NUMERICAL INVESTIGATION OF BUFFET PHENOMENON WITH URANS EQUATIONS

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In transonic flow conditions, the shock / turbulent boundary layer interaction and flow separation may induce instabilities called "buffet" on the wings of an aircraft. This unsteady behaviour of the flow could provoke structure vibrations named "buffeting" which can restrict the flight domain of the aircraft. The issue cannot be easily undertaken in wind tunnel campaigns because of the dynamic behaviour of model structures, and also because of strong Reynolds number effect.

Numerical methods are promising approaches to predict buffet onset and to study its "natural" unsteady characteristics. Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) would be very useful to study accurately this complex unsteady phenomenon. Nowadays, these methods remain too much CPU expensive on such complex transonic configurations with high Reynolds numbers. Then, the Unsteady Reynolds Averaged Navier-Stokes (URANS) equations are used to study this type of flow. Many hypothesis are necessary for the closure of this system of equations, the most important is the turbulence modelling thanks to one or more transport equations. Nevertheless, the quite low CPU cost of this modelling approach allows complex configurations to be modelled and several computations to be performed.

Previous numerical studies of the buffet have been performed [1-4] on two dimensional flows. This paper first presents latest computations of two-dimensional buffet based on previous studies' conclusions. The accuracy of this modelling approach is demonstrated thanks to an experimental database. Then, a second configuration is presented. It corresponds to a wall-to-wall swept wing. The computations based on infinite swept wing hypothesis are compared to the wall-to-wall swept wing ones and to measurements. The effect of side walls on the unsteadiness of the flow is demonstrated.

Numerical methods

All computations presented in this paper are based on the ***elsA*** software [5] developed by

ONERA and CERFACS in France. It uses structured grids and many numerical methods and turbulence modelling can be applied. First buffet computations [1-4] had been obtained with the Spalart-Allmars model [6], but in this paper results will only be presented with the Menter SST model (SST) [7] and the EARSM model of Shih, Zhu and Lumley (SZL) [8]. These two turbulence models had been previously selected [2-4]. The spatial discretisation of the mean field relies on second order central differences (Jameson scheme [9]) with the use of first and third order dissipation terms in order to avoid numerical instabilities. As for the turbulent field, a second order upwind scheme (Roe scheme) is used with a TVD correction [10]. The resolution of the equation system is performed thanks to an implicit LU method with a relaxation technique [11]. Concerning time accurate simulations, a second order Gear scheme with five Newton sub-iterations is employed.

Two-dimensional case

Experiments were carried out in the S3 wind tunnel of ONERA Chalais-Meudon (see Jacquin et *al.* [12]). The model is based on the OAT15A supercritical airfoil. It is characterised by a *12.3%* thickness-to-chord ratio, a *230 mm* chord length and a thick trailing edge equals to *0.5%* of the chord. Laminar-turbulent transition was fixed on the model thanks to a carborundum strip at $x/c = 7\%$. The equipment of the model is based on 68 static pressure sensors and 36 unsteady Kulite pressure transducers. The cross-section of the test chamber is equal to $0.78 \times 0.78\ m^2$. Upper and lower walls are flexible in order to impose the flow streamlines and to limit their effects on the mean flow. The adaptation technique is a static mechanism, based on a steady flow hypothesis. Various flow conditions were investigated (variations of Mach number and angle of attack) but in this paper, we will only focus on the following: $M_\infty = 0.73$, $Pi = 10^5\ Pa$, $Ti = 300\ K$, $Re_{AMC} = 2.8\ 10^6$ and angles of attack from 2.5^o to 3.91^o.

During previous studies, Goncalvès et *al.* [1] had shown the quality of buffet simulation with URANS equations and wall functions. Then, Brunet [2] selected different turbulence models and numerical methods described previously. Next, Brunet and *al.* [3] demonstrated the quality of the selected numerical and modelling methods on this test case and Thiéry et *al.* [3-4] showed the effect of upper and lower walls on the unsteadiness of the flow in buffet conditions.

