NUMERICAL PREDICTION OF SHOCK INDUCED OSCILLATIONS OVER A 2D AIRFOIL: INFLUENCE OF TURBULENCE MODELLING AND TEST SECTION WALLS

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ABSTRACT

The present study deals with recent numerical results from on-going research conducted at ONERA/DMAE regarding the prediction of transonic flows, for which shock wave/boundary layer interaction is important. When this interaction is strong enough (M≥1.3), Shock Induced Oscillations (SIO) appear at the suction side of the airfoil and lead to the formation of unsteady separated areas. The main issue is then to perform 2D unsteady computations applying appropriate turbulence modelling and relevant boundary conditions with respect to experimental ones. Computations were performed with the ONERA object-oriented software **elsA**, using the URANS-type approach, closure relationships being achieved from transport-equation models. Applications are provided for the OAT15A airfoil data base (Jacquin et al., 2005); tests were conducted in the ONERA S3 Chalais Meudon wind-tunnel equipped with self-adaptive upper and lower walls. These experiments are rather well documented for unsteady CFD validation (r.m.s. pressure, phase-averaged data, . . .). URANS results have emphasized the importance of modelling the test section geometry when carrying out 2D unsteady computations to *(i)* capture SIO as precisely as possible and, *(ii)* objectively evaluate the capabilities of turbulence models to predict such flows.

INTRODUCTION

The present study is devoted to the prediction of Shock Induced Oscillations (SIO) over a two-dimensional (2D) rigid airfoil by resolving the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations.

For transonic aircraft wing applications, such oscillations are mainly caused by shock wave / boundary layer interaction, which is closely linked to large separated regions. The response of the wing structure to these aerodynamic instabilities (buffet) corresponds to the well-known buffeting phenomenon. These aerodynamic excitations are mainly attributed to pressure fluctuations growing in generated separated areas (e.g. shock footprint, trailing edge, ...). Several studies were devoted to the understanding as well as the control of SIO (Ekaterinaris and Menter, 1994; Gillan et al., 1997; Lee, 2001; Caruana et al., 2003). Although buffeting is not dangerous or destructive for civil aircraft, it mainly affects the aircraft manoeuvrability and consequently the flight envelop. Thus, flow instabilities need to be clearly identified. The present numerical study deals only with aerodynamic issues, even though fluid-structure coupling should be addressed when considering real three-dimensional aircraft wings.

The periodic motion of the shock occurred at a single low frequency (∼100Hz) depending mainly on the airfoil and test-section geometries. The turbulence induced next to the wall and in the separated regions is governed by a wide range of high frequencies. The frequency gap between the turbulence and the buffet allows to use the URANS-type approach, the mean flow being resolved from the unsteady RANS solution and the turbulence being modelled.

Experiments were recently conducted in the transonic wind-tunnel of the ONERA Centre of Chalais Meudon aiming to generate a consistent data base for unsteady CFD validation.

The objectives of the present numerical investigation have been *(i)* to determine the ability of turbulence models to reproduce unsteady separated flows and, *(ii)* to run computations under conditions as close as possible to the experimental ones, mainly by taking into account the upper and lower wind-tunnel walls.

TEST CASE - OAT15A AIRFOIL

Experiments were rather recently performed in the transonic S3 wind-tunnel of ONERA Centre of Chalais Meudon in the framework of SIO scrutinization (Jacquin et al., 2005). A 2D airfoil (OAT15A cross section, chord length c=230 mm, relative thickness t/c=12.5%, blunt trailing edge e/c=0.5%) was mounted in the test section (0.8 x 0.76 m^2). The experimental set-up was defined with the aim of providing a two-dimensional flow to the best possible degree compared to previous experiments conducted with such an airfoil; the aspect ratio of 3.5 was chosen to minimize the 3D effects without avoiding them, yet. The upper and lower wind-tunnel walls are self-adaptive, i.e. flexible instead of being slotted. From the measured wall pressure distributions, the resolution of the linearized Euler equations outside of the test section allows to determine the shape of the walls so that they correspond to flow streamlines. Next, the displacement induced by the presence of the boundary layers is taken into account to adapt the shape of the upper and lower wind-tunnel walls. It has to be pointed out that this technique only allows to adapt the walls to the time-averaged flow.

