NUMERICAL PREDICTION OF TRANSONIC BUFFETING BY MEANS OF STANDARD AND TIME-DEPENDENT TURBULENT MODELS

E. Orlik
Laboratoire PRISME, Université d'Orléans,
8, rue Léonard de Vinci, 45071 Orléans cedex 2, France

N. Mazellier
Laboratoire PRISME, Université d'Orléans,
8, rue Léonard de Vinci, 45071 Orléans cedex 2, France

A. Kourta
Laboratoire PRISME, Université d'Orléans,
8, rue Léonard de Vinci, 45071 Orléans cedex 2, France

ABSTRACT

We present the preliminary results from a numerical investigation of transonic buffeting on an OAT15A airfoil using the two-equation transport models k-ω SST and k-ε with low-Re corrections by means of damping functions. The influence of the turbulence model, the transition and 3D configurations onto the physics of the buffeting are presented. Even though shock-induced oscillations are observed, some discrepancies with experimental results are found. A refined model of turbulent viscosity, based on a semi-deterministic approach, is proposed and is currently implemented in the computational software and used in order to improve the buffeting prediction.

INTRODUCTION

Airfoil submitted to an external fluctuating force undergoes buffeting. In the case of a transonic airfoil, buffeting results from the shock/boundary-layer interaction inducing self-sustained oscillations which strongly alter the airfoil performances (Lee 1990). The complex physics underlying the transonic buffeting currently suffers of an accurate prediction in order to either prevent its occurrence or to minimize its influence.

Garnier and Deck (2010) investigated the buffeting process by means of Large Eddy Simulations (LES) coupled with Reynolds-Averaged Numerical Simulation (RANS). The spectral content was well reproduced in comparison with the experimental results reported by Jacquin et al. (2005). Nevertheless, the statistics of the static pressure differed significantly from the experiments, partly because the convergence of the computation is not ensured accounting for the time and resource consuming feature of LES. The slow dynamics featuring the transonic buffeting process allows for the use of low-consuming numerical approaches such as the Unsteady Reynolds-Averaged Simulation (URANS). However, the prediction of the buffeting phenomenon is extremely sensitive to the closure turbulent model, as shown by Thiery and Coustol (2006) who pointed out that the two-equation transport model k-ω SST performed the best. Nevertheless, the authors reported some discrepancies between their results and an experimental database (Jacquin et al. 2005), especially regarding the dynamics.

In order to overcome this drawback, we propose to couple the standard turbulence models with a refined eddy turbulent viscosity model, first introduced by Kourta (1999) and afterwards validated by Kourta et al. (2005) for the buffeting prediction. The paper is organized as follows. The computation conditions and numerical influence are first briefly described. Then, the preliminary results from URANS computations obtained with standard turbulence models are discussed. Also the influence of the transition and 3D configurations on the buffeting are reported. Finally, the time-dependent Reynolds-stress model is presented and preliminary results in steady regime are shown and discussed.

COMPUTATIONAL CONDITIONS

In this study, we simulate the flow over an OAT15A airfoil with a chord of 0.23m allowing for the comparison with the experiments reported by Jacquin et al. (2005). This airfoil is a supercritical airfoil with a thickness to chord ratio of 12.3% and a thick trailing edge of 0.5% of the chord length. Computations have been done at angle of attack (AoA) 3.5°, 4° and 4.5°.

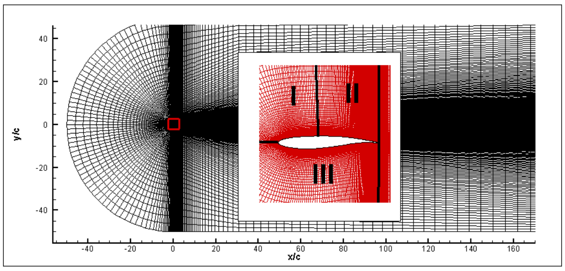

Figure 1. Typical example of the computational domain and mesh. The insert focuses on the mesh close to the airfoil.

