AIRFRAME NOISE PREDICTION BY MEAN OF A ZONAL RANS/LES APPROACH

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ABSTRACT

Some hybrid CFD/CAA methods have generally to be used for the numerical simulation of trailing-edge noise (see Manoha et al. (2002) for instance). This study focusses on the first step of such hybrid methods, which is to get an accurate description of the unsteady aerodynamic sources by the mean of a 3D unsteady simulation of the flow. Such a simulation is however generally still away from the numerical capabilities of "usual" supercomputers. This paper proposes a zonal LES method for the numerical prediction of the aerodynamic noise sources. This method allows to perform only some zonal LES close to the main elements responsible of sound generation, while the overall configuration is only treated by a RANS approach. Attention will be paid to the particular boundary treatment at the interface between the RANS and LES regions. The method is first assessed in the simulation of a flat plate ended by a blunted trailing-edge, and then applied to the simulation of the flow over a NACA0012 airfoil with blunted trailing-edge.

INTRODUCTION

This study deals with the numerical prediction of the aerodynamic noise generated by airfoils. More particularly, it focusses on the problem of trailing-edge noise. This complex problem remains however out of reach of DNS/LES methods. For this reason, some hybrid CFD/CAA methods have been developed in the past few years (see Manoha et al. (2002) for instance), in which an unsteady CFD simulation is used to get a prediction of the acoustic sources, which are then used as an entry data of an acoustic propagation solver. This study focusses on the first step of this hybrid method. Indeed, Large-Eddy Simulations of realistic flows remain generally still away from the numerical capabilities of "usual" supercomputers. In this paper a zonal RANS/LES method is proposed to perform some numerical predictions of aerodynamic noise sources at a moderate computational cost. The main idea is then to perform only some zonal LES close to the main elements responsible of sound generation, while the overall configuration is only treated by a much cheaper RANS approach. However, the main difficulty remains the coupling between the RANS and LES regions. In this paper, a particular attention will be paid to the treatment of turbulent boundary layers at the inflow of the LES region.

The proposed approach is described in the first section of the present paper. Then, a first test case is considered in the second section to assess the approach. This case deals with the flow over a flat plate ended by a blunted trailing-edge. Finally, the third part of the paper presents some early results of the application of the zonal RANS/LES method to the numerical simulation of the noise sources generated by the flow around a NACA0012 airfoil with a blunted trailing-edge.

THE ZONAL RANS/LES APPROACH

For a large overview of the zonal RANS/LES method, the reader is referred to the works by Labourasse and Sagaut (2002). The principle of the method is to decompose the flowfield U as a mean part and a fluctuating part. The mean part $\langle U\rangle$ can be computed using a classical RANS parametrization on the whole configuration, while the calculation of the fluctuating part U' is achieved locally thanks to a LES-like simulation. This decomposition represents a triple decomposition of the full unsteady field U as:

$$U = \langle U\rangle + U' + U_{SGS} = \overline{U} + U_{SGS} \qquad (1)$$

where $\overline{(.)}$ corresponds to the LES filtering, and U_{SGS} refers to the (unresolved) subgrid scales in the LES terminology.

Starting from the filtered and Reynolds-averaged compressible Navier-Stokes equations, some evolution equations can be simply derived for the perturbation field U'. These equations are referred to as the Non-Linear Disturbance Equations (NLDE):

$$\frac{\partial U'}{\partial t} + \mathcal{N}\left(U' + \langle U\rangle\right) - \mathcal{N}(\langle U\rangle) = \mathcal{T}_L - \mathcal{T}_R \qquad (2)$$

where U is the vector of the conservative variables, $\mathcal{T}_R$ and $\mathcal{T}_L$ denote respectively the classical Reynolds and subgrid-scale terms, and $\mathcal{N}$ denotes the Navier-Stokes operator:

$$\mathcal{N}(U) = \left(\begin{array}{c} \nabla.(\rho u) \\ \nabla.(\rho u \otimes u) + \nabla p - \nabla.\sigma \\ \nabla.\left((\rho E + p)u\right) - \nabla.\left(\sigma : u\right) + \nabla.Q \end{array}\right) \qquad (3)$$

where p is the pressure, ρ the density, u the velocity vector, ρE the total energy, σ the viscous stress tensor, and Q the viscous heat flux vector.