Tests were carried out at the following aerodynamic conditions: Reynolds number based on the chord length Re_c=3 10^6, free-stream Mach number M_∞=0.73, stagnation temperature $T_{i\infty}$=300 K and angles of attack (α) varying from 1.36^o to

3.9^o. The transition was tripped at x/c=7% on both sides of the airfoil using a carborundum band (average height 0.095 mm). The experimental buffet onset appeared at α=3.25^o, and the greatest collection of unsteady data was obtained at 3.5^o, where the shock moved over about 0.2c at a frequency of 69Hz. Several types of measurements are available for CFD validation purpose: Schlieren type visualisations, time-averaged (static pressure taps and Reynolds-averaged 3D LDV), fluctuating (Kulite transducers) and phase-averaged data (3D LDV measurements coupled with a conditional analysis).

NUMERICAL TOOLS

Solver and Numerical Methods

Computations were performed with the ONERA object-oriented software **elsA**, solving the three-dimensional compressible Reynolds-Averaged Navier-Stokes equations for multiblock structured grids, using finite-volume method with cell-centered discretization (Cambier and Gazaix, 2002). The fluxes are computed with two second-order-accurate schemes; the Jameson scheme is used for the mean flow fluxes computation with artificial dissipation terms while the Roe scheme is applied to the turbulent transport equations with an anisotropic correction.

The implicit time integration is performed with the dual-time stepping method which combines *(i)* a physical time step, linked to the frequency range of the phenomenon under investigation and, *(ii)* a fictitious dual-time step, related to a steady process to increase convergence between each physical time step. The implicit stage is provided by an approached linearization method with a LU factorization associated with a relaxation technique.

Several tests were performed to ensure that the time consistency was reached such that 300 iterations per cycle were imposed to capture unsteadiness. About ten cycles were necessary to obtain self-sustained SIO while five extra cycles were used to control the periodicity.

Turbulence Modelling

The turbulence closure relies upon the Boussinesq assumption; the eddy viscosity μ_t is then expressed using the turbulent scales (length and velocity) obtained by solving transport equations. Following on previous validations carried out for separated flows (Furlano et al., 2001; Coustols et al.,2003), four models were chosen:

- the one-equation transport model from Spalart and Allmaras (1992), referred to as [SA]. The model was built up empirically to reproduce flows of increasing complexity.
- the two-equation transport model k-ω/k-ε from Menter (1994) in the BaSeLine version, referred to as [BSL]. Menter retained the reliable form while eliminated the free-stream dependency of the k-ω type models.
- the two-equation transport model k-ω/k-ε from Menter (1994) with the Shear Stress Transport correction, referred to as [SST]. The model is derived from the [BSL] model. The correction applied on the definition of μ_t is based on the Bradshaw's assumption that the principal shear-stress is proportional to the turbulent kinetic energy. Improvements would be brought for adverse pressure gradients boundary layers.
- the two-equation transport model k-kL from Daris and Bézard (2002), referred to as [KKL]. The model is based on a generic form of the transport equations for the turbulent scales and the constants of the model are analytically derived to respect some basic physical features, following Catris and Aupoix (2000), opposite to existing models.

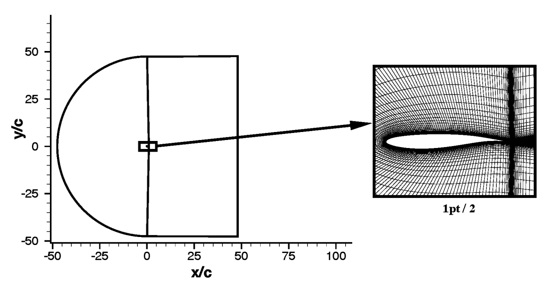
The [SA] and [SST] models have been recommended by NASA Langley for evaluating transonic flows over different test cases (Marvin and Huang, 1996), while the [KKL] model has been rather recently developed at ONERA and successfully applied for adverse pressure gradients boundary layers. The [BSL] model will provide a reference for the evaluation of the [SST] model.