The grid used to performed computations is presented in Fig. 1. 493 mesh nodes describe upper and lower sides of the airfoil and 49 the thick trailing edge. The far field conditions are imposed at 50 times the chord length. About 50 cells describe the boundary layer in the shock region. The $y+$ parameter of first cells at wall is about *0.5* everywhere. Total mesh nodes are equal to 86,530. A grid adapted to wall functions has been generated from this one thanks to the merging of 24 first cells at wall in order to obtain a $y+$ parameter equals to about *50* in attached boundary layers.

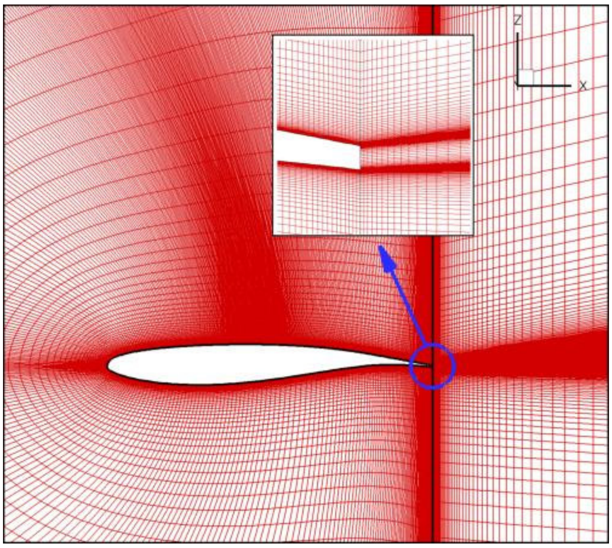

Fig. 1

During experiments, a very strong unsteadiness was measured at angles of attack higher or equal to 3.25^o. This unsteadiness corresponds to the buffet and it is characterised by a natural oscillating movement of the shock location, forced by the unsteady coupling between the shock and the separated area induced by this shock (see [1-4, 12]). Then, first computations were performed at $\alpha = 2.5^o$ in order to validate our modelling out of buffet conditions *i.e.* in steady conditions. SZL and SST turbulence models where evaluated with and without wall functions. Pressure coefficients computed along the airfoil are compared in Fig. 2 with measurements. Results are quite similar except in the shock region where SST model predicts a better upwards location of this shock in comparison with experiments. Moreover, in the trailing edge region on the upper side, pressure is lower with the SST model which shows the prediction of a small separated area. Computations with or without wall functions are quite similar, but the shock is in a more upstream location with wall functions.

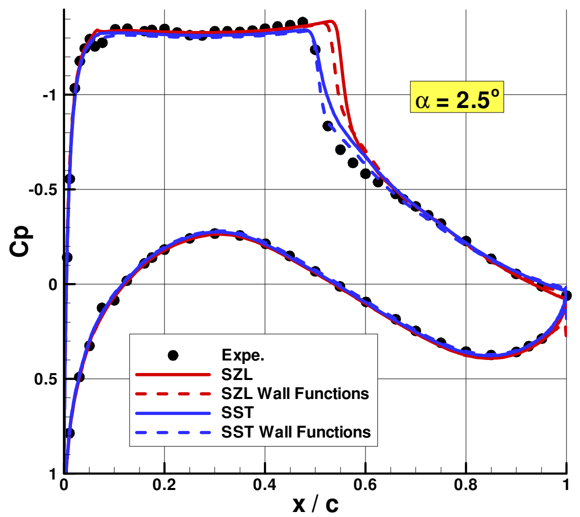

Fig. 2

Then, time accurate simulations were carried out at angles of attack equals to 3.5^o and 4.0^o. Time steps were equal to $1.91\ 10^{-7}\ s$ without wall functions and $9.55\ 10^{-7}\ s$ with wall functions. As shown in Fig. 3 presenting time evolution of shock location, established unsteady solutions are obtained whatever the modelling approach at 3.5^o and 4.0^o. This unsteady behaviour of the flow is characterised by a sinusoidal movement of the shock at a frequency equals to *78 Hz* (*69 Hz* during experiments). SZL modelling develops more unsteadiness than SST and the shock oscillations are in more upstream locations. Finally, the use of wall functions with the SZL does not change the unsteady solution at 4.0^o.

