Numerical simulation of the turbulent separation reattachment flow around a thick flat plate.

C. Tenaud¹, Y. Fraigneau¹ & V. Daru¹,²

¹ LIMSI - UPR 3251 CNRS, BP.133, 91403 ORSAY Cedex, FRANCE, ² ENSAM, 151 Boulevard de l’Hôpital 75013 Paris, FRANCE.
E-mail: Christian.Tenaud@limsi.fr

Abstract. This work concerns the turbulent flow generated around a thick flat plate to study the relationship between instantaneous flow structures and the unsteady pressure field. LES results compare favorably to experiments thanks to using a high order scheme. Mean and fluctuating quantities are very well predicted in both the detachment and the reattachment regions. Dimensionless frequencies, characteristic of flapping and shedding phenomena, have also been recorded that are in agreement with experiments.

1. Introduction

This work deals with the numerical simulation of the turbulent flow generated around a thick flat plate with a sharp leading edge. This configuration constitutes an academic model for studying the main features of massively separated turbulent flows, encountered for instance around vehicles. One of the fundamental issues relates to the mechanisms driving the acoustic field in the surroundings of the body of an automobile, train or aircraft. Understanding these mechanisms is essential to develop noise reduction process. A major challenge is then the accurate prediction of the coupling between eddy structures and the unsteady pressure field [Hoarau et al. (2006)]. This coupling is central to acoustic source generation along the solid surfaces and in the core of the flow. Thus, a compressible flow approach, associated to a highly accurate and efficient numerical scheme, is needed to investigate such phenomena.

Regarding the flow around a blunt flat plate, though experimental studies [Castro & Epik (1998); Cherry et al. (1984); Djilali & Gartshore (1991); Kiya & Sasaki (1985)] have already been conducted, few numerical simulations of this flow configuration exist in the literature. They essentially concern incompressible flow simulations [Tafti & Vanka (1991); Yang & Voke (2000); Yang & Abdalla (2009)].

The final objective of this work is to provide LES reference solutions, in conjunction with experimental data that have been recorded at the Pprime laboratory of Poitiers. This database will serve to develop analysis methodologies regarding the phenomena described above. In this paper, we validate our numerical results by comparison with experimental measurements, coming from both the Pprime laboratory and the literature [Cherry et al. (1984); Kiya & Sasaki (1985)].
2. Numerical procedure

The governing equations are the compressible Navier-Stokes equations coupled with an ideal gas equation of state, written in a dimensionless form by using the reference values of the density \( \rho_\infty \), the velocity \( U_\infty \), and the length scale \( L_0 \). This study is restricted to air flow with a constant specific heat ratio \( \gamma = 1.4 \) and a constant Prandtl number \( Pr = 0.73 \). The Reynolds number is based on the reference values: \( Re_L = \rho_\infty U_\infty L_0 / \mu(T_\infty) \). \( Ma = U_\infty / (\gamma RT_\infty) \) is the Mach number (where \( R \) is the constant of the gas, \( R = 287 \text{ J.Kg}^{-1}.\text{K}^{-1} \)). \( \mu(T_\infty) \) is the dimensionless dynamic viscosity related to the reference temperature \( T_\infty \) by a Sutherland’s law. In the LES framework, these equations are filtered with an implicit spatial filter combined with the density-weighted Favre decomposition [Favre (1965)].

To account for the kinetic energy dissipation occurring at small-scales, the deviatoric part of the subgrid scale tensor is related to the strain rate tensor of the resolved velocity field by using a subgrid viscosity by assuming a Boussinesq hypothesis. To overcome the influence of the subgrid modeling on LES results, several simulations have been conducted by using two subgrid viscosity models: the mixed scale model, first introduced by Ta Phuoc [Ta Phuoc (1994)], used by Sagaut [Sagaut (1998)] for incompressible flow calculations and extended to the compressible flow regime in [Tenaud & Ta Phuoc (1997); Doris et al. (2000)] and the dynamical subgrid-scale model, based on the Germano’s procedure [Germano et al. (1991); Germano (1992)], developed to better account for the local flow structure, improving the modeling of the anisotropic behavior. Results obtained with both models are compared and analyzed hereafter.