Computational Conditions

Two Approaches. Weak inviscid / viscous coupling computations at a steady state (α=2.5^o) concluded that corrections on M_∞ and α were not necessary for undertaking Navier-Stokes computations under free-stream conditions. This confirmed that the self-adaptive upper and lower walls associated with a relatively large value of airfoil aspect ratio minimize the influence of wind-tunnel walls, at least for a steady flow.

Nonetheless, in order to perform unsteady computations and to be closer to testing conditions, two different approaches have been considered:

- the "standard" approach, referred to as the "inf." approach. The numerical domain was a 2D CH-type mesh extending over 50c and composed of about 75,000 grid points (Fig. 1a.). Free-stream conditions were imposed and deduced from experimental values of α, Mach and Reynolds numbers.
- the "new" approach, referred to as the "conf." approach. Earlier studies from Furlano et al. (2001) and Garbaruk et al. (2003) have demonstrated the importance of taking



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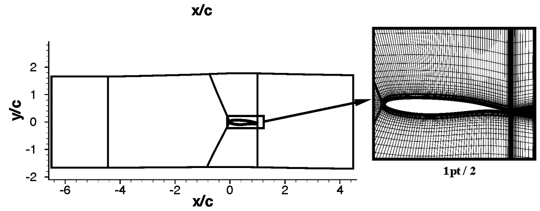

b.

Figure 1: Sketch of computational domain (a.: "inf." approach, b.: "conf." approach) - OAT15A airfoil.

into account the wind-tunnel walls for transonic flows. The OAT15A aspect ratio being relatively high, only the upper and lower walls were considered in the numerical boundary conditions and the 2D mesh definition. The mesh extent was adjusted to reproduce the experimental boundary-layer thickness at the entrance of the test section. The mesh extended then from 6.5c upstream to 4.5c downstream of the airfoil, composed of about 110,000 grid points (Fig. 1b.). At the entrance, experimental total quantities were imposed while at the exit, the static pressure was fixed with respect to the experimental Mach number (Thiery and Coustols, 2005b).

At last, a mesh convergence study was performed for the two approaches.

Aerodynamic Conditions.

Aerodynamic conditions (M_∞ and α) were validated with the time-averaged pressure distributions obtained with the [SA] model (Fig. 2). Along the airfoil, the computed pressure coefficient for the "inf." and "conf." approaches agreed with the experimental one in the region upstream of the shock and along the pressure side (Fig. 2a.). This tends to confirm that the aerodynamic conditions for the airfoil were well adjusted and the adaptation of the wind-tunnel walls was well managed for the time-averaged flow. The differences observed for $0.4 \leq x/c \leq 0.6$ on the suction side have nothing to deal

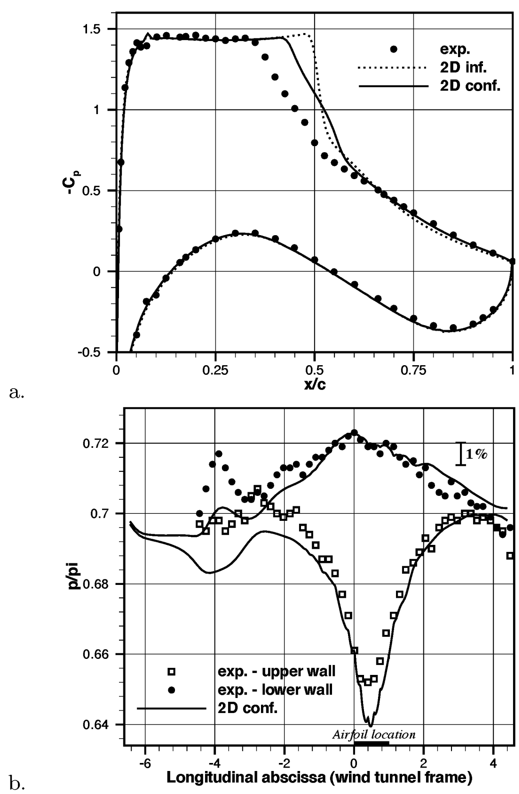

Figure 2: Time-averaged pressure distributions obtained with the [SA] model (a.: along the airfoil for "inf." and "conf." approaches, b.: on the upper and lower wind-tunnel walls for the "conf." approach) - OAT15A airfoil - M_∞=0.73, Re_c=3 10^6, α=3.5^o.

with boundary condition adaptation and will be discussed in the next section.

