Buffeting Alleviation using Active Flow Control

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Abstract
In this paper we consider the possibility of using active flow control devices for SWBLI and to enable buffeting alleviation. Our target configuration is a classical biconvex aerofoil at transonic speeds in the range of Mach 0.76 and Reynolds 10 mil. The model is equipped with standard transducers and pressure sensors and is under investigation in the INCAS 1.2m x 1.2m supersonic wind tunnel. Controls used in wind tunnel experiment are custom made SJ actuators, surface mounted and operated as either single units or arrays. The information from experiment is compared with the simulations made using DxUNSp CFD simulation platform in a complex attempt for active flow control assessment.

1. Introduction

1.1 The Buffeting Phenomena

Transonic buffeting flow phenomena appears in many aeronautical applications ranging from internal flows such as around turbo-machinery blades to flows over aircraft. Unsteady shock/boundary-layer interaction (SWBLI) affects drastically aerodynamic performance and is a potential major threat for overall safety. The capability to accurately predict such phenomena is of technological significance in experimental facilities (wind tunnels) and a real challenge for current state of the art computational platforms. (Figure 1 – buffeting experiment in INCAS supersonic wind tunnel, schlieren pictures using colored filter normal to the flow direction, Mach 0.762, Reynolds 8 mil.).

The transonic buffeting flow is characterized by a self-excited periodic 180^0 out-of-phase motion of the shocks over the upper and lower surface of the rigid airfoil. A shock-wave forms near the trailing edge just above a region of trailing-edge separation. Its strength increases as the local velocity ahead of the shock increases. The increased strength gives rise to shock-induced separation, and the shock wave and separated region begin to move forward. The local surface velocities upstream of the shock continue to increase and stabilize in a maximum velocity distribution. As the shock continues forward into a region of locally lower velocities, it diminishes in strength and vanishes as the separation point reverts to the trailing edge to complete the cycle. Meanwhile, the identical process is occurring on the lower surface 180^0 out of phase. This periodic phenomenon causes oscillations in the global aerodynamic forces.

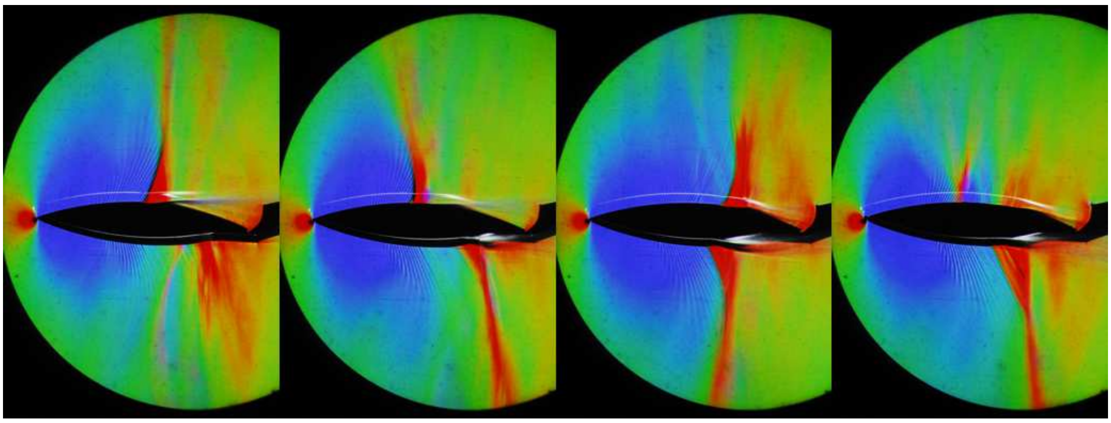

Figure 1 : Schlieren pictures for 18% biconvex, 1 deg., Mach 0.762, Reynolds 8 mil.

The capability for controlling the buffeting phenomena needs extensive knowledge related to the SWBLI mechanisms, combined with the requested technology for active flow control. The use of flow control devices such as synthetic jets (SJ) has the capability for such type of control. The usage of this type of technology is possible due to the progress achieved through complex numerical simulations combined with experimental wind tunnel investigations.