It was shown (Labourasse and Sagaut, 2002) that solving the perturbation equations instead of the full LES equations allows to minimize the sensitivity of the solution to numerical errors and to consider some reduced domain sizes. This thus allows to perform locally a LES coupled with a global RANS simulation.

RANS/LES BOUNDARY TREATMENT

To prevent reflections at the LES zone interfaces where the mean field is imposed as a boundary condition, an extension of the characteristic theory (Thompson (1987)) to the perturbation formulation has first been retained as boundary condition in the previous works dealing with this zonal LES method (see Sagaut *et al.*(2004) for more details). The approach has been applied to the simulation of the unsteady flow in some realistic configurations such as a low-pressure turbine blade (Labourasse & Sagaut (2002), Sagaut *et al.*(2004)) and the slat cove from a high-lift wing profile (Terracol *et al.*(2003)).

However, such a boundary treatment appears only valuable in the case in which quasi-laminar boundary layers are present at the inflow of the LES region. A particular treatment is still needed to account for some fully-developed turbulent boundary layers (TBL) at inflow. In this study, two methods have been retained to account for the coherent turbulent structures present in TBL:

- The first one is to combine a compressible extension of the recycling strategy developed by Lund *et al.*(1998) with the previous characteristic boundary treatment and apply it to the perturbation variables at the LES region inflow. The principle of the method is to extract some perturbations U' in a plane located downstream of the inflow plane, and inject them at the inflow location after an appropriate rescaling. In this study, the compressible extension proposed by Sagaut *et al.*(2004) has been retained, which consists in applying a simple recycling treatment to the pressure and temperature variables. The algorithm then reads:

  $$\left\{ \begin{array}{lcl} u'_i\big|_{in}\left(y^+_{in},t\right) & = & \beta\, u'_i\big|_{rec}\left(y^+_{rec},t\right) \\ T'\big|_{in}\left(y^+_{in},t\right) & = & T'\big|_{rec}\left(y^+_{rec},t\right) \\ p'\big|_{in}\left(y^+_{in},t\right) & = & p'\big|_{rec}\left(y^+_{rec},t\right) \end{array} \right. \qquad (4)$$

  where β represents the ratio of the friction velocities at the inflow (in) and recycling (rec) planes: $\beta = \frac{u_\tau^{(in)}}{u_\tau^{(rec)}}$. This approach has been proven to be efficient when dealing with boundary layer simulations with reduced streamwise extent in several studies, and may thus appear as a good candidate for the present zonal approach. However, it is to be noted that the main difficulty relative to this approach remains to initiate the recycling process. In general, a secondary TBL/channel flow simulation has to be used to provide some appropriate perturbations. Moreover, such a process may introduce a non-physical recycling frequency due to the artificial streamwise periodicity introduced in the simulation, which depends on the location of the recycling plane.

- The second one is to perform a synthetic reconstruction of the typical structures present in TBL. For this purpose, an approach based on the one developed by Sandham *et al.*(2003) for supersonic flows has been retained.

Table 1: Analytical TBL parameters

j	$C_{1j}\,\frac{U_\infty}{u_\tau^{(in)}}$	$C_{2j}\,\frac{U_\infty}{u_\tau^{(in)}}$	y_j^{max}	λ_z^+	τ^+	ϕ_j
1	15.2	-5	$12\ \mu/u_\tau^{(in)}$	100	100	0
2	5.6	-2.8	δ^*	133	32	0.1
3	5.6	-2.8	$2\delta^*$	200	58	0.2
4	5.6	-2.8	$3\delta^*$	400	109	0.3