Moreover, the time-averaged pressure on the upper and lower walls pointed out rather appropriate boundary conditions for the "conf." approach (Fig. 2b.). The discrepancy observed between experimental and computed pressure values near the entrance section are induced by the 2D-type numerical domain, for which a compromise has to be found between the Mach number and the static pressure, respectively at the entrance and the exit sections.

UNSTEADY RESULTS

Lift Evolution Versus Time

The first step in the turbulence model validation has been to check the appearance of self-sustained oscillations: lift evolution versus time is presented in Fig. 3 for the four above-cited models and the two numerical approaches.

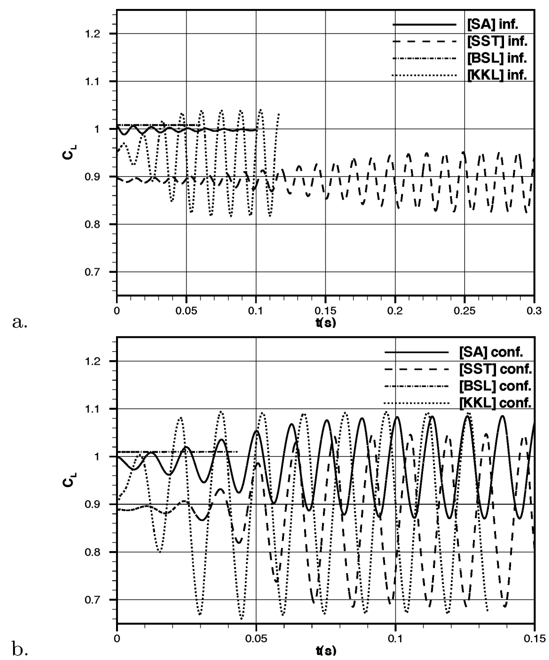

Figure 3: Lift evolution versus time (a.: "inf." approach, b.: "conf." approach) - OAT15A airfoil - M_∞=0.73, Re_c=3 10^6, α=3.5^o.

Results with the "inf." approach (Fig. 3a.) highlight a steady behaviour for the [BSL] and [SA] models while the [KKL] and [SST] models develop lift oscillations. By taking into account the upper and lower wind-tunnel walls (Fig 3b.), the [SA] model can develop unsteadiness while the [BSL], [KKL] and [SST] models behavior remain unchanged: however, the lift oscillation amplitudes of the [KKL] (resp. [SST]) model are increased by a factor of 2 (resp. 2.5). Moreover, the time-averaged lift coefficient is not affected by the account of upper and lower wind-tunnel walls.

As well for the "inf." as for the "conf." approach, comparisons between turbulence models demonstrate a large discrepancy on the time-averaged lift coefficient; it is closely linked to the difficulty to correctly predict the shock location since the pressure gradient is nearly null upstream of the shock. For the "inf." approach (Fig. 3a.), the lift amplitude of the [KKL] model is 2 times larger than the [SST] model one, while accounting for the test section walls widely reduces the gap between the two models. For the "conf." approach (Fig. 3b.), the [KKL] and [SST] models predict oscillations about 2 times larger than those of the [SA] model. The SST correction brings strong improvement to the [BSL] model behaviour, allowing to compute unsteady flow, whatever the approach.

At last, as an unsteady solution is predicted, the numerical SIO frequency depends slightly on the turbulence model (∼71-78Hz). When the wind-tunnel walls are modelled, a decrease of 3Hz is observed whatever models, predictions being closer to the experimental value (69Hz). These results demonstrate that the frequency is not a selective parameter for turbulence models validation; it is consistent with the buffet modelling proposed by Lee (2001) since the frequency being mainly governed by the airfoil and test-section geometries.