The resolution of the filtered Navier-Stokes equations has been performed by means of a finite volume approach. In the LES framework, LES computations must use numerical schemes that can represent small scale structures with a minimum of numerical dissipation to minimize the interactions with the sub-grid scale modeling. In the present study we used a coupled time and space scheme which is 7th-order accurate (in both time and space), named OS7 and developed by Daru & Tenaud (2004) for discretizing the convective fluxes. A second order centered scheme is used for viscous fluxes [Daru & Tenaud (2009)]. A directional Strang splitting is then applied for multidimensional solutions.

Simulations were performed on a parallel / vectorial supercomputer (NEC - SX8). A trivial domain decomposition by means of the MPI protocol, is adopted to decrease the restitution time. The computational domain is split into 8 sub-domains having \( 135 \times 61 \times 113 \) grid points each. The OS7 stencil spreading over 9 grid points, sub-domains are overlapped over 5 grid points in each direction. On other words, quantities on 5 planes are exchanged per direction through the interface between two consecutive sub-domains.

We consider an adiabatic blunt flat plate having a thickness \( H \) (taken as a reference length scale \( L_0 = H \)), mounted parallel to a free stream. It is equipped with a right-angled corner leading-edge. This flat plate spans the computational domain horizontally in its centerline. The inlet boundary is located \( 10H \) upstream of the sharp leading edge to minimize its influence on the uniform inlet boundary condition. The flat plate has a streamwise length of \( 25H \), extending up to the streamwise outlet boundary. Simulations, that are not reported here for clarity, were previously performed on several domain dimensions to check the influence of the domain extents on the LES results. The domain sizes we retained to analyze LES results are \( L_x = 35H \) in the streamwise direction, \( L_y = 5H \) in the spanwise direction and \( L_z = 17H \) in the normal to the flat plate direction. These dimensions, comparable to those used by [Lamballais et al. (2010); Yang & Abdalla (2009)], are required to largely weaken the influence of the domain boundaries. At the upstream boundary, a uniform flow is prescribed \( (\rho_\infty, U_\infty, T_\infty) \) leading to the previously defined Mach \( (Ma = 0.115) \) and Reynolds \( (Re_H = 7500) \) numbers. To handle tractable LES regarding the CPU time consumption, the Reynolds number has been chosen ten times smaller than in the Pprime experiments. Moreover, let us note that this value is four
to ten times smaller than experimental values found in the literature [Castro & Epik (1998); Cherry et al. (1984); Kiya & Sasaki (1983, 1985)].

As spanwise homogeneity is recovered in many experiments, for instance Kiya et al. Kiya & Sasaki (1983) recovered flow uniformity over ±3.5H on both sides of the midspan, periodicity is considered in the spanwise direction to study the intrinsic flow behavior without lateral wall-border effect. At the outlet as well as on upper and lower boundaries, non-reflecting conditions are prescribed by using characteristic based conditions Poinso & Lele (1992).

A mesh refinement study has been undertaken to check its influence on statistics. The mesh that gives rather grid independent results, consists in \((N_x \times N_y \times N_z) = (269 \times 121 \times 225)\) grid cells along the streamwise, spanwise and normal to the wall directions. Uniformly distributed grid points are used in the spanwise direction with a grid spacing of \(\delta y^+ = 16.6^+\), in terms of wall units. To well capture the separation-reattachment dynamics, non-uniform grids are however used in the streamwise \((x)\) and normal to the wall \((z)\) directions. The mesh is then tightened in the normal to the wall direction to ensure a first cell size above the wall less than one wall unit \((\Delta z^+ = 0.94^+)\). It is also tightened in the shear layer region edging the separation bubble. In the streamwise direction, it is refined both at the leading edge and in the reattachment region \((2.4^+ \leq \delta x^+ \leq 24^+)\). Though the mesh is stretched in the \(x-\) and \(z-\) directions, the grid spacing ratio between two consecutive cells is less than 13% over the computational domain.