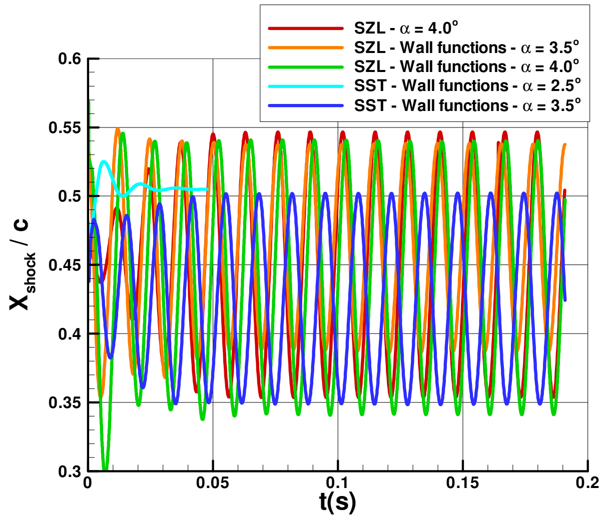

Fig. 3

Mean pressure distributions allow the global quality of computations to be checked. Results for 3.5^o and 4.0^o are presented in Fig. 4. Small pressure gradient values in the shock region are linked to its wide displacement during the unsteady buffet phenomenon. Main differences between computations and measurements are located in the shock / detached boundary layer region. Indeed, all computations predict quite good results concerning pressure levels in the separated and shock regions. These well computed pressure levels demonstrate the very accurate modelling performed in the separated area. Comparisons between computations have shown the ability of wall functions to model this complex unsteady phenomenon with detached boundary layers, and one more time SST model predicts the most upstream location of the shock at 3.5^o. Finally, the unsteadiness of the flow is higher at 4.0^o than at 3.5^o.

Analysing mean pressure of an unsteady phenomenon is not sufficient to estimate the quality of time accurate simulations. Then, in

Fig. 5 RMS pressure levels are presented for the same computations. Negative *x/c* values describe the lower side of the airfoil, the pick is linked to the movement of the shock and the "V" shape behind the pick corresponds to a "pulsation" of the separated region. Computations are in a good agreement with experiments and conclusions remain the same. At *3.5°*, pressure fluctuations are slightly underestimated and at *4.0°* slightly overestimated.