As shown in Figure 1, the mesh consists in a C-type domain subdivided into three blocks. Both 2D and 3D computations have been performed even though most of the results reported here concern the 2D configuration. An adiabatic no-slip wall condition is imposed on the airfoil boundary, while non-reflecting conditions are used on the external boundaries. The far-field flow conditions imposed on the external boundary are identical to those reported by Jacquin et al. (2005), i.e., M_∞=0.73, P_i =10^5 bar, T_i =300 K and Re_c =2.8 ×10^6.

In this study, two numerical solvers are used: a commercial one, i.e. Fluent and another one developed by the DynFluid laboratory (ENSAM School at Paris). It is worth noticing that most of the results reported here have been obtained with Fluent. Both codes are cell-centered finite volume and the compressible Reynolds-Average Navier-Stokes equations are resolved (Favre variables). Calculations have been performed using the 2nd order upwind implicit spatial scheme with a local time imposed by CFL = 5. Note that the computations performed with Fluent are unsteady, whilst only steady results are reported for the DynFluid code. For the unsteady computations, a dual-time stepping method has been used.

The two-equation transport models k-ω SST and k-ε are used to simulate the turbulence with low-Re corrections by means of damping functions. Therefore, the dimensionless mesh size normal to the wall is $y_w^+ < 1$. Besides the standard models available on these codes, we have implemented, into the DynFluid code, a time-dependent model based on the work of Kourta (2005). The first results obtained with this original model are reported at the end of the last section.

NUMERICS INFLUENCE

Buffeting is a complex phenomenon implying a strong shock / boundary-layer interaction. Both shock motion and boundary layer expansion have to be well resolved in both space and time in order to predict correctly buffeting. Meanwhile, time consuming computations have to be prescribed. For that reasons, the mesh has to be properly designed in order to fulfill both conditions. The grid convergence has been investigated by building different meshes, whose parameters are gathered in table 1.

The results displayed in Figure 2 show the time variation of the lift coefficient Cl computed for the three meshes. The oscillations observed in each case testify to the occurrence of buffeting. One can remark that the predicted buffet period weakly depends on the mesh refinement.

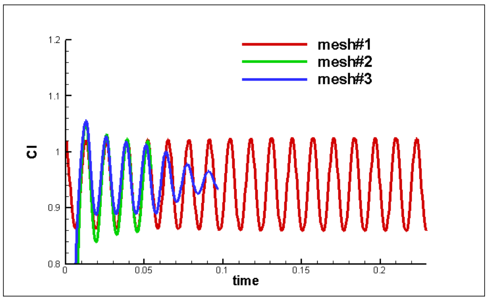

Figure 2. Time history of the lift coefficient for various mesh refinement.

Table 1. Description of meshes.

Mesh	Zone 1	Zone 2	Zone 3
#1	52×140	100×140	170×140
#2	52×140	200×140	170×140
#3	150×140	400×140	170×140

However, the results obtained for the finest mesh, i.e. mesh #3, clearly evidence a significant damping of the buffeting. Such behavior has been pointed out by several authors. One may expect that a coarse mesh may induce enough numerical errors enable to excite the flow instabilities responsible for the onset of buffeting. Regarding to this preliminary results, the medium mesh, i.e. mesh #2, has been chosen in the following.

Figure 3 shows the influence of the time step value onto the buffeting prediction. One can observe that the buffeting is damped with increasing time step even though the oscillation period is well captured.

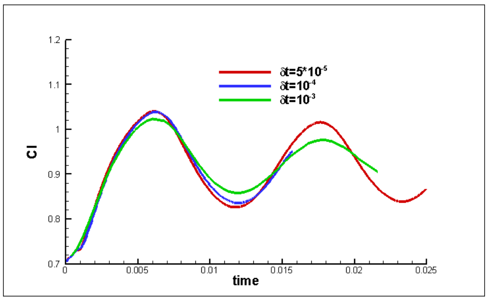

Figure 3. Lift history for various time steps.