  Again, the approach is combined with the characteristic boundary treatment for the perturbation variables. At the inflow, the streamwise (u'_1) and wall-normal (u'_2) components of the velocity fluctuations are computed as follows:

  $$\begin{array}{lcl} u'_i & = & U_\infty \sum_{j=1}^{4} C_{ij} \cos(\beta_j z + \phi_j) \sin(\omega_j t) \\ & & \times \left(\frac{y}{y_j^{max}}\right)^{n_j} \exp\left(-\left(\frac{y}{y_j^{max}}\right)^{n_j}\right) \end{array} \qquad (5)$$

  where U_∞ is the reference velocity and m is the number of modes to be considered. The first mode ($j = 1$) provides a representation of the near-wall streaks, while higher-order modes ($j > 1$) represent some larger structures with a spanwise extent growing up through the boundary layer. The coefficients β_j and ω_j are chosen to match the typical sizes of the coherent structures present in TBL, as in Sandham *et al.*(2003). The peak perturbation location are respectively fixed to $\left(y_1^{max}\right)^+ = 12$, and $y_j^{max} = (j-1)\delta^*$, $j > 1$, where δ^* is the displacement thickness at the inflow location. The parameter ϕ_j denotes some spanwise phase shift coefficients. The amplitude coefficients C_{ij} have been tuned to match as well as possible typical TBL RMS profiles. The exponent n_j has also been introduced, to modify the envelope of the first mode, with $n_1 = 1 - \frac{1}{6}\left(1 + \tanh\left(10\left(y - y_1^{max}\right)\right)\right)$, and $n_{j\neq 1} = 1$. Finally, the spanwise component u'_3 is derived from a divergence-free condition. In practice, a white noise is also added in the boundary layer zone, with a maximum amplitude of 4% of the reference velocity. In this study, four different modes were considered. The values of each parameter used here are detailed in table 1. For this purpose, we introduce (in wall units) the spanwise spacing of the synthetic structures $\lambda_z^+ = \frac{2\pi u_\tau^{(in)}}{\beta_j \mu}$, and their lifetime $\tau^+ = \frac{2\pi\left(u_\tau^{(in)}\right)^2}{\omega_j \mu}$ where μ denotes viscosity.

NUMERICAL METHOD

The spatial scheme retained in this study is the modified AUSM+P scheme developed by Mary & Sagaut (2002). This scheme takes advantage of a wiggle detector that allows to limit the numerical dissipation of the scheme to the zones where odd-even numerical wiggles are detected. Elsewhere, the scheme acts as a centered non-dissipative scheme well-suited for LES applications. For time integration, a second-order accurate implicit Gear scheme, based on an approximate Newton solver has been used. Finally, the subgrid-scale model retained in this study is the selective mixed-scale model fully described in the works by Lenormand *et al.*(2000)

APPLICATION TO THE HYBRID FLAT PLATE / BASE FLOW CONFIGURATION

To assess the proposed approach, the flow over a thin flat plate ended by a blunted trailing-edge has been considered. This leads to an acoustic wave emission at the trailing-edge. A reference LES on the full configuration (”FULL”) taking into account the boundary layer transition process has first been carried out. In this simulation, the flat plate extends over $60h$, with h the trailing-edge thickness. The spanwise extent of the domain is $L_z = 4h$, with periodicity conditions. A laminar Blasius velocity profile with a thickness of $\delta_0 = 0.27h$ has been imposed at the inflow, with a small random perturbation added to initiate the natural transition process. The Reynolds number based on the trailing-edge thickness is $Re_h = 10,000$, and the Mach number of the flow is 0.5.