The fact that the exit boundary condition is a constant static pressure, which imposes perturbations to be damped, raises the question of whether the SIO frequency is not closely linked to the domain extent. Therefore, another grid was generated to shift the exit from 4.5 to 8.5c downwards. Unsteady results with the [SA] model were unchanged, the predicted frequency remaining close to the experimental value (Thiery and Coustols, 2005b).

Results obtained with the [SA] model with the "inf." approach are quite surprising considering previous studies on SIO or separated flows. Investigations on the grid refinement, the mesh topology or the over-thickening of the boundary layer at tripping location were carried out with that model but they did not bring any improvement. Only an increase of more than one degree of incidence allowed to develop SIO with the "inf." approach (Thiery and Coustols, 2005a).

Pressure Distributions

The unsteady r.m.s pressure distributions along the airfoil are discussed to evaluate the levels of unsteadiness provided by the computations and to compare them to the measured ones (Fig. 4a. and b.). Typically, three main levels can be distinguished ; *(i)* small levels ($\sim 0.02 q_0$) on the pressure side and on the first 40% of the suction side, *(ii)* medium levels ($\sim 0.1 q_0$) in the unsteady separated area downstream the shock (x/c≥0.6) and, *(iii)* large levels ($\sim 0.3 q_0$) in the vicinity of the shock location (0.4≤x/c≤0.6).

Considering the "inf." approach (Fig. 4a.) and applying the [SST] model, numerical values are particularly in good agreement with the experimental ones though the levels are slightly under-estimated all over the airfoil. The location of the time-averaged shock, which corresponds approximately to the maximum of fluctuations, is rather well predicted. The [KKL] model predictions demonstrate stronger fluctuations and a wider range of SIO than the [SST] model do. Moreover, the maximum of fluctuation is about 0.08c downstream of the experimental one.

Concerning the "conf." approach (Fig. 4b.), as pointed out with the evolution of the lift coefficient versus time, fluctuations increase for the [SST] and [KKL] models, degrading results especially on the pressure side and upstream

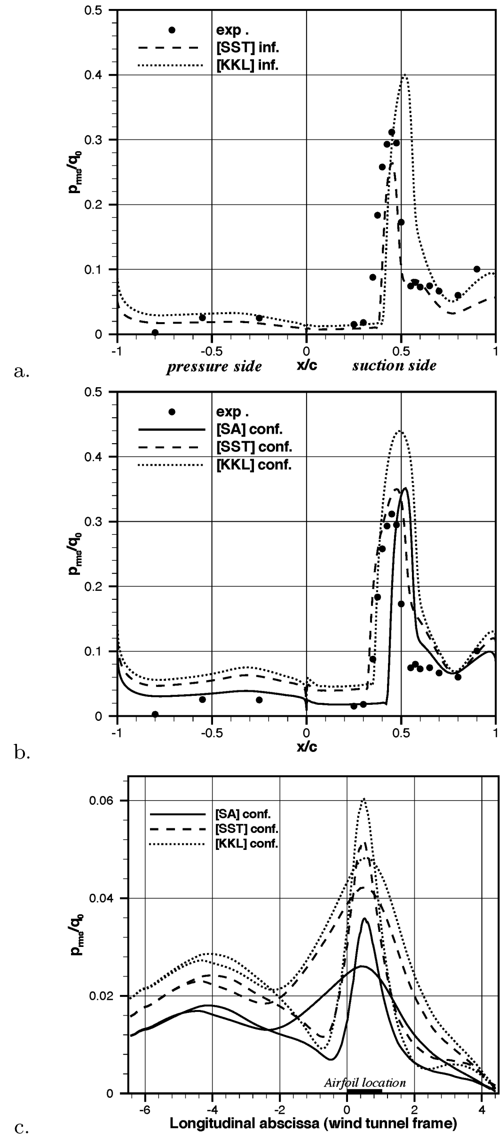

Figure 4: Unsteady r.m.s. pressure distributions (a.: along the airfoil for the "inf." approach, b.: along the airfoil for the "conf." approach, c.: on the upper and lower wind-tunnel walls for the "conf." approach) - OAT15A airfoil - M_∞=0.73, Re_c=3 10^6, α=3.5^o.

of the shock. The [SA] model is in better agreement with the experiments but the location of the time-averaged shock is about 0.08c downstream of the experimental one. At last, the predictions of all models gather for 0.6≤x/c≤1 and reproduce quite well the experimental evolution, particularly the fluctuation increase next to the trailing edge. That result might indicate that the unsteady separated area is mainly governed by the shock instability, enhanced by the wind-tunnel walls modelling.