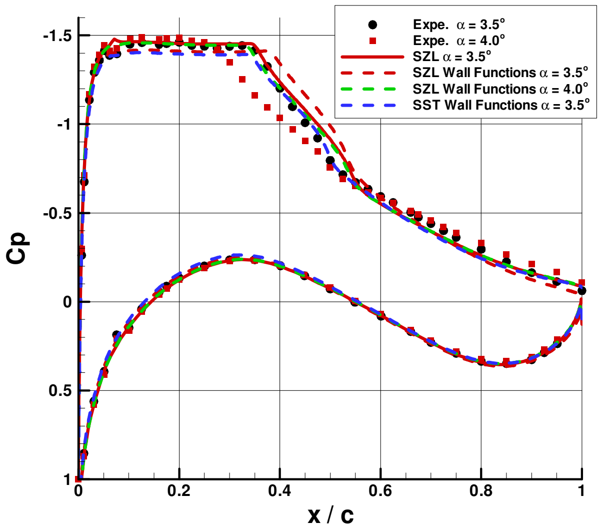

Fig. 4

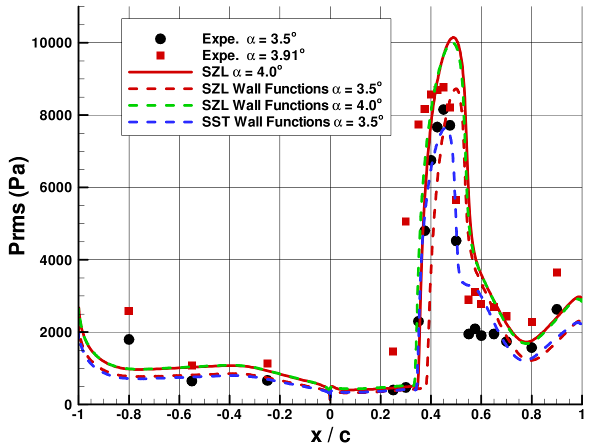

Fig. 5

Previous quantities do not allow analysing the frequency dynamic behaviour of the flow. Power spectral densities of pressure signals on the upper side of the airfoil in the trailing edge region (*x/c = 90%)* are presented in Fig. 6. The main frequency of the buffet and its harmonics are correctly simulated (*76 Hz* for computations / *69 Hz* for experiments), but levels at high frequencies are highly underestimated, which is characteristic of URANS simulations where chaotic frequencies of the turbulence are averaged. The frequency of the buffet computed is caused by acoustic origins. All computations show the same kind of curves, differences coming from high frequencies.

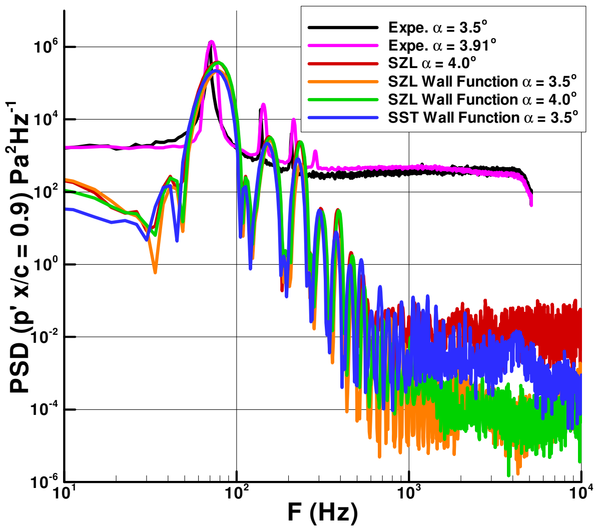

Fig. 6

In Fig. 7, the power spectral analysis of pressure signal on the whole upper side and for the calculation with the SZL model without wall functions at *4.0°* is presented. The main frequency of buffet at *76 Hz* is easily observable from the leading edge to the trailing edge as well as its harmonics in the shock region because of the squared signal characteristic of a shock movement. At high frequencies, upstream to the shock, levels are very low which demonstrates the lower band filter behaviour of the supersonic region. Downstream to the shock, levels in high frequencies are higher but are probably issued of "pure" numerical instabilities since the URANS modelling is unable to capture the chaotic behaviour of the turbulence in a separated region.

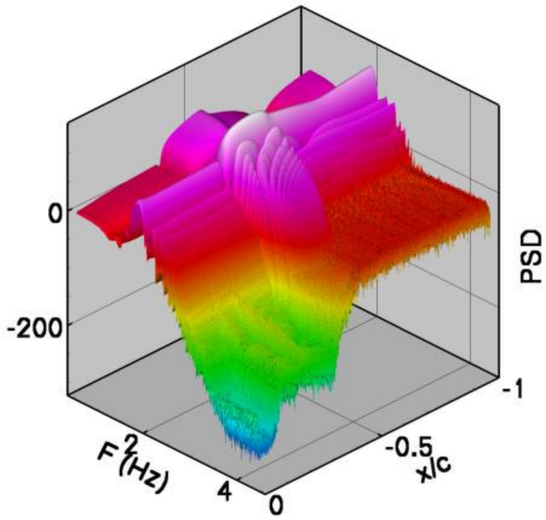

Fig. 7

This two-dimensional study shows the ability of URANS simulations to compute accurately with or without wall functions the main frequency of the buffet phenomenon, but high "chaotic" frequencies are inaccessible. Indeed, whatever the modelling approach, steady and unsteady characteristics (RMS pressure and main frequency) of the buffet are in good agreement with measurements.