1.2 Experimental Investigation

The mechanism of the self-excited oscillation is not well understood although the topic has been explored by several researchers ([1], [2], [3], [4], [5]). The investigation on the biconvex airfoil suggests that the transonic periodic flows are initiated by an asymmetric unsteady disturbance. The shock-induced separation changes the effective geometry of the airfoil, which causes the forward and rearward movement of the shock depending on whether the stream tube decreases or increases. The necessary but not sufficient condition for the periodic flow to appear is that the shockwave be strong enough to cause boundary-layer separation. The Mach number just upstream of the shock should be in the range between 1.14 and 1.24.

Tijdeman ([3]) notes that flow conditions in the region between the onset of the trailing edge separation and fully separated flow are very sensitive to Reynolds number and the location of transition from laminar to turbulent flow. Tijdeman also identified three types of shock motion, denoted type A, B**,** and C. In type A shock motion, the shock wave remains distinct during the oscillation cycle, with a periodic variation of shock location and shock strength. In type B shock motion, the shock wave weakens and disappears during a portion of the cycle, generally during the forward propagation of the shock along the surface. For type C motion, the shock wave on the airfoil remains distinct and propagates forward along the airfoil chord and off the airfoil leading-edge.

Experimental tests of rigid circular arc airfoils have been reported by McDevitt ([1], [2]) and Mabey ([4]). McDevitt studies give details of tests of an 18 percent thick airfoil for Reynolds numbers covering laminar to fully developed turbulent flows. The wind tunnel walls were contoured to approximate the inviscid stream-lines over an airfoil at M = 0.775. Periodic unsteady air flows were observed over a narrow Mach range whose extent depended upon whether Mach number was increasing or decreasing. For increasing Mach numbers, oscillations occurred for 0.76 < M < 0.78 while for decreasing Mach number the range was wider, 0.73 < M < 0.78 (Figure 2). The reduced frequency of the oscillations ($k = \frac{\pi f c}{U_\infty}$) was 0.48. For the 18-percent biconvex experiments of McDevitt, a substantial hysteresis effect in the unsteady flow boundary was reported.

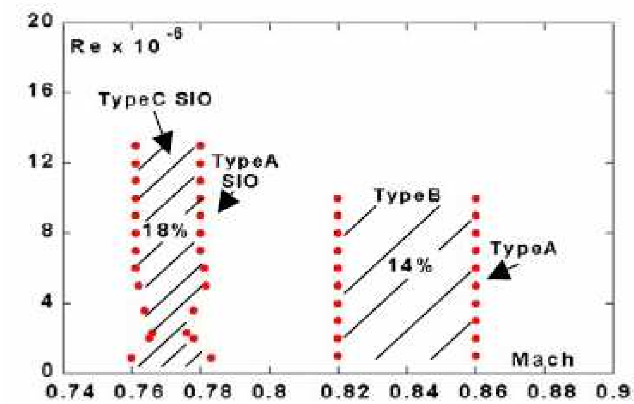

Figure 2 : Regions of buffeting on biconvex 18%

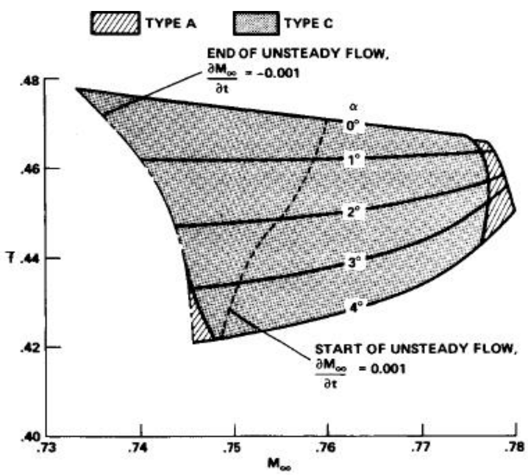

Figure 3 : Buffeting frequency for biconvex 18%

Mabey studied similar periodic flows for a series of circular with thickness between 10–20 %. Two necessary criteria evident from the experimental results for the existence of the periodic unsteady flow are given: thickness/chord ratio greater than 12 percent and local Mach number upstream of the terminal shock wave in the range 1.24 < M < 1.40.