The time-averaged pressure distributions on the upper and lower wind-tunnel walls are not really affected by turbulence modelling. Although, a comparison is provided on the r.m.s. pressure distributions (Fig. 4c.); results obtained with the three turbulence models have quite similar evolutions along

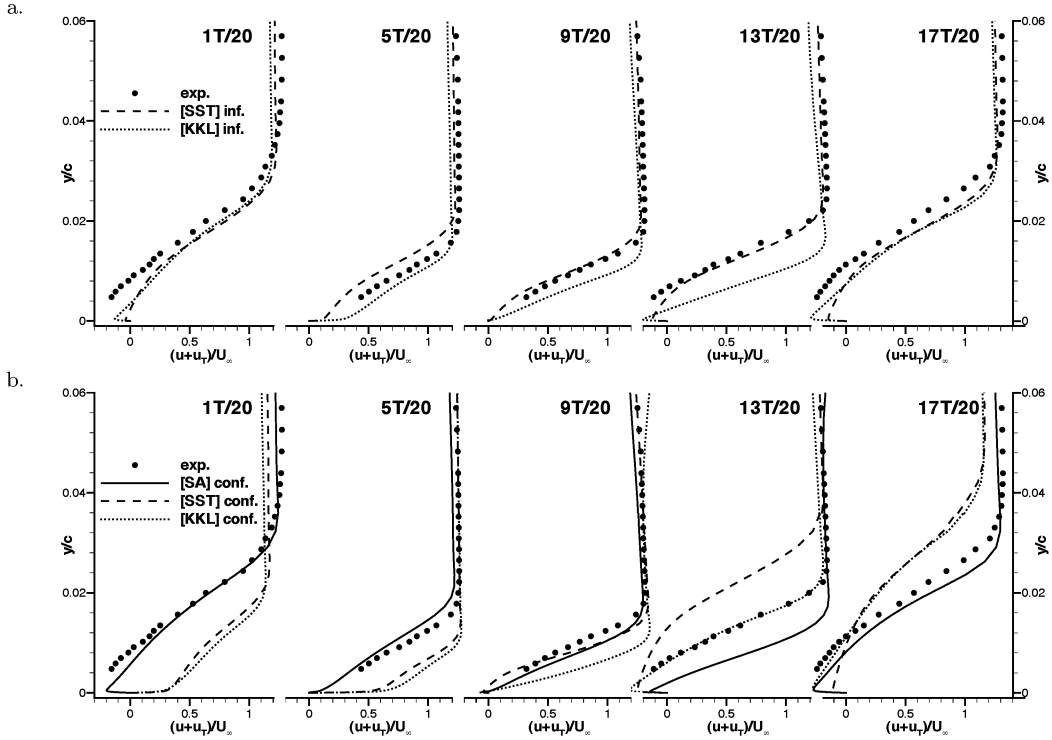

Figure 5: Unsteady velocity profiles at x/c=0.6 for 5 phases in the SIO period sliced into 20 phases (a.: "inf." approach, b.: "conf." approach) - OAT15A airfoil - M_∞=0.73, Re_c=3 10^6, α=3.5^o.

the upper and lower wind-tunnel walls, levels being ordered in the same way as on the airfoil (Fig. 4a. and b.). In the upstream part of the test section (l/c≤-2), fluctuations are nearly constant ($\sim 0.02 q_0$) and equivalent to the levels computed on the pressure side of the airfoil. Next to the airfoil location (0≤l/c≤1), the r.m.s. pressure distributions reach a maximum equal to about 15% of the maximum of fluctuations reached on the airfoil. For l/c≥1, the levels decrease to zero since the boundary condition at the exit section imposes a constant static pressure. Then, the fluctuations on the upper and lower wind-tunnel walls exist and are not negligible with respect to the airfoil ones. Indeed, the adaptation of the walls was managed for the time-averaged flow.