Wall-to-wall swept wing

This second study is based on the same supercritical airfoil, but the wing is swept with an angle equals to 24^o. The model was installed in the T128 wind tunnel of TsAGI [13] and its chord length is constant between side walls and equals to *0.5 m* normal to the leading edge. Cross test-section is equal to $2.75 \times 2.75\ m^2$. A twist distribution is applied to the model in order to maintain a constant lift coefficient along the span and mainly in the mid region. Laminar-turbulent transition was fixed at *7%* of the chord thanks to a carborundum technique. The equipment of the model consists of two sections at *1/3* and *2/3* of the span with steady pressure sensors and a section at half-span with unsteady pressure taps. Various flow conditions were investigated during experiments, but in our studies, we have only focused on the following: $M_\infty = 0.8$ – $Re_{AMC} = 6\ 10^6$ – $Ti = 300K$. Because of important three-dimensional effects during experiments, it was difficult to determine the angle of attack corresponding to buffet onset and no wide shock movement was observed. Nevertheless, in separated conditions a main aerodynamic buffet frequency has been measured at *29 Hz*.

Two types of computations were performed. The first one is based on the infinite swept wing hypothesis and the second one is the wall-to-wall swept wing calculation. Section mesh is exactly the same as in the previous two-dimensional study, and the swept angle is taken into account. Concerning the wall-to-wall wing, the twist distribution is applied and side walls of the wind tunnel are considered as slipping walls. Only wall functions with the SZL model are used and the final mesh is composed of *3.6* million nodes. Time step used for time accurate simulations is equal to $2.1\ 10^{-6}\ s$.

First, computations were performed at a low angle of attack equals to 2.0^o in order to model a flow without massive separation, before buffet onset, *i.e.* in steady conditions. Pressure distributions are presented in Fig. 8. One more time, computations are in good agreement with measurements but they place the shock in a too much downstream location. Small three-dimensional effects from side walls can be observed on section *y/b = 1/3*. On others sections, pressure distributions of the wall-to-wall wing and the infinite wing are in good agreement which shows the quality of the twist distribution applied to the model, but without massive separation.

Then, time accurate simulations were performed at 3.5^o with both approaches. Lift coefficients as a function of physical time are represented in Fig. 9. The infinite swept wing develops a very unsteady solution like the one observed in previous two-dimensional study. Main frequency simulated of the buffet phenomenon is equal to *34 Hz* (*29 Hz* during experiments). Regarding the wall-to-wall computation, the main frequency remains the same, but the unsteady behaviour of the flow is completely damped and the solution can be considered as steady. It seems that this modelling is able to capture instability at *34 Hz*, but because of the averaging of the turbulence performed by the URANS equations, no fluctuations computed in the flow can excite this aerodynamic eigen mode. Indeed, with URANS equations, the chaotic behaviour of the separated region is averaged.