1.3 Numerical Investigation

Computational methods for periodic oscillations about circular arc airfoils have been pursued at a number of differing levels of physical approximation to the flow equations. Several authors reported successful simulations for buffeting flows on reference 18% biconvex aerofoil ([6], [7], [8]).

Levy successfully computed such oscillations for this aerofoil using a Navier-Stokes flow solver. Levy's code uses a MacCormack's explicit solution scheme with an algebraic eddy viscosity model. He modified the code to simulate the contoured wind tunnel walls and shown their substantial influence on the global overall flow field. Steady computed Mach contours for Mach numbers of 0.72 and 0.78, corresponding to trailing - edge and shock induced separations, respectively, and unsteady flow for M = 0.754. The reduced frequency of the computed oscillation s is 0.40, about 20 percent lower than the measured frequency ([2], [4]).

Steger and Bailey reported an application to the problem of aileron buzz using an implicit approximate factorization solution algorithm for the Navier-Stokes (NS) equations using the Baldwin - Lomax algebraic model. The unsteady flow occurred at a higher Mach number (M =0.783) than that of Levy (M = 0.754), which can partly be attributed to the free-air boundary conditions. The computed reduced frequency (0.41) was close to that of Levy (0.40) although both are low in comparison to experiment (aprox. 0.48).

LeBal1eur 's calculations were also made in free-air with a small disturbance potential method including an interacted two equation integral viscous model. Steady shock-induced separation was computed at M = 0.788 and unsteady periodic flow at M = 0.76. The reduced frequency (0.34) was lower than either of the two Navier-Stokes solutions and can be considered as very inaccurate as compared with other methods.

Some calculations have been made by Edwards using the implicit upwind-biased Navier-Stokes algorithm using an algebraic turbulence model Baldwin - Lomax . The tunnel walls were modeled and boundary conditions appropriate for internal flow were used, i.e., the downstream pressure and upstream enthalpy, entropy, and flow direction were specified. The results indicated unsteady flow at a higher Mach number than Levy; steady trailing - edge separation occurred at M =0.754 and unsteady periodic flow at M = 0.78, although the Mach number for onset of the unsteadiness was sensitive to whether or not the divergence of the tunnel boundary to account for boundary layer growth was included. The reduced frequency of the type B unsteady motion was 0.406, in close agreement with the calculations of both Levy and Steger.

A three-dimensional compressible flow solver for unstructured hybrid grids of arbitrary elements has been tested by Möller ([10]). The parallel flow solver is based on a nondecentered finite volume scheme. For steady flows, the equations are integrated toward steady state with an explicit multi-stage Runge-Kutta scheme. Several different turbulence models are available. He use the two-equation *k*−w model by Wilcox combined with the explicit algebraic Reynolds stress model (EARSM).

Rumsey ([11]) used an upwind CFL3D code. Spatial differencing is used for the inviscid terms, and flux limiting is used to obtain smooth solutions in the vicinity of shock waves. All viscous terms are centrally differenced. The equations are solved implicitly in time with the use of a three-factor approximate factorization (AF). The flux-difference splitting (FDS) method of is employed to obtain fluxes at the cell faces. The turbulence models with one-equation is decoupled from the Navier-Stokes equations. The reduced frequencies and the hysteresis region are predicted with reasonable accuracy. The predicted reduced frequency is 0.477 at M = 0.74.

