NUMERICAL SIMULATION OF TRANSONIC BUFFET OVER AIRFOIL

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1 Introduction

The transonic buffet is an aerodynamic phenomenon which results in a self-sustained periodic motion of the shock over the surface of the airfoil, due to the development of instabilities caused by the boundary layer separation and the shock wave interaction. This problem is of primary importance for aeronautics applications because it can lead to the buffeting phenomenon through the mechanical response of the wing structure. The large amplitude periodic variation of lift associated with buffet limits the cruising speed of commercial aircrafts and severely degrades the manoeuvrability of combat aircrafts.

The unsteady resolution of the Navier-Stokes equations is realized with various transport-equation turbulence models in which corrections are added for non-equilibrium flows. The lack of numerical efficiency due to the CFL stability condition is bypassed by the use of a wall law approach and a dual time stepping method. Comparisons are made with experimental results obtained for the transonic RA16SC1 supercritical airfoil. They show the interest of the use of the SST correction or realizability conditions to get correct predictions.

2 Numerical methods

The numerical simulations have been carried out using an implicit CFD code solving the uncoupled RANS-turbulent systems for multi-domain structured meshes. This solver is based on a cell-centered finite-volume discretization. Numerical fluxes are computed with the Jameson scheme for the mean flow and a second-order Roe scheme for the turbulence transport equations.

Time integration is performed through a matrix-free implicit method. The feature of this method is that the storage of the Jacobian matrix is completely eliminated which lead to a low-storage algorithm. The implicit time integration procedure leads to a system which is solved with a Point Jacobi relaxation algorithm.

For steady state computations, convergence acceleration is obtained using a local time step and the full approximation storage multigrid method.

For unsteady computations, a dual time stepping method is used to overcome the lack of numerical efficiency of the global time stepping approach.

3 Turbulence Models

Various one and two-equation turbulence models are used for the present study :

- the Smith $k-l$ model
- the Wilcox $k-\omega$ model
- the Menter $k-\omega$ model
- the high Reynolds version of the Jones-Launder $k-\varepsilon$ model
- the Kok $k-\omega$ model
- the Spalart-Allmaras model

3.1 Durbin correction - link with realizability

Based on the realizability principle a minimal correction was derived for two-equation turbulence models and was shown to cure the stagnation-point anomaly (Durbin96). The condition to ensure realizability in a three-dimensional flow is :

$$C_\mu \leq \frac{1}{s\sqrt{3}} \quad ; \quad s = \frac{k}{\varepsilon} S \quad ; \quad S^2 = 2S_{ij}S_{ij} - \frac{2}{3}S_{kk}^2 \tag{1}$$

It allows to obtain a weakly non-linear model with a C_μ coefficient function of the dimensionless mean strain rate :

$$C_\mu = \min\left(C_\mu^o, \frac{c}{s\sqrt{3}}\right) \quad \text{with} \quad c \leq 1 \tag{2}$$

where C_μ^o is set to the constant value 0.09.

4 Wall law approach

At the wall, a no-slip condition is used coupled to a wall law treatment. It consists in imposing the diffusive flux densities, required for the integration process, in adjacent cells to a wall. The shear stress and the heat flux are obtained from an analytical velocity profile. As concerns the turbulent quantities, the turbulent kinetic energy is set equal to zero at the wall and its production is computed from the velocity profile. The second turbulent variable is deduced from an analytical relation and is imposed in adjacent cells to a wall.
To use the wall law approach with the multi-grid algorithm, the wall law boundary condition is applied on the fine grid and the classical no-slip condition is applied on the coarse grids.

5 Numerical results

5.1 Experimental conditions

The experimental study has been conducted in the S3MA ONERA wind tunnel with the RA16SC1 airfoil. It is a supercritical airfoil with a relative thickness equal to 16% and a chord length equal to $180mm$. The flow conditions are : $M_\infty = 0.732$, $T_i = 283K$, $Re_c = 4.2\,10^6$ and the incidence varies from 0 to 4.5°. Transition is fixed near the leading edge at $x/c = 7.5\%$ on both sides of the airfoil.