UNSTEADY COMPUTATIONS

In this part, we report the results obtained with the solver Fluent in unsteady configuration. Here, we attempt to quantify the influence parameters such as the turbulence model or the transition onto the physics of the buffeting. Furthermore, the first results obtained in 3D configurations are presented.

Standard turbulent models

The variation of the mean pressure coefficient (pressure normalized by dynamic pressure at free stream conditions) computed with the k-ω model is plotted in Figure 4. For comparison, the values obtained by Jacquin et al. (2005) are also reported. Even though an excellent collapse between both numerical and experiment results is found (see also Table 2), the numerical data were obtained with a noticeably higher angle of attack (AoA=4.5° while the experimental AoA equals 3.5°). This is supported by the root-mean square fluctuating pressure coefficient C_p' displayed in Figure 5 which agrees very well with the experimental data for the highest numerical angle of attack AoA.

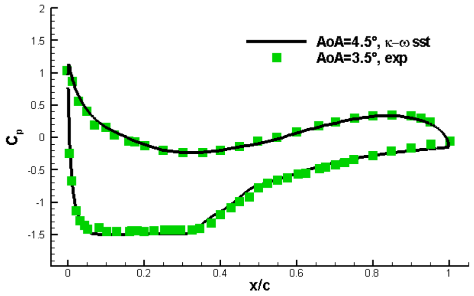

Figure 4. Variation of the mean pressure coefficient.

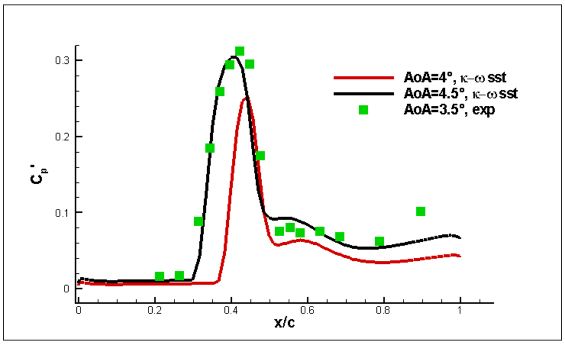

Figure 5. Variation of the root-mean square pressure coefficient on the upper side.

These results evidence that the level of the mean and the fluctuating pressure is strongly sensitive to the angle of attack. However, the pressure dynamics is weakly dependent on this parameter as evidenced in Figure 6 which displays the time evolution of the lift coefficient for two angles of attack, 4° and 4.5° respectively. This figure shows that beyond an initial transient time, the buffeting is well captured. Nevertheless, one can see that its amplitude is slightly damped for the lowest incidence AoA.

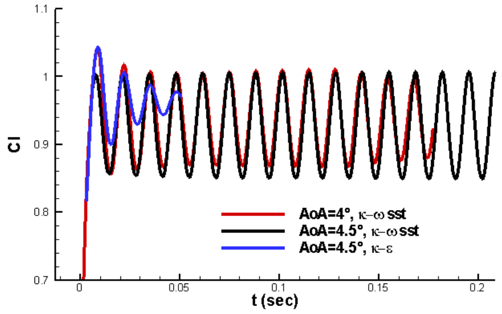

Figure 6. Time history of lift coefficient for different turbulent models and angle of attack (4° and 4.5°).

Furthermore, the dynamics of the buffeting evaluated by means of the dimensionless frequency (Strouhal number) predicted by the numerical simulations is in good agreement with the results reported in literature (see Table 2).

Table 2. Comparison with experiment and other computations.

Case	Strouhal number	Mean lift coefficient
Jacquin et al. (2005)	0.078	0.91
Kourta et al. (2005)	0.072	0.965
Present study	0.072	0.924

The influence of the turbulence model on the buffeting prediction is also provided in Figure 6 where the k-ω model is compared to the k-ε model at the same angle of attack. One can clearly see that even though the standard k-ε model captures the lift oscillation, its amplitude is strongly damped. This may be due to the overestimation of the turbulent viscosity.

Transition and 3D effects on buffeting

It is worth noticing that the results discussed hereinbefore have been obtained for 2D fully turbulent flow. In order to improve the comparison between the simulations and the experiments, the influence of both the laminar/turbulent transition and the 3D effects have been assessed separately.

