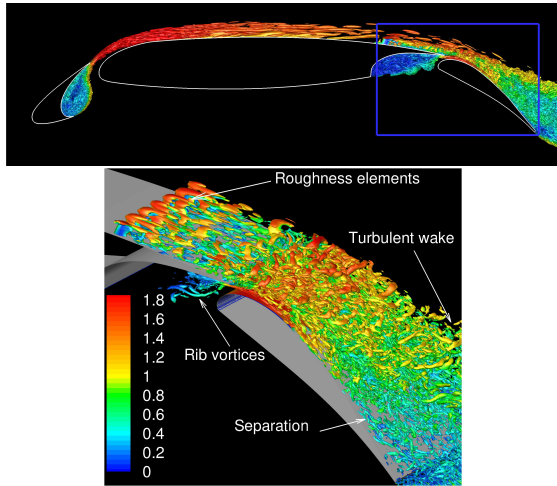


Figure 8: Isosurface of the Q criterion coloured by the velocity magnitude $\|\mathbf{u}\|/U_0$ in the flap area (top view: $Q \frac{c^2}{U_0^2} = 100$; zoom: $Q \frac{c^2}{U_0^2} = 3000$). Adapted from [24].

oped realistic turbulence.

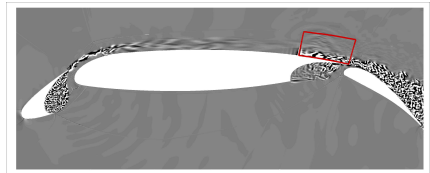
The robustness of the method is tested in the flow around a three-element airfoil with WMLES in the upper boundary layer near the trailing edge of the main element. The proposed modelling methodology has been assessed on the LEISA three-element airfoil designed by DLR[28] for flow conditions corresponding to aircraft approach. The chord Reynolds number is $Re_c = \frac{U_0 c}{\nu} = 2.09 \times 10^6$ (with $U_0 = 51 \text{ m.s}^{-1}$ and $c = 0.6 \text{ m}$). In addition, the streamwise (respectively spanwise) grid resolution is $\Delta x/\delta_0 = 0.086$ (respectively $\Delta z/\delta_0 = 0.026$) corresponding to $\Delta x^+ = 250$ (respectively $\Delta z^+ = 75$) when expressed in inner scales. Note also that the computational domain length where mode 3 is retained (see figure 7(a)) is $L_x/\delta_0 = 3.2$ making the WMLES very challenging and thus permits to assess the efficiency of the proposed methodology.

The salient features of the instantaneous flow field are highlighted in Figure (8). The flow in the slat cove displays a large recirculation bubble bounded by a shear layer emanating from the slat cusp and reattaching near the slat trailing edge. Similarly, the flap cove also behaves like a shallow cavity. In spite of the very short relaxation distance allowed, self-sustainable resolved turbulence is generated in the outer layer in the ZDES mode 3 zone with significantly less spurious noise than with an approach involving White Noise instead of ZIBC roughness elements. Both approaches are compared in Figure (9), showing the instantaneous $-\frac{1}{\rho} \frac{\partial p}{\partial t}$ field so that both sound waves and turbulent flow regions are evidenced. The contamination from the white noise application is clearly visible since nearly spherical waves can be seen from the region very near the RANS (mode 0 domain) to WMLES (mode 3 domain) transition (see figure 9(a)). These waves appear to have their highest amplitude near the inlet boundary but contaminate the whole pressure field as discussed in [27]. Conversely, the calculation based on the immersed roughness elements induces significantly less spurious noise at the inlet (see figure 9(b)) since the use of non-moving obstacles has the great advantage of being steady and produces less spurious noise than the inflow method based on the introduction of random velocity fluctuations. Note also that the ZDES grid count for this latter test case is more than two orders of magnitude lower than the Wall-Resolved LES

requirement [29] and a unique mesh is involved, which is much simpler than some multiple-mesh strategies devised for WMLES or turbulent inflow.



(a) ZDES mode 3 - anisotropic White Noise - Dynamic Forcing



(b) ZDES mode 3 - ZIBC - Dynamic Forcing

Figure 9: Instantaneous field of $-\frac{1}{\rho} \frac{\partial p}{\partial t}$. Grid details: $N_{xyz} = 50 \times 10^6$, $N_z = 128$, $L_z/c = 0.16$. Adapted from [24].

5 Conclusion

The debate concerning the zonal/non-zonal treatment of turbulence is useful and the authors think that both zonal and non-zonal methods will probably grow because both are needed and one may expect that the next improvements of both approaches of turbulence modelling should be mutually beneficial.

The versatility of ZDES lies in its capability to be used not only in an industrial framework as argued above, but also for academic research. Among the next foreseen challenges in applied numerical aerodynamics, one may cite the capture of the boundary layer dynamics including transition and pressure-gradient-driven separation issues.

Acknowledgment

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