5.2 Computational conditions

For the computations, experimental corrections are used. The Mach number is decreased by 0.09 and the angle of attack is decreased by 1° at all incidences with respect to experiment. The grid is a C-type topology. It contains 321x81 nodes, 241 of which are on the airfoil. This mesh has been obtained from a fine mesh, with y^+ values of order of unity near the wall, by removing 16 lines near the wall.

5.3 Comparison of turbulence models

The frequency f and the amplitude of the lift coefficient ΔC_L are reported on the table 1 for all turbulence models and for three angles of attack corresponding respectively to the buffet onset, the established phenomenon and the buffet exit i.e. the back to a steady state.

First, we examinate the capacity of turbulence models to restitute the natural unsteadiness of the flow without and with any correction. The Spalart-Allmaras model is able to reproduce the buffet phenomenom, the frequency being underestimated with respect to the experimental values. The Smith $k-l$ model need a correction to obtain unsteady results. The Smith correction does not seem to be efficient for these unsteady computations. Yet, the SST corrections make the model able to simulate the buffet. The Jones-Launder $k-\varepsilon$ model is able to provide unsteady solutions without correction. Yet, the lift amplitude is largely underestimated for $\alpha = 4^o$ and the model completely damps the natural unsteadiness for the onset. The shock induced oscillations appear to an angle of attack of 3.7^o rather than 3^o for the experimental value. The Wilcox and Menter $k-\omega$ models fail to compute this application, results obtained being completely steady. The add of the SST correction to the Menter model allows to predict self-sustained oscillations with a very good agreement with respect to the experimental data. The Kok $k-\omega$ is able to compute natural unsteadiness for the established phenomenom but the buffet onset and the buffet exit are not predicted.

When comparing all turbulence models, the best results are clearly obtained with the SST Menter model, for the three angles of attack. The buffet exit is predicted only with this model.
The add of the cross-diffusion term $\mathrm{grad}\,k.\mathrm{grad}\,\omega$ in the ω equation of the Menter model, in comparison with the Wilcox model, does not make the model able to predict shock induced oscillations. Then, the SST limiter shows its great influence and the improvments brought.
When regarding the unsteady results of the Kok model, it appears that the calibration of the constant has also a great influence. We have change the constant values, following all constraints, to show the sensitivity of the model to the cross-diffusion term for these unsteady computations. The increasing of the σ_d coefficient induces an increasing of the amplitude of the lift coefficient for all angles of attack and, especially, allows to predict the entrance in the

	$\alpha = 3^o$		$\alpha = 4^o$		$\alpha = 5^o$	
model	f (Hz)	ΔC_L	f (Hz)	ΔC_L	f (Hz)	ΔC_L
experiment	**88**	**0.11**	**100**	**0.308**	**probably steady state**	
Spalart-Allmaras	82	0.0146	92	0.325	100	0.55
$k-l$	-	-	steady state		-	-
$k-l$ corrected	-	-	steady state		-	-
$k-l$ SST	79.5	0.0084	97.6	0.296	101.8	0.53
$k-\varepsilon$	steady state		95.6	0.17	97.6	0.43
$k-\varepsilon$ SST	steady state		95.6	0.48	101.8	0.67
$k-\varepsilon$ Durbin	85.2	0.012	93.7	0.437	101.8	0.67
$k-\omega$ Wilcox	-	-	steady state		-	-
$k-\omega$ Menter	-	-	steady state		-	-
$k-\omega$ SST Menter	90	0.11	96.6	0.33	steady state	
$k-\omega$ Kok	steady state		94.6	0.26	95.6	0.48
$k-\omega$ Kok SST	steady state		94.6	0.26	96.6	0.445
$k-\omega$ Kok Durbin	steady state		94.6	0.26	96.6	0.45

Table 1: Frequency and amplitude of the lift coefficient

shock induced oscillations domain.

The RMS values of the pressure fluctuations over the airfoil are also compared with experimental results but are not presented here.

6 Conclusion

The prediction of shock induced oscillations has proved to be sensitive to the turbulence modelling. The present paper shows the interest of the use of a SST correction or realizability conditions to obtain a better prediction of the transonic buffet over the RA16SC1 airfoil. For the Kok model, a recalibration of the constants allows to improve the results for these unsteady computations.