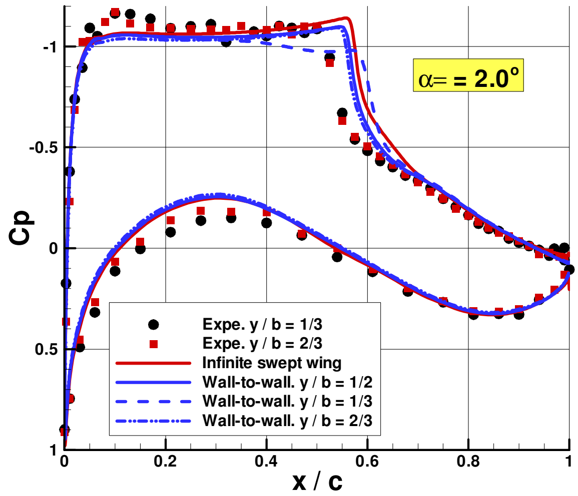

Fig. 8

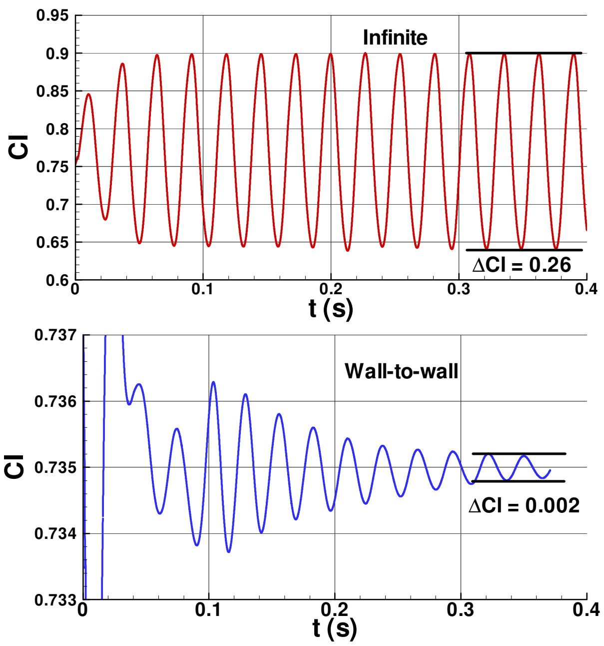

Fig. 9

Regarding the pressure distributions in the two measured sections (Fig. 10), one can observed strong three-dimensional effects in these flow conditions. Despite of the very limited modelling of side walls (slipping conditions), the agreement between the wall-to-wall computation and measurements is very good. Indeed, the shock location and pressure level in the separated region are well predicted. The infinite swept wing hypothesis shows a too strong instability for the buffet and its pressure level in the separated region is well computed for section *y/b = 2/3* but not at all for *y /b = 1/3*.

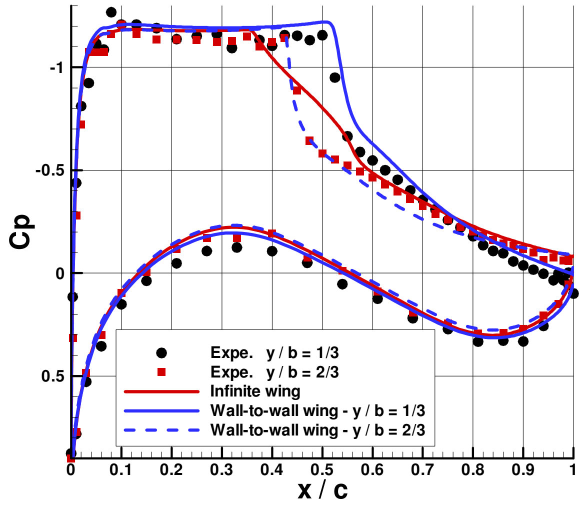

Fig. 10

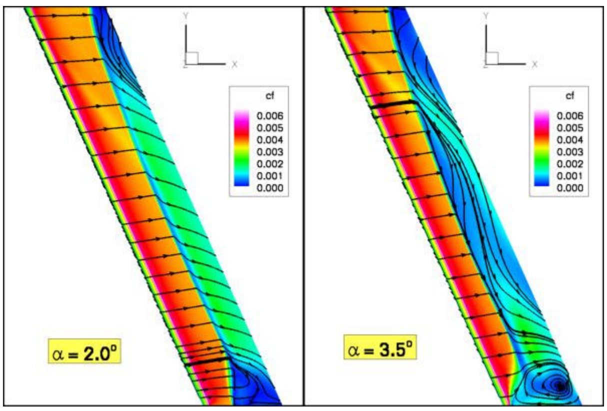

Fig. 11

The visualization of skin friction lines (Fig. 11) allows the topology of the flow to be understood. Then at *2.0°*, the flow remains attached on most part of the model except in corners after the shock. These corner flows are probably not simulated with accuracy because of the slipping conditions on side walls. At this angle of attack, a very small separated region can be observed at the shock foot, and this shock is parallel to the leading edge on most part of the model. At *3.5°*, the flow is massively detached after the shock which is not perfectly parallel to the leading edge because of strong three dimensional effects. In this flow condition, the infinite swept wing hypothesis can not be considered for accurate computations.

Conclusion

These studies have shown the accuracy of URANS modelling to predict two-dimensional buffet. Indeed, steady and unsteady results are in a good agreement with measurement and the main frequency of the phenomenon is correctly predicted. As for the wall-to-wall swept wing, the infinite swept wing hypothesis in sufficient at low angles of attack, without massive separation. When massive separated regions occurred, three-dimensional effects become very strong and it is necessary to take into account side walls, which effects are very important on the unsteady behaviour of the flow. Then, URANS modelling performed is able to capture the main frequency of the buffet but the solution is completely damped since no "chaotic" fluctuations excite the flow.

In the future, same kind of flow will be computed thanks to more complex modelling like DES or LES and more realistic configurations (wing / body) will be investigated.

Acknowledgments

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