In this simulation, the natural transition process is accounted for, and occurs at a location of $45h$ upstream of the trailing-edge. Then, a shorter computational domain located close to the trailing-edge has been considered. The streamwise extent of the flat plate region has been reduced to $11h$ in this case. As a mean field, we have chosen to use here the averaged LES field, to be able to compare our results with those from the full LES. At this inflow location, the boundary layer thickness is $\delta \simeq h$. Three zonal LES simulations have been performed: the first one uses only the characteristic boundary treatment at inflow (”LAM”), while the second one takes advantage of an additional recycling treatment for the perturbations (”REC”), and the third one (”ANA”) relies on the use of the analytic TBL model (4). Figure 1 shows the mean and RMS velocity profiles obtained in each case at a location of h upstream of the trailing-edge. It is to be noted that only the zonal simulations using a particular turbulent treatment at inflow lead to some results in good agreement with the full reference LES. These two simulations also exhibit a highly three-dimensional flow behavior, with a good representation of the typical structures present in TBL (see Fig. 2). Figure 3 shows the strong wave pattern emitted at the trailing-edge in the zonal simulation ”ANA” (the full computational domain is shown). As it can be seen in Fig. 4, the different simulations exhibit a peak at a Strouhal number of about $St = 0.24$ in the acoustic spectrum, with several harmonics. This figure reveals that the inflow treatment based on the recycling treatment leads to some numerical errors in the highest wavenumbers. More precisely, the additional broadband peak around $St \simeq 0.95$ has been clearly identified as the frequency associated to the cycling procedure.

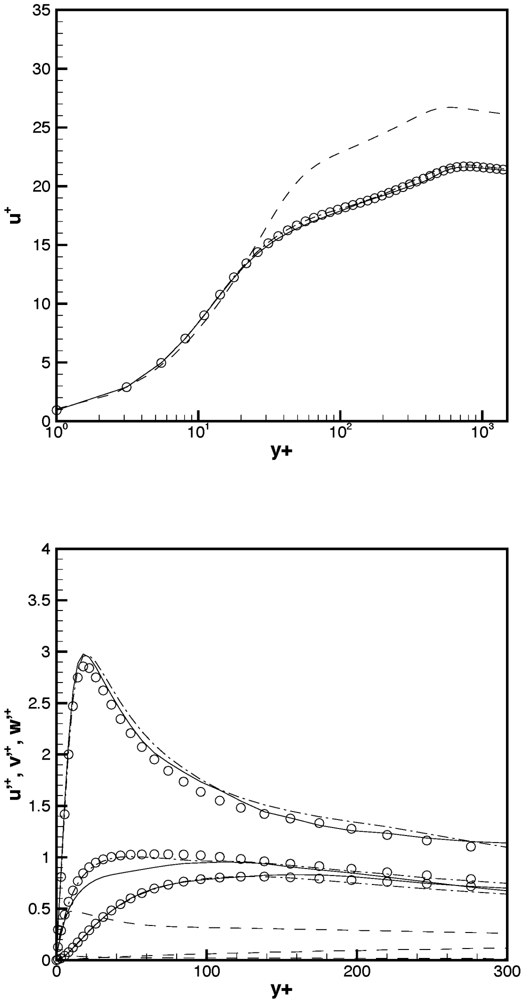

Figure 1: Mean streamwise (top) and RMS (bottom) velocity profiles. Symbols: Full LES; dashed line: LAM; dash-dotted line: REC; solid line: ANA

APPLICATION TO NACA0012 AIRFOIL

This case deals with the application of the method to the numerical prediction of the noise generated by the flow past a NACA0012 airfoil with a blunted trailing-edge, at a 5° angle of attack. The chord of the profile is $c = 60.95cm$, and the Mach number of the flow is $M = 0.205$, leading to a chord-based Reynolds number of $Re_c = 2,860,000$. The thickness of the trailing-edge is $h = 2.5mm$. All these parameters, except the angle of attack, match those of the NASA experiment of Brooks & Hodgson (1981).

This configuration has been extensively investigated in the works by Manoha *et al.*(2002), who performed a coupling between a compressible LES performed around the full airfoil, and acoustic propagation techniques combining the use of Linearized Euler Equations (LEE) and integral methods. Despite the success of the proposed LES/CAA coupling, the LES used as a basis for the study was subject to strong limitations in terms of grid resolution. In particular, the use of a spanwise extent which was sufficient to ensure a correct development of the spanwise structures at the trailing-edge led to an under-resolution of the TBL, and thus to some too small boundary layer thicknesses at the trailing-edge. The result was a strong overestimation of the main expected frequency of the associated acoustic wave emission.