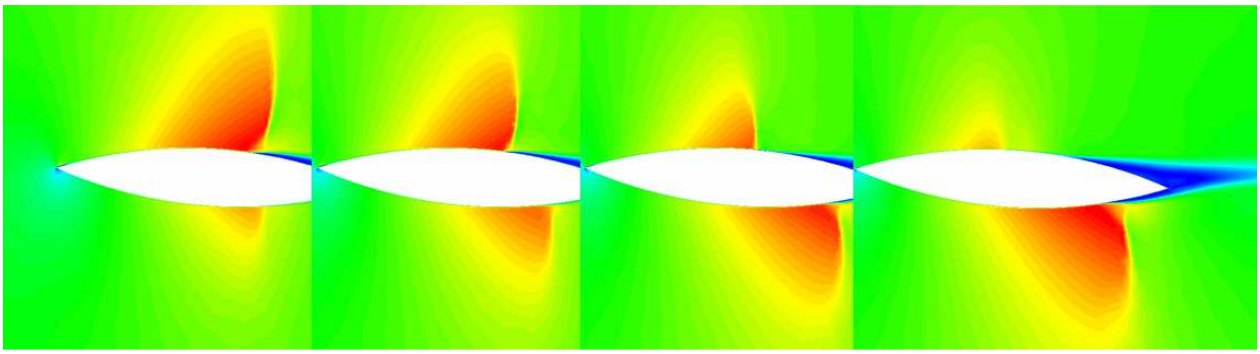

Figure 4 : URANS simulations for 18% biconvex, 3.5 deg., Mach = 0.75, Reynolds = 11 mil.

A typical computation for the biconvex 18% aerofoil using the geometry of INCAS supersonic wind tunnel with solid walls test section is presented in Figure 4. This simulation is performed on a 3D geometry using DxUNSp CFD code developed by the authors, and results are presented for a reference cross section at 40% spanwise location. This URANS approach uses k-eps turbulence model and dynamic mesh adaptation based on local indicator based on flowfield data ([9]). For a particular configuration at Mach 0.75, Reynolds 11 mil. and 3.5 deg. incidence, the computed reduced frequency for the buffeting oscillation was 0.455, somehow very close to the experimental values presented in [3] (Figure 2).

Efficient and robust computations of steady and unsteady separated flows, including steady separation bubbles and self-excited shock-induced oscillations have been obtained. The oscillation onset boundaries and frequencies are accurately predicted, as is the experimentally observed hysteresis of the oscillations with Mach number.

1.4 SJ Actuator

The controls used are SJ devices that have individual characteristics for the frequency and velocity profile. Several numerical studies for the actuator simulation using CFD analysis were performed in order to asses the effect of their operational characteristics[11]. From these results, for a complex analysis of their influence on a body, only the top speed and the frequency for a sinusoidal operating mode were selected. Other characteristics for the velocity profile at the SJ exit (i.e. the influence of the external flows conditions or the geometry of the nozzle) were neglected in this phase. Such actuators have been designed and experimentally tested in INCAS wind tunnels for various flow control problems (Figure 5).

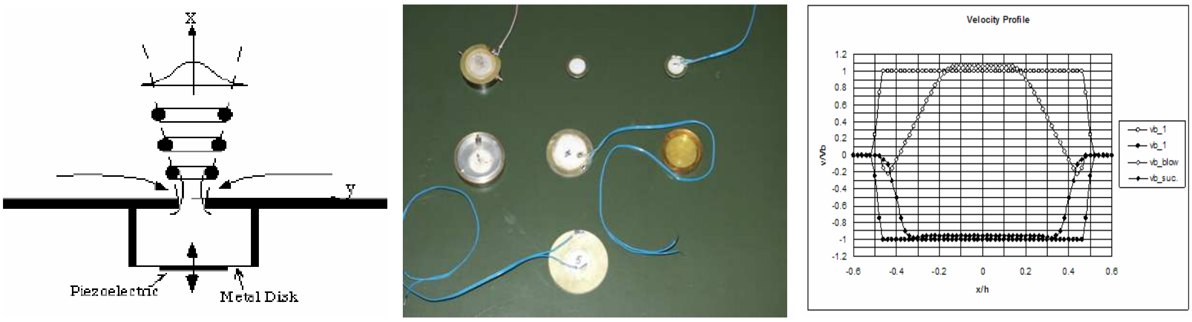

Figure 5 : SJ actuators - schematics, designs and velocity profiles

For numerical simulations, actuators are identified by the locations of the vertices on the surface. In every region, an array of actuators is operating in identical conditions. This makes an array of SJ to act like an individual actuator. If individual actuators in the same region are considered to operate at different conditions (for the top speed and frequency), then this increases the number of controls on the surface.