3. Numerical results

The sharp corner at the leading edge fixes the detachment. Boundary layer separation then occurs over a large extent. The upper part of the separation bubble is bounded by a spatially developing mixing layer whose initial stage is certainly laminar and breakdowns toward turbulence through Kelvin-Helmholtz instability modes and higher modes with lambda-shape like patterns, further downstream. The flow behavior within the mixing layer development is mainly responsible of the separation extent [Castro & Epik (1998)]. According to numerous experimental works [Castro & Epik (1998); Cherry et al. (1984); Kiya & Sasaki (1983, 1985)], separation extent is about \(L_R = 5H\). Several flow parameters such as the tunnel blockage, spanwise end-walls and the spanwise aspect ratio, free stream turbulence intensity, for instance, undoubtedly influence the mixing layer development and consequently the \(L_R\) value [Castro & Epik (1998); Cherry et al. (1984); Hancock & Castro (1993)]. When the mixing layer impacts the plate surface, a turbulent boundary layer develops further downstream. Two main unsteadinesses of the separation are generally educed: the shedding and the flapping modes. The former is relative to the vortex shedding and is associated with the usual large scale motions of the shear layer. The latter, the low-frequency flapping mode, is an overall dynamical mechanism links to successive enlargements and shrinkages of the separated zone.

We first validate LES results obtained through the use of the mixed-scale model. We then studied the influence of the subgrid-scale model by comparing first results with those obtained by means of dynamical vorticity model. We finally analyze the space and time dynamics of the flow in the vicinity of the leading edge. Let us note that present LES results are obtained without free-stream turbulence because studying its influence is not the purpose of this paper and could be studied numerically in the next future.

3.1. Validation of LES results.

LES results are compared to data coming from experiments recorded at the EOLE facility of the Pprime Institut of Poitiers [Sicot et al. (2010)]; an anechoic open section wind tunnel. The test model is a blunt flat plate, having a thickness of \(H = 30\) mm, a length of \(1300\) mm and a spanwise extent of \(460\) mm, equipped with a sharp leading-edge and mounted at the mid-height of the nozzle section, parallel to the free stream. The experiments were performed at a free stream
velocity of $U_\infty = 40 \text{ m.s}^{-1}$. The Reynolds number of the experiments is $Re_H = 7.8 \times 10^5$. These data have not yet been published. However, as we will see hereafter, they are in very good agreement with results coming from the literature. To assure the validation of the present LES results, they are also compared to published numerical data coming from both DNS and LES as well as detailed results of well known experiments.

For comparisons we need to evaluate mean quantities (noted $\langle \cdot \rangle$) that are calculated by using integrations in both time and spanwise (homogeneous) direction: $\langle \cdot \rangle = \frac{1}{L_y \tau} \int_{L_y} \int_{\tau} dt \; dy$, where $\tau$ is the integration period. Dimensionless times are estimated by means of the inlet velocity ($U_\infty$) and the plate thickness ($H$). Mean quantities are computed as soon as a statistically converged state is reached. This convergence is checked on the time evolution of the $L^1$, $L^2$- and $L^\infty$-norms of both the mean and $r.m.s.$ values of the velocity components and the pressure. We assumed that it was reached for a dimensionless time of about $t_0 = 110$. Statistical quantities are then calculated over a dimensionless time interval of $\tau = 340$, corresponding approximately to forty vortex shedding events.

The spanwise averaged value of the reattachment length constitutes the first characteristic quantity of the separation. It is generally defined as the distance from the leading-edge where the average (in time and spanwise direction) value of the wall shear stress reaches zero. The $L_R$ value predicted by using the mixed-scale model is $L_R = 3.68$. The reattachment length is however slightly lowered by the dynamic vorticity model since $L_R = 3.38$. Current predictions underestimate the mean reattachment length since the generally admitted value across the literature is $L_R = 5H$ [Cherry et al. (1984)], for however high Reynolds number flows, which has clearly been recovered in the Pprime experiments [Sicot et al. (2010)]. Nevertheless, the current predictions are consistent with a previous LES study of separated leading-edge flow [Yang & Voke (2000)] that recorded weaker value ($L_R = 2.58$) than experiments ($L_R = 2.75$) for moderate Reynolds number ($Re_H = 3450$), though the leading-edge is semi-circular. As mentioned earlier, this quantity however seems very sensitive to flow parameters since $L_R$ is distributed in between [4, 5.5] in the literature for high Reynolds number flows [Cherry et al. (1984)], depending for instance on the the tunnel blockage, the spanwise extent or the free stream turbulence intensity. Though the current $L_R$ value is rather close to the lower bound of the experimental values, a Reynolds number effect or a solid blockage might explain the weak value of $L_R$. While predicted values of the mean reattachment length ($L_R$) do not quite agree with measurements obtained at a higher Reynolds number, LES results on velocity and pressure, for instance, can be compared with different data obtained at several Reynolds numbers, when quantities made dimensionless by using reference values at infinity, are plotted versus dimensionless coordinates using $L_R$ as reference length.