Phase-Averaged Boundary Layer Profiles

The SIO period was discretized into twenty phases and five of them are compared to the numerical unsteady profiles (Fig. 5). The velocity profiles were extracted downstream of the shock, at x/c=0.6, where the boundary layer is periodically attached (seven phases from 4T to 11T/20) and then separated (thirty phases from 12T to 3T/20).

For the "inf." approach (Fig. 5a.), the [SST] model prediction presents a really good agreement with experiments since the time evolution of the boundary layer profile is well reproduced. Nonetheless, the intensity of the back-flow seems to be under-estimated. The [KKL] model prediction is not far from experiments but demonstrates a delay to develop the separated area, which can induce a large error on the boundary layer thickness (e.g. about 35% at phase 13T/20). The problem might be linked to the poor prediction of the shock location (maximum of fluctuations about $0.08c$ downstream of experiments).

The impact of the upper and lower wind-tunnel walls on the boundary layer profiles is very important for the predictions provided by the [SST] and [KKL] models (Fig. 5b.). At phase 1T/20, the computed boundary layers are completely attached while the measured one is separated. At phase 17T/20, the thickness of the separated region is widely over-estimated (∼30%). At last, the [SA] model result provides the best prediction using the "conf." approach, with a delay to develop the separated region at phase 13T/20, yet.

These results are really encouraging since all models are based on the Boussinesq hypothesis, which does not figure on any "history" effect and does not correctly simulate the momentum transfer in the separated areas. That might be another evidence that the separation downstream of the shock is mainly governed by the shock instability, and not by the turbulence modelling.

CONCLUDING REMARKS

Results presented in the paper dealt with unsteady computations of Shock Induced Oscillations (SIO) over the 2D rigid OAT15A airfoil. A turbulence models validation has been performed with two different approaches: *(i)* the "inf." approach under free-stream conditions and, *(ii)* the "conf." approach in which the upper and lower wind-tunnel walls were taken into account.

Four turbulence models have been evaluated: the [SA], [BSL], [SST] and [KKL] model. Unsteady results obtained with the [SST] and [KKL] models with the "inf." approach highlight their ability to easily develop separated area while the [SA] model needs to be triggered by the modelling of the upper and lower walls of the test section to compute SIO. The wind-tunnel walls modelling has no effect on the steady results obtained with the [BSL] model, though the [SST] and [KKL] predictions are completely destabilized and move away from experiments. The SST correction has improved the behaviour of the [BSL] model with respect to the prediction of the separated regions. Then, the best agreement with the experimental observations is obtained with either the [SST] model using the "inf." approach or the [SA] model using the "conf." approach.

The pressure distributions on the upper and lower wind-tunnel walls demonstrate that the adaptation was well managed for the time-averaged flow. Nonetheless, large pressure fluctuations were observed on these walls, at least equal to the levels on the pressure side of the airfoil.

The major impact of the modelling of the wind-tunnel walls is to increase the fluctuation levels along the airfoil. Moreover, the fluctuations in the separation downstream of the shock seem to be mainly governed by the shock instability, not by the turbulence modelling. The turbulence model allows unsteadiness to develop and influences the amplitude of the shock motion. The frequency appears to be mainly linked to the inviscid flow.

The presented results indicate that the modelling of the upper and lower walls is prerequisite to objectively evaluate the capabilities of turbulence modelling to capture SIO. Indeed, the upper and lower wind-tunnel walls fix the time-averaged flow streamlines, not the instantaneous one. Moreover, one can wonder if other instabilities are involved, in particular transverse one might develop over the separated area; they might play a role in the SIO development and could be partially resolved by a 3D computation.