Several types of simulation were made (Figure 6). For the case of only external influence, the exit flow profile used was of polynomial type. A generalized blowing law was used as:

$$v(t) = V_b(x) \cdot \sqrt{\frac{L_{ref}}{2H}} \cdot V_\infty \cdot \left[\sqrt{c_\mu} + \sqrt{\langle c_\mu \rangle} \cdot \sin\left(2\pi \cdot F^+ \frac{V_\infty t}{L_{ref}} \right) \right] \tag{1}$$

$$V_b(x) = \begin{cases} V_b^0 \\ V_b^0 \cdot \sin[\pi \cdot (0.5 + x)] \\ V_b^0 \cdot \{\sin[\pi \cdot (0.5 + x)]\}^2 \end{cases} \quad \text{and} \quad \begin{array}{ll} H = \dfrac{1}{V_b^{0^2}} \displaystyle\int V_b^{\,2}(x) \cdot dx & c_\mu = 2\dfrac{H}{L_{ref}} \left(\dfrac{V_b^0}{V_\infty} \right)^2 \\ F^+ = \dfrac{f \cdot L_{ref}}{V_\infty} & \langle c_\mu \rangle = 2\dfrac{H}{L_{ref}} \left(\dfrac{\langle v(t) \rangle}{V_\infty} \right)^2 \end{array} \tag{2}$$

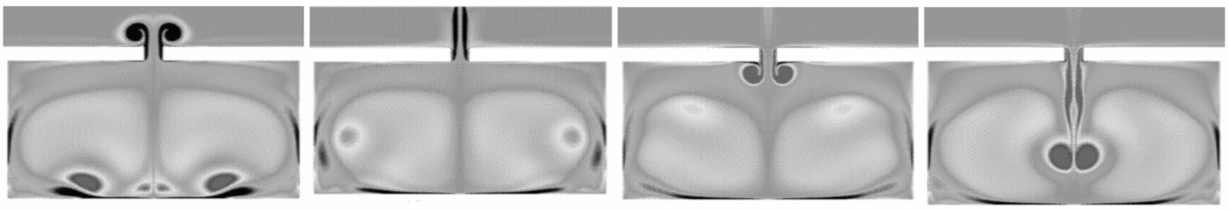

Figure 6 : URANS SJ actuator simulation

Operating frequencies are considered in the range of 0…1500 Hz and the maximum blowing/suction top speed is supposed to be in the range of 0…150 m/s. For numerical evaluations, nondimensionalizations were performed for the reduced frequency in the range of $F^+ = 1 \ldots 10$. The flow induced by the actuator is supposed to have a low level of turbulence, so the same conditions for the viscous variables are considered as for free stream boundary conditions.

In order to use such SJ actuators for numerical simulations, global velocity profiles have been computed and recorded in order to enable a lower computational effort and to avoid complex discretisations (Figure 5). Such approach has been already investigated with successful results in previous applications ([11]).

2. The Buffeting Experiment Setup

2.1 Wind Tunnel Facility

INCAS 1.2 m x 1.2 m wind tunnel is of the blowdown type with a speed range from low subsonic (M = 0.1) to a maximum supersonic Mach number of 3.5. This range includes transonic Mach numbers which are obtained through use of a perforated wall transonic test section. The transonic section is easily incorporated into the wind tunnel circuit when required.