Figure 1 shows the predicted streamwise distribution of the wall mean pressure coefficient ($C_p = 2 \frac{\langle P \rangle_{wall} - P_\infty}{\rho_\infty U_\infty^2}$) and its $r.m.s.$ value ($C_{p, r.m.s} = 2 \sqrt{\langle p'^2 \rangle_{\infty}}$, both compared to the experimental results of Cherry et al Cherry et al. (1984). Regarding the LES results obtained with the mixed-scale model, the predicted $C_p$ values fit very well the experiments in the first part of the boundary layer detachment. Downstream, the $C_p$ raises up to the reattachment. This $C_p$ increase has to be related to the mean flow deceleration in the longitudinal direction, upstream of the reattachment. The LES results with the mixed-scale model predict correctly the location from where the pressure raise occurs and correctly foresee this deceleration. Downstream the reattachment, present LES overpredict the experimental values by roughly recovering the mean pressure value at infinity. While the general trend of the $C_p$ distribution is predicted by using the dynamic vorticity model, discrepancies compared to experimental data are larger than with the mixed-scale model. By using the dynamic vorticity model, the $C_p$ value is clearly underpredicted in the first part of the detachment and the pressure raise occurs more upstream.
and over a greater extent than with the mixed-scale model.

Though some discrepancies are noticeable on the streamwise distribution of $C_{Prms}$, the general trend of experimental data is recovered by the present LES results. LES with the mixed-scale model predicts the $C_{Prms}$ peak magnitude of 0.138 at a location $x/L_R = 0.79$. These magnitude and location are in very good agreement with the DNS values of Tafti & Vanka (1991). Nevertheless, compared to experimental data of Cherry et al. (1984), the maximum magnitude of $C_{Prms}$ is overpredicted by the mixed-scale model and its location is more upstream than in the experiments which locate the $C_{Prms}$ maximum value close to the reattachment point (Fig. 1). These results tend to show that the present LES with the mixed-scale model, while in agreement with the DNS of Tafti & Vanka (1991), predicts a premature turbulence growth. Besides, the LES results using the dynamic vorticity model show large discrepancies compared to experimental data while the maximum magnitude of $C_{Prms}$ is rather well predicted. However, compared to results obtained with the mixed-scale model, the lower $C_{Prms}$ peak value predicted by the dynamic vorticity model is accompanied with largely smeared longitudinal gradients and a much more premature fluctuation growth. This behavior might be related to a too large diffusion that could be later analyzed on the velocity profiles.

![Figure 1. Streamwise wall pressure distributions obtained by LES either with the mixed-scales model (——) or with the dynamic vorticity model (- - - -), compared to experiments from Cherry et al. (1984) (dots), on both the mean (left) and the fluctuating (right) pressure coefficients.](image)

The streamwise ($<U>$) and the normal to the wall ($<W>$) component profiles are in a good agreement with the Pprime experiments though the Reynolds number is much higher in the experiments. Similar trends as the ones predicted by the mixed-scale model are also noticeable on mean streamwise velocity profiles coming from both the DNS of Tafti & Vanka (1991) and the LES of Yang & Voke (2001). Comparisons on Reynolds stress component profiles between LES results and Pprime experiments [Sicot et al. (2010)] are illustrated at several streamwise locations, in figures (2), (3) and (4). The location of the mixing layer is rather well predicted. Then, it is not necessary to redefine the vertical coordinate as Tafti & Vanka (1991) did. Uncertainties of measurements are noticeable, mainly in the free stream where high turbulence intensity is recorded at several locations. As the first location ($x/L_R = 0.2$) the dynamic vorticity model largely overpredicts turbulence intensities and the turbulent shear-stress. This must come from the vertical gradient of the mean streamwise velocity that is greater than the experimental one at this location. On the opposite, the mixed-scale model agrees very well with experimnts, especially on the vertical $rms$ component (Fig. 3) and the turbulent shear-stress (Fig. 4), though the peak of the streamwise $rms$ component within the mixing layer is barely underpredicted (Fig. 2). Further downstream, LES results obtained with
both models agree rather well, although a thicker mixing layer as well as a thicker boundary layer are clearly predicted by the dynamic vorticity model. Compared to Pprime experiments, LES overestimated turbulence intensities in the middle part of the detachment ($x/L_R = 0.6$).