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REFERENCES

Cambier, L., and Gazaix, M., 2002, "**elsA**: an efficient object-oriented solution to CFD complexity", *Proceedings, 40^{th} AIAA Aerospace Sciences Meeting & Exhibit, Reno, Nevada, USA*, AIAA Paper 2002-0108.

Caruana, D., Mignosi, A., Robitaillé, C., and Corrège, M., 2003, "Separated flow and buffeting control", *Flow, Turbulence and Combustion*, Vol. 71, No. 1-4, pp. 221-245.

Catris, S. and Aupoix, B., 2000, "Towards a calibration of the length-scale equation", *International Journal of Heat and Fluid Flow*, Vol. 21, No. 5, pp. 606-613.

Coustols, E., Schaeffer, N., Thiery, M., and Cordeiro Fernandes, P., 2003, "Unsteady Reynolds-Averaged Navier-Stokes Computations of Shock Induced Oscillations over Two-Dimensional Rigid Airfoils", *Proceedings, 3^{rd} International Symposium of Turbulence and Shear Flow Phenomena, Sendaï, Japan, June 25-27*, Vol. 1, pp. 57-62.

Daris, T., and Bézard, H., 2002, "Four-equations models for Reynolds stress and turbulent heat flux predictions", *Proceedings, 12^{th} International Heat Transfer Conference, Grenoble, France, August 18-23*.

Ekaterinaris, J. A., and Menter, F. R., 1994, "Computation of separated and unsteady flows with one- and two-equation turbulence models", *AIAA Journal*, Vol. 32, pp. 23-59.

Furlano, F., Coustols, E., Rouzaud, O., and Plot, S., 2001, "Steady and unsteady computations of flows close to airfoil buffeting: Validation of turbulence models", *Proceedings, 2^{nd} International Symposium on Turbulence and Shear Flow Phenomena, Stockholm, Sweden, June 27-29*, Vol. 1, pp. 211-216.

Garbaruk, A., Shur, M., Strelets, M., and Spalart, P. R., 2003, "Numerical Study of Wind-Tunnel Walls Effects on Transonic Airfoil Flow", *AIAA Journal*, Vol. 41, No. 6, pp. 1046-1054.

Gillan, M. A., Mitchell, R. D., Raghunathan, S. R., and Cole, J. S., 1997, "Prediction and control of periodic flows", *Proceedings, 35^{th} AIAA Aerospace Sciences Meeting & Exhibit, Reno, Nevada, USA*, AIAA Paper 1997-0832.

Jacquin, L., Molton, P., Deck, S., Maury, B., and Soulevant, D., 2005, "Experimental study of the 2D oscillation on a transonic wing", *To appear in Proceedings, 35^{th} AIAA Fluid Dynamics Conference, Toronto, Canada, June.*

Lee, B. H. K., 2001, "Self-sustained shock oscillations on airfoils at transonic speeds", *Progress in Aerospace Sciences*, Vol. 37, pp. 147-196.

Marvin, J. G., and Huang, G. P., 1996, "Turbulence Modeling. Progress and future outlook", *Proceedings, 5^{th} International Conference on Numerical Methods in Fluid Dynamics, Monterey, CA, USA, June 24-28.*

Menter, F. R., 1994, "Two-equation eddy-viscosity turbulence models for engineering applications", *AIAA Journal*, Vol. 32, No. 8, pp. 1598-1605.

Spalart, P. R., and Allmaras, S. R., 1994, "A One-Equation Turbulence Model for Aerodynamic Flows", *La Recherche Aérospatiale*, Vol. 1, pp. 5-21.

Thiery, M., and Coustols, E., 2005a, "URANS Computations of Shock Induced Oscillations Over 2D Rigid Airfoil: Influence of Test Section Geometry", *Proceedings, 6^{th} ERCOFTAC International Symposium on Engineering Turbulence Modelling and Measurements, Sardinia, Italy, May 23-25.*

Thiery, M., and Coustols, E., 2005b, "URANS Computations of Shock-Induced Oscillations over 2D Rigid Airfoils: Influence of Test Section Geometry", *Submitted for publication in Flow, Turbulence and Combustion, 2005, revised version in progress.*