It has thus be chosen to apply the zonal LES approach to the simulation of this kind of flow. A 2D steady RANS calculation (using the Spalart-Allmaras model) has first been performed over the full configuration. The grid used for this computation was composed of 321,600 meshpoints. Then, a small 3D LES region surrounding the trailing-edge has been defined, in which the proposed approach is applied (see Fig. 5).

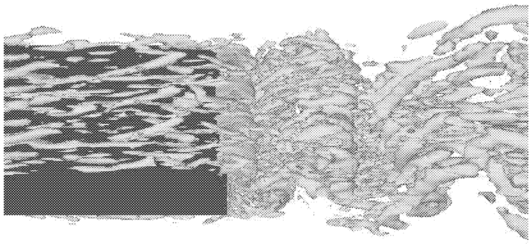

Figure 2: 3D view of the flow close to the TE (zonal LES)

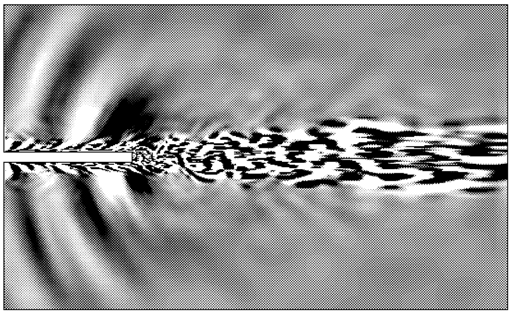

Figure 3: Dilatation field $\Theta = \nabla.u$ (zonal LES)

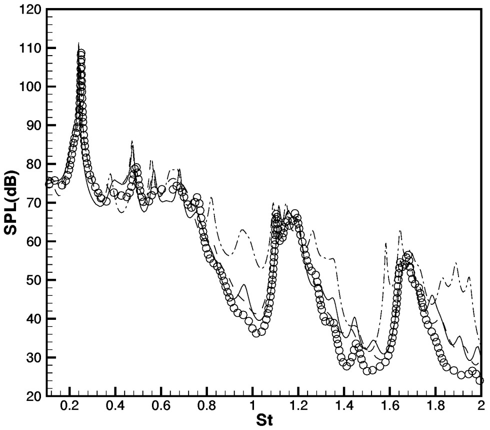

Figure 4: Pressure spectrum at $10h$ above the TE. Same key as fig. 1

The significant reduction of the extent of the LES region allows to consider a rather large spanwise extent of 1.67% of chord ($L_z = 1cm \simeq \delta$). The mesh considered here for the LES region, which matches the classical LES requirements in terms of resolution, is composed of roughly 5.4 millions of points (with 84 meshpoints in the spanwise direction). Finally, it has been chosen to use the analytical TBL model as inflow condition for the LES region. Figs. 6 and 7 show respectively some preliminary results of the spanwise vorticity component and of the dilatation field obtained close to the trailing-edge after a physical integration time of 26 ms.