Further downstream, intensities of the Reynolds stress components are better estimated, though slight underpredictions are noticeable on the streamwise component (Fig. 2) and the cross-correlation (Fig. 4). The maximum magnitude of the \( r_{\text{rms}} \) and cross-correlation values occur close to ($x/L_R = 0.6 - 0.8$) which is somewhat more upstream than in the experiments since maxima are reached close to the reattachment ($x/L_R = 0.8 - 1$). Then, the mean turbulence intensities decrease further downstream, to recover classical turbulent boundary layer levels while the turbulent boundary layer is far away of reaching an equilibrium state. Let us remarks that these considerations on streamwise locations and magnitudes of mean turbulent quantity maxima are quite consistent with the streamwise distribution of the \( r_{\text{rms}} \) pressure coefficient (Fig. 1). To highlight the distortion occurring in the boundary layer detachment and just downstream, we plot the correlation coefficient between the streamwise and the vertical fluctuations (Fig. 5) which is almost constant in a standard turbulent boundary layer, \( i.e. \frac{-<u'w'>}{(r_{\text{rms}, u}, r_{\text{rms}, w})} \approx 0.45 \). We also plot the ratio between the turbulent shear-stress and the turbulent kinetic energy which normally recovers an almost constant value \( \frac{-<u'w'>}{<k>} = \sqrt{C_\mu} \approx 0.3 \) following classical constant value for standard turbulent boundary layer. Results obtained by means of the two subgrid-scale models rather agree each other. At the second location ($x/L_R = 0.4$), the mixed-scale model predicts peaks on \( \frac{-<u'w'>}{(r_{\text{rms}, u}, r_{\text{rms}, w})} \) and \( \frac{-<u'w'>}{<k>} \) within the mixing layer while the dynamic vorticity model recovers almost constant quantities across the separation. This might suggest that the dynamics in the mixing layer occurs earlier than with the mixed-scale model which is also in agreement with streamwise evolutions of both the mean quantity and the Reynolds stress profiles presented above. A few differences are also visible in the outer part of the flow. These two lacks of agreement must be attributed to the extra diffusion produced by the dynamic vorticity model. Across the detachment, maxima of ratios are situated within the mixing layer exhibiting however rather high values compared to the standard values. At the reattachment and further downstream, though high levels are recorded across the boundary layer, they decrease in the streamwise direction to reach values (\( i.e. \frac{-<u'w'>}{(r_{\text{rms}, u}, r_{\text{rms}, w})} = 0.48; \frac{-<u'w'>}{<k>^2} = 0.33 \)) that are rather close to standard values at the most downstream location analyzed ($x/L_R = 2$).

**Figure 2.** Profiles of $<u^2>^{1/2}/U_\infty$: LES results with either the mixed-scale model (——) or the dynamic vorticity model (- - - -), compared to Pprime experiments (●).
follows: \( \delta_\omega(x) = \frac{(\langle U \rangle_{\max} - \langle U \rangle_{\min})}{\max_z (\frac{\partial\langle U \rangle}{\partial z})} \). \( \delta_\omega \) must follow a linear evolution versus the main flow direction [Brown & Roshko (1974); Cherry et al. (1984)] as far as the mixing layer reaches the similarity region. The distribution of \( \delta_\omega \) along the main flow direction is presented on the figure (6) for both models. It is clear that, compared to the mixed-scale model, the dynamic vorticity model gives a premature growth of the mixing layer which seems consistent with the premature growth of the turbulence seen on the analysis of both the pressure coefficients (Fig. 1) and the Reynolds stress profiles (Fig. 2, 3, 4). However, the expansion of the mixing layer predicted by the dynamic vorticity model agrees very well with the classical averaged slope value \( \langle d\delta_\omega/dx \rangle = 0.17 \) recovered by Cherry et al. (1984). While the expansion predicted by the mixed-scale model is greater, \( \delta_\omega \) growth rate also agrees very well with the upper bound of expansion rate values generally admitted for a single-stream mixing layer (i.e. with effectively zero velocity on one side) which are in between 0.145 and 0.22 [Brown & Roshko (1974)].