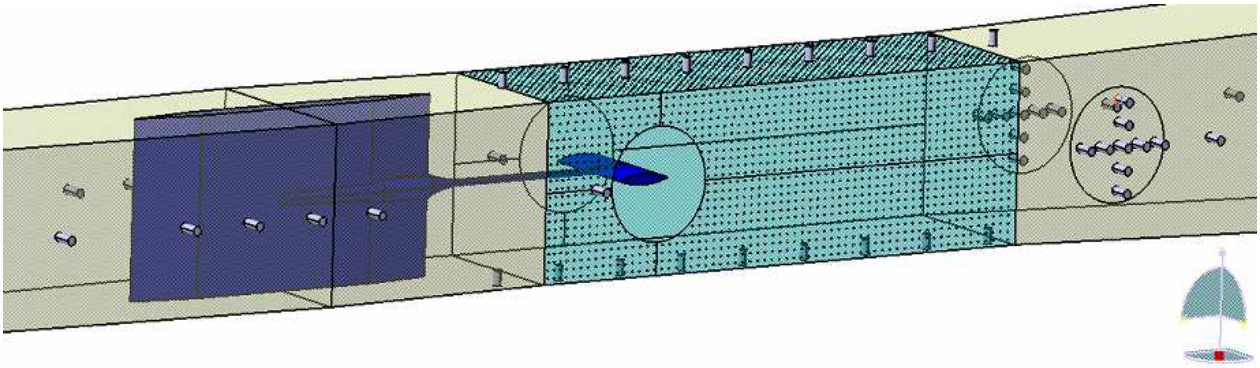

Figure 7 : INCAS supersonic wind tunnel

For normal operation the control valve is manipulated to give a constant stagnation pressure and the stagnation temperature remains at approximately 20°C during a run. This latter is effected by causing the air to flow through a matrix of long steel tubes (18 mm diameter) at the outlet of the air storage. The mass of the tubing is about 200 tons and through its large thermal capacity this mass maintains air temperature to a value close to its initial value (approximately 20°C at all times).

As a run is initiated, the air from the Storage Tanks flows into the Settling Chamber. This flow is regulated by the Control Valve to maintain the desired stagnation pressure in the settling chamber and the noise and turbulence levels are reduced to acceptably low values by baffles and screens. The air then accelerates in the Flexible Nozzle to give the desired test section Mach number. After the air has passed through the Test Section, it is slowed down in the Variable and Fixed Diffusers and finally discharged through an Exhaust Silencer to atmosphere.

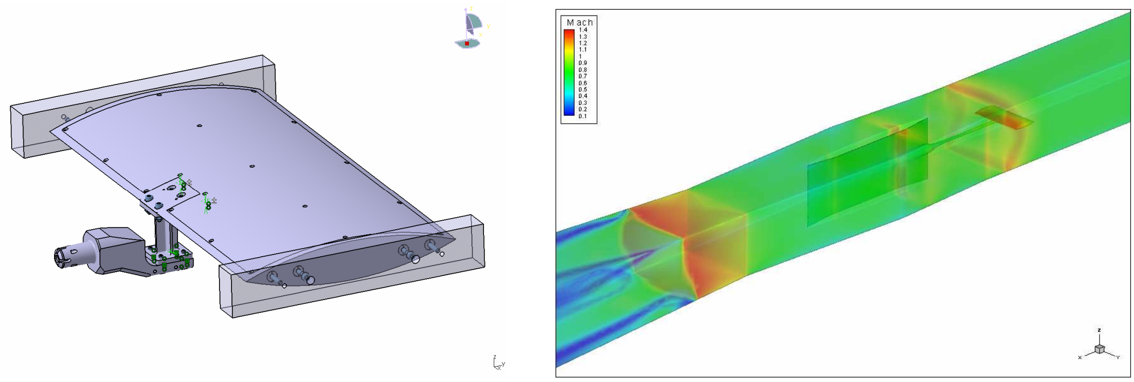

Figure 8 : Model and global flowfield in INCAS supersonic wind tunnel

2.2 Model Design

The model used is composed of 3 main parts: the biconvex model, model support and the model sting. In order to be used inside INCAS Trisonic Wind Tunnel, all models are designed and manufactured according to a very strict AQ system. The basic model is a biconvex airfoil 18%, generated based on analytical equation. The model support and the sting are designed so that the model is located in the center of the schlieren windows. The rotation center is located in the center of the model and this is also the center of the window.