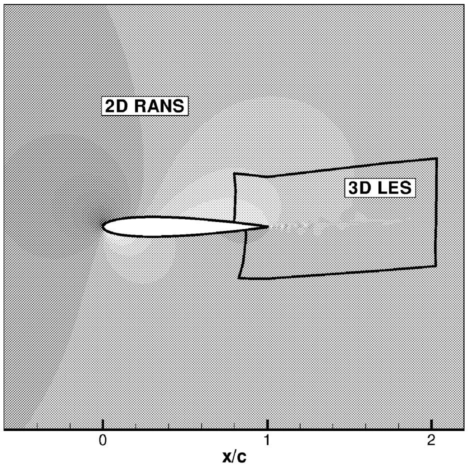

Figure 5: NACA0012 configuration

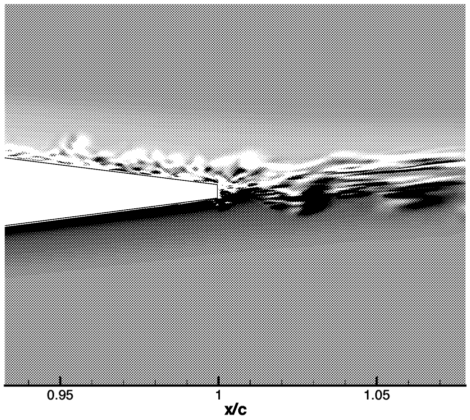

Figure 6: Spanwise vorticity

A turbulent vortex shedding is clearly observed, leading to an acoustic wave emission. Fig. 8 shows that this acoustic wave emission is associated to a broadband peak in the pressure spectrum, at a frequency of about 2,300 Hz, which is lower than the one reported by Brooks and Hodgson (around 3,000 Hz) in their experiment at a 0° angle of attack. This difference is however not so surprising when considering the 5° angle of attack which leads to a significantly thicker TBL at the trailing-edge on the suction side. Moreover, the amplitude of the main broadband peak in the pressure spectrum is well predicted (roughly 88 dB in the experiment). This result is thus much more consistent with the experiment than the one corresponding to the LES reported in the works by Manoha *et al.*, in which a main frequency of about 5000 Hz was obtained, with a global overestimation of 3 dB of the pressure levels.

CONCLUSIONS AND FUTURE WORKS

The proposed zonal LES method has been shown to allow to get a significant reduction of the cost of the simulations

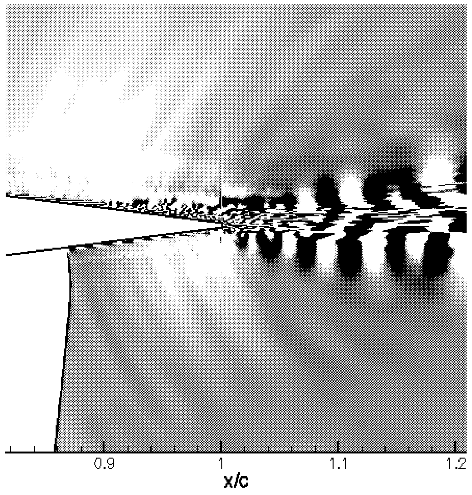

Figure 7: Dilatation field $\Theta = \nabla . u$ (zonal LES)

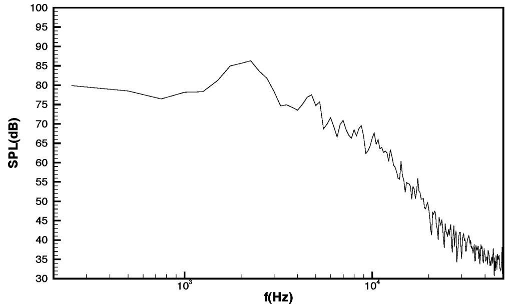

Figure 8: Pressure spectrum at the TE. Same key as fig. 1

associated to the numerical prediction of aerodynamic acoustic sources in comparison with classical LES. The analytical model of TBL used at inflow has been shown here to be the only one which allows to reproduce properly both the TBL and acoustic properties of a trailing-edge flow. The method has been assessed on an academic configuration, and then applied to a more realistic flow (NACA0012 airfoil). In this last case, the first results obtained with the zonal approach display a quite good agreement with some reported experimental results. It is to be noted here that previous classical LES performed on the same configuration did not exhibit a such good agreement, since the grid resolution could not be fine enough on the full configuration when a significant spanwise extent was considered.

In the future, a more extensive analysis and validation of the zonal NACA0012 simulation will be performed. Then, the zonal LES method will be used as the first step of a hybrid LES/CAA approach. In particular, it will be coupled with a high-order finite-difference Euler solver (Manoha *et al.*(2002), Terracol *et al.*(2003)) to describe the mid- and far-field noise radiation.

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