3.2. Spectral analysis.
Separated–reattached flows are characterized by two basic frequency modes which are related to shedding and flapping phenomena. The vortex shedding resulting from the large scale motion of...
the mixing layer, is characterized by a frequency peak band around $f L_R/U_\infty = 0.6 - 0.8$ (called the shedding mode) [Cherry et al. (1984); Kiya & Sasaki (1985)]. The flapping phenomenon is an overall dynamical mechanism linking to successive enlargements and shrinkages of the separated zone. Its characteristic frequencies (namely the flapping mode) are much lower than the shedding modes, e.g. $f L_R/U_\infty \approx 0.12$ [Cherry et al. (1984); Kiya & Sasaki (1985)]. Streamwise velocity fluctuations are recorded at three locations: in the mixing layer at the early stage of the mixing layer development ($x = 0.3 L_R, z = 0.158 L_R$), above the separation at the mid separation ($x = 0.61 L_R, z = 0.61 L_R$) and above the boundary layer downstream the reattachment ($x = 0.152 L_R, z = 0.61 L_R$). Energy spectra of the streamwise component of the fluctuating velocity are plotted on the figure (7).

These characteristic dimensionless frequencies are clearly visible on these energy spectra where the first group corresponds to the flapping modes and the second group is related to the shedding modes. A peak is also clearly visible around $f L_R/U_0 = 3.4$ (Fig. 7-right). This frequency is attributed to the Kelvin-Helmholtz mode of the mixing layer since the Strouhal number ($St_\omega = f \delta_\omega/U_c = 0.33$) resizes by using the local vorticity thickness ($\delta_\omega$) of the mixing layer and the local convective velocity ($U_c$) is in very good agreement with the value generally admitted, recorded experimentally by numerous authors [Bernal & Roshko (1986)]. At higher frequencies, the decaying rate of the energy fits with the well-known $-5/3$ slope over slightly less than one decade. As pressure–velocity coupling is a key point in aeroacoustic prediction, we also performed energy spectrum of the static pressure. It comes out that the pressure seems to be strongly coupled to the velocity since flapping, shedding and Kelvin-Helmholtz modes are also displayed on pressure spectra. We must however note that the Kelvin-Helmholtz mode is mainly dominant on the pressure spectra that might explain preliminary results from Pprime Institute showing that acoustic sources are mainly attributed to mixing layer transverse 2D modes.

4. Conclusion

LES results obtained with a high-order scheme coupled with the mixed-scale subgrid model, favorably compare to experiments on the separated-reattached flows over a blunt flat plate. The main flow features are quantitatively well predicted, namely the shedding, the flapping modes, the growth of the turbulent mixing layer edging the separation, and the statistical fields when coordinates are re-scaled by using the reattachment length ($L_R$). Compared to experiments,
higher discrepancies are recorded by the dynamic vorticity model mainly due to a premature turbulence growth. *LES* results with the mixed-scale model show similar trends as the ones coming from both the *DNS* of Tafti & Vanka (1991) and the *LES* of Yang & Voke (2001). Some small discrepancies are however noticeable, mainly on the reattachment length, that might be explained by a low Reynolds number effect or a too important solid blockage. These relevant points need to be investigated in the near future.

**Acknowledgement:** Authors would like to greatly acknowledge experimentalists from Pprime Institut of Poitiers who recorded experimental data, for their valuable comments and discussions on data. This study has received financial support from the Agence National de la Recherche (ANR) through the DIB project (ANR-07-BLAN-0177). This work was granted access to the HPC resources of IDRIS under the allocation 2011-i2011020324 made by GENCI (Grand Equipement National de Calcul Intensif).

**References**

**BERNAL, L. P. & ROSHKO, A.** 1986 Streamwise vortex structure in plane mixing layers 170, 499–525.

**BROWN, G. L. & ROSHKO, A.** 1974 On density effects and large structure in turbulent mixing layers. *Journal of Fluid Mechanics* 64, 775–816, part 4.

**CASTRO, I. P. & EPIK, E.** 1998 Boundary layer development after a separated region. *Journal of Fluid Mechanics* 374, 91–116.