Design loads were estimated using a CFD preliminary analysis of the flow (using DxUNSp CFD platform), with specific corrections based on the internal operating procedures. Flow regimes were considered as in Table 1. The model is designed to accommodate pressure probes and location for SJ actuators. Pressure is provided in 240 points on the surface. During a test run, 32 pressure points are measured on the model, using a SCANIVALVE digital scanning system located inside the model. Several runs are performed for a full pressure data acquisition.

The model support includes transducers for global loads and dynamic behavior of the model. The model is designed and manufactured using CATIA environment. All information for CFD analysis is based on a basic definition of the model in this integrated design environment. It is important to mention the fact that for this particular experiment, the model was manufactured using a hybrid sandwich design, with more than 80% of the structure made from a special non-metallic material in order to reduce the global weight and thus to minimize vibrations (we stress the importance of the buffeting phenomena as unsteady flow configuration over rigid model).

2.3 Experiment Setup

The experiments are designed in order to enable buffeting on the model. With respect to the requirements for CFD analysis, the following procedure has been agreed, as part of a work performed in UFAST FP6 project:

- A set of experiments were performed in solid wall section. A special regime where buffeting is present was identified. This regime was evaluated also from global overall interference effects and a decision to continue in this section was justified based on experimental observations (schlieren images).
- A second validation was considered using the porous section for the experiments. In this test section the plenum chamber has a strong impact and global overall flow conditions are as close as possible to the free flow conditions. However, this has a negative impact on the CFD analysis due to the difficulties related to the modeling of flow inside plenum chamber.

The experiments were performed in transonic conditions, using the schlieren system as a first instrument in order to assess the buffeting phenomena. Also, when it was decided to be used, the perforated wall test chamber with variable porosity was also prepared with schlieren windows. Porosity was adjusted based on test from schlieren images and pressure distribution on porous walls.

The flowfield configuration was based on a classical biconvex aerofoil (18%) at transonic speeds in the range of Mach 0.7 – 0.8 (target Mach number using wind tunnel settings). Incidence range was considered from 1 to 3 deg., and Reynolds influence was also investigated in the range of 5 to 10 mil.

Shock location on the model is expected from 55% to 85% chord length on both upper and lower surfaces, alternating in the buffeting phenomena. Frequency of the oscillation was expected is in the range of 40 to 50 Hz.

In order to have enough time for all measurements (both on the model and on the walls of the test section), the active part of a test run was in the range of 30 to 45 seconds (almost 60 seconds for blown down sequence). This was a challenging demand since the mass flow requested was close to the limit of the wind tunnel capability.

Table 1 : Experimental flow cases data

Mach	Incidence (deg)	Reynolds (mil/m)	P0 (bar)	T0 (Kelvin)
0.75	1 – 3	5-12	1.4 – 3	293
0.76	1 – 3	5-12	1.4 – 3	293
0.77	1 – 3	5-12	1.4 – 3	293

Identification of the buffeting phenomena was possible due to the analysis of the schlieren images captured using a digital camera having ISO 1600 sensitivity and 10 mil. pixels resolution. A sequence of 75 pictures was recorded for every run, so that most of the phases of the SWBLI could be captured. Images were stored on a dedicated computer and custom graphic post-processing procedure was used in order to have animations of the phenomena.

The experiments with SJ controls were performed using an array of 12 actuators located on the upper side of the aerofoil at 70% in chord, using an operating frequency of 1500 Hz. The actuators were operated in phase and were equally distributed spanwise.

The large schlieren system existing at INCAS supersonic wind tunnel was used (aprox. 800 mm diameter), using several filters. A 3 bands color filter was initially used in order to have a correlation of the images with the numerical analysis. Then the “standard” graded grey filter was used for technical evaluations. The filters were used in both parallel and normal position with respect to the flow direction. Finally most of the pictures used the filter normal to the flow direction, thus enabling the visualization for the gradient parallel with the flow.

Based on the information provided by the schlieren images and the information from the pressure sensors on the side