In the case of the transition, a laminar region is imposed up to x/c ~ 7%. Beyond this location, the flow is turbulent. Figure 7 shows distribution of mean friction coefficient C_f (normalized by dynamic pressure at free stream conditions) in comparison with the fully turbulent case. As expected, the transition occurrence is responsible for a strong increase of the friction coefficient. However, beyond x/c ~ 20%, the results obtained with the transition are quite close to those obtained with the fully turbulent condition. However, one can see that the average location of the shock is shifted downstream for the transition case.

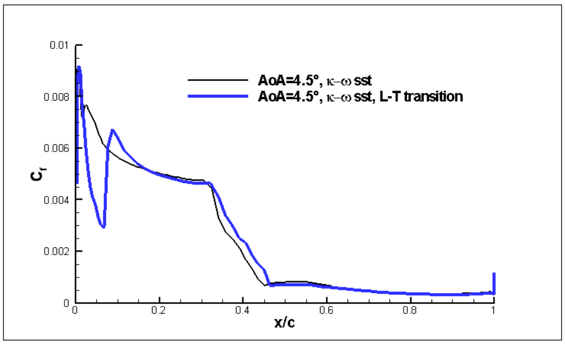

Figure 7. Distribution of C_f with fully turbulent flow and with the laminar/turbulent transition.

Figure 8 displays the influence of the transition on the root-mean square pressure coefficient C_p'. When transition is used, the maximum location is fairly well reproduced. This behavior agrees with the results reported in Fig. 7.

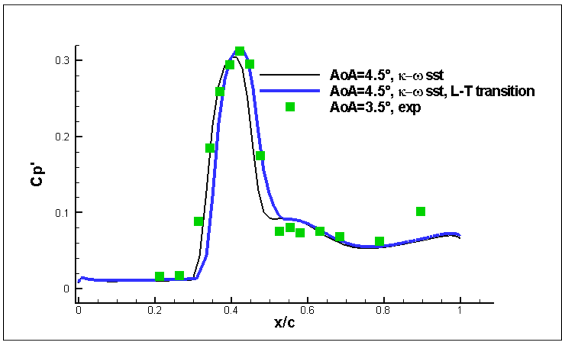

Figure 8. Effect of transition.

The 3D computations have been performed on extruded 2D mesh with 20 nodes in the spanwise direction. The influence of the 3D effects is shown in Figure 9 in comparison with the results obtained in the 2D configuration. The amplitude of the pressure fluctuation is noticeably underestimated. Furthermore, the maximum location is slightly shifted downstream.

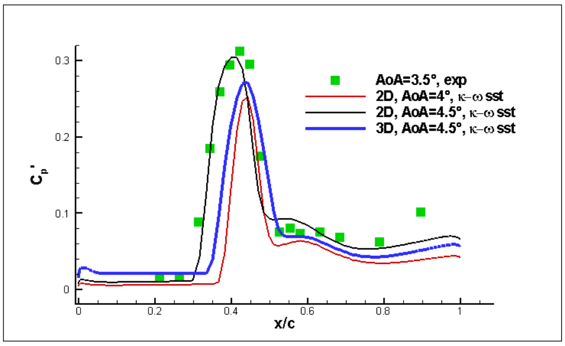

Figure 9. Effect of 3D computation.

From these results, one may conclude that the buffeting prediction is fairly well predicted in the 2D configuration with both transition and fully developed conditions. Nevertheless, the agreement with the experimental results has been obtained with a significantly higher angle of attack. These results may be attributed to the overestimation of the turbulent viscosity which is compensated by increasing the angle of attack.

THE TURBULENT TIME-DEPENDENT MODEL

For the reasons enumerated hereinbefore, we propose in the following an improvement of the turbulence modeling by means of a time-dependent model which has been implemented in the DynFluide code.

The basics

The originality of this study is dedicated to the implementation of a suitable unsteady turbulence model in order to improve the buffeting prediction. This model is based on a semi-deterministic approach where a physical variable can be decomposed into a coherent part and a random part. This approach is similar to that developed by Shih et al. (1995) for the Reynolds-stress tensor

$$\tau_{ij} = -\rho\overline{u_i u_j} = 2\mu_t (S_{ij} - \frac{1}{3} S_{kk}\delta_{ij}) - \frac{2}{3}\rho k \delta_{ij},$$

where the turbulent viscosity is given by $\mu_t = C_\mu \rho k^2/\varepsilon$. The turbulent viscosity coefficient C_μ is defined as follows

$$C_\mu(\eta,\xi) = \frac{2}{3}\frac{1}{A_1 + \eta + \gamma_1 \xi},$$

$$\eta = \frac{k}{\varepsilon} S, \quad \xi = \frac{k}{\varepsilon}\Omega$$

where S and Ω stand for the strain rate and the rotation rate of the mean flow, respectively. A_1 and γ_1 are numerical constants equal to 1.25 and 0.9, respectively.

The value of the parameter C_μ is therefore locally dependent on the dynamics of both the mean flow and the turbulence unlike standard turbulent viscosity-based models where it is fixed to 0.09. This formulation enables the turbulent model to be self-adaptive to the dynamics of both the mean flow and the turbulence aiming therefore to reproduce some characteristics such as anisotropy for instance. This original model has been implemented in the numerical code developed by the DynFluid Laboratory.

Preliminary results in steady regime

We present, in this study, the first results obtained with the time-dependent model. These results have been obtained in a steady configuration. Even though this condition is not representative of the real physics of the buffeting it enables to assess the suitability of the model with low consuming cost. Note that the residuals do not converge due to the occurrence of the shock motion (pseudo-buffeting).

The mean pressure coefficient C_p obtained with the standard k-ε model and the time-dependent model is plotted in Figure 10. The results obtained for both the minimum and maximum lift are reported in this plot. For the later condition, one can see that the results obtained with both turbulence models are almost undistinguishable. However, when lift reaches its minimum value, the time-dependent model seems to perform better in comparison with the experimental results.

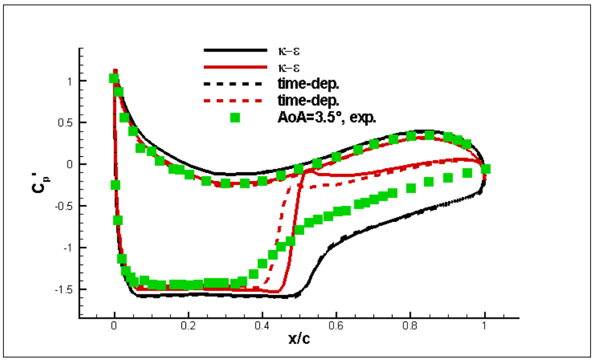

Figure 10. Variation of the mean pressure coefficient for AoA=4.5° obtained with the standard turbulent model k-ε (solid lines) and with the time-dependent model (dashed lines) at the maximum(black) and minimum lift (red).

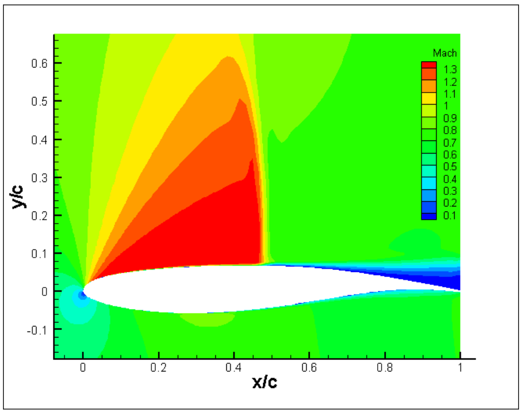

Figure 11. Steady regime, κ-ε turbulent model, minimum lift, AoA=4.5°.

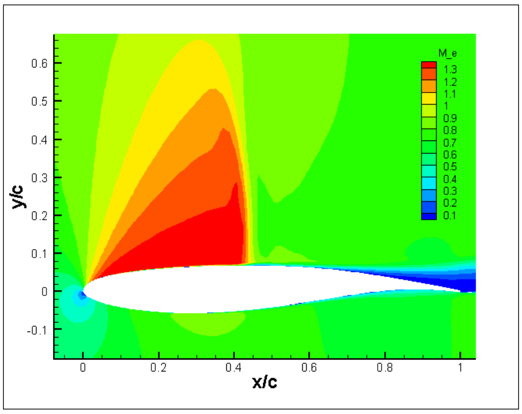

Figure 12. Steady regime, time-dependent turbulent model, minimum lift, AoA=4.5°

A comparison of the contour plot of Mach number between the standard k-ε model and the time-dependent model is given in Figures 11-14 when the lift coefficient reaches either its maximum or minimum values (extreme positions of the shock). One can see that the shock position noticeably changes reflecting the unsteadiness of the flow.

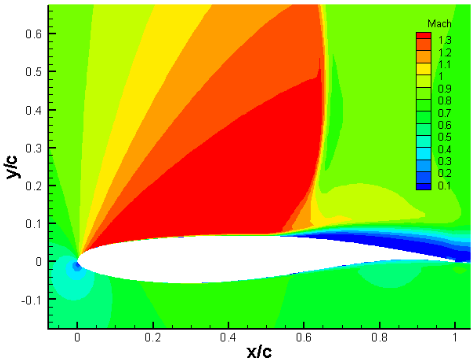

Figure 13. Steady regime, k-ε turbulent model, maximum lift, AoA=4.5°.

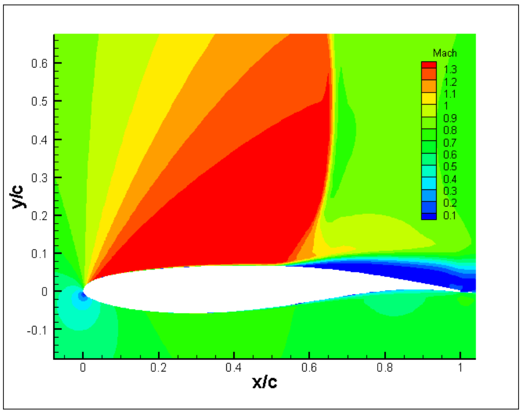

Figure 14. Steady regime, time-dependent turbulent model, maximum lift, AoA=4.5°.

Even though, the results obtained from both models seem very similar, the local variation of the parameter C_μ displayed in Figure 15 evidences large departure from its standard value, i.e. 0.09. This shows the ability of the time-dependent model implement in this study to self-adapt to the flow dynamics.

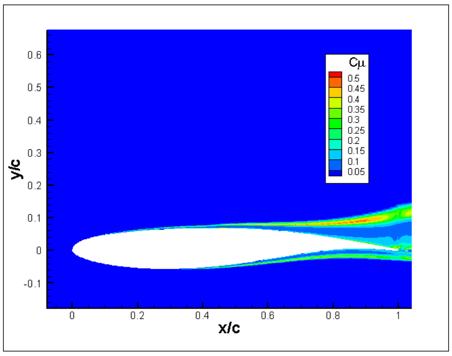

Figure 15. Typical variation of C_μ for the time-dependent model in steady computation, minimum lift, AoA=4.5°.

CONCLUSIONS AND PERSPECTIVES

The numerical simulations of a transonic airfoil by means of the standard turbulence models have been used to capture the buffeting. Even phenomenon is well reproduced by k-ω sst, some discrepancies are observed with the experimental data. The agreement with the experimental results has been obtained with a higher angle of attack and with the 2D airfoil.

A refined Reynolds-stress model, based on a semi-deterministic approach, is implemented to k-ε with low-Re corrections in order to improve the buffeting prediction. Preliminary results in steady regime are obtained and show the ability of the time-dependent model to self-adapt to the flow dynamics. Unsteady computations with the time-dependent turbulent model are currently under progress.

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