**CHERRY, N.J., HILLIER, R. & LATOUR, M. E. M.P.** 1984 Unsteady measurements in a separated and reattaching flow. *Journal of Fluid Mechanics* 11, 13–46.

**DARU, V. & TENAUD, C.** 2004 High order one-step monotonicity preserving schemes for unsteady flow calculations. *Journal of Computational Physics* 193, 563–594.

**DARU, V. & TENAUD, C.** 2009 Numerical simulation of the viscous shock tube problem by using a high resolution monotonicity-preserving scheme. *Computers & Fluids* 38, 664–676.

**DJILALI, N. & GARTSHORE, I. S.** 1991 Turbulent flow around a bluff rectangular plate part i: experimental investigation. *ASME J. Fluid Eng.* 113, 51–59.

**DORIS, L., TENAUD, C. & TA PHUOC, L.** 2000 Les of spatially developing 3d compressible mixing layer. *C.R. Acad. Sci. Paris* t. 328, Srie II b, 567–573.
Favre, A. 1965 Equations des gaz turbulents compressibles. II méthode des vitesses moyennes; méthodes des vitesses macroscopiques pondérées pas la masse volumique. *Journal de Mécanique* 4 (4), 391–421.

Germano, M. 1992 Turbulence: the filtering approach. *Journal of Fluid Mechanics* 238, 325–336.

Germano, M., Piomelli, U., Moin, P. & Cabot, W. H. 1991 A dynamic subgrid-scale eddy viscosity model. *Physics of Fluids A: Fluid Dynamics* 3, 1760–1765.

Hancock, P. E. & Castro, I. P. 1993 End effects in nominally two-dimensional separated flows.

Hoarau, C., Bore, J. & Laumonier, J. abd Gervais, Y. 2006 Analysis of the wall pressure trace downstream of a separated region using extended proper orthogonal decomposition. *Physics of Fluids* 18 (055107).

Kiya, M. & Sasaki, K. 1983 Structure of a turbulent separation bubble. *Journal of Fluid Mechanics* 137, 83–113.

Kiya, M. & Sasaki, K. 1985 Structure of large scale vortices and unsteady reverse flow in the reattaching zone of a turbulent separation bubble. *Journal of Fluid Mechanics* 154, 463–491.

Lamballais, E., Silvestrini, J. & Laizet, S. 2010 Direct numerical simulation of flow separation behind a rounded leading edge: Study of curvature effects. *International Journal of Heat and Fluid Flow* 31, 295–306.

Poinsot, T. J. & Lele, S. K. 1992 Boundary conditions for direct simulations of compressible viscous flows. *Journal of Computational Physics* 101, 104–129.

Sagaut, P. 1998 *Introduction la simulation des grandes chelles pour les coulements de fluides incompressibles*. Springer-Verlag.

Sicot, C., Bauré, J., Brizzi, L.-E. & Gervais, Y. 2010 Private communication. *Tech. Rep.*

Ta Phuoc, L. 1994 Aérodynamique instationnaire turbulente - aspects numériques et expérimentaux. Journée thématique DRET.

Tafti, D. K. & Vanka, S. P. 1991 A three-dimensional numerical study of flow separation and reattachment on a blunt plate. *Physics of Fluids A* 3 (12), 2887–2909.

Tenaud, C. & Ta Phuoc, L. 1997 LES of unsteady compressible separated flow around NACA 0012 airfoil. In *Lecture Notes in Physics* (ed. P. Kutler, J. Flores & J.J. Chattot), , vol. 490, pp. 424–429. 15th International Conference on Numerical Methods in Fluid Dynamics, Monterey, CA, June 1996.

Yang, Z. & Abdalla, I. E. 2009 Effects of free-stream turbulence on a transitional separated-reattached flow over a flat plate with a sharp leading edge. *International Journal of Heat and Fluid Flow* 30 (5), 1026–1035.

Yang, Z. & Voke, P. R. 2000 Large-eddy simulation of separated leading-edge flow in general co-ordinates. *Int. J. Meth. Engng.* 49, 681–696.

Yang, Z. & Voke, P. R. 2001 Large-eddy simulation of boundary-layer separation and transition at a change of surface curvature. *Journal of Fluid Mechanics* 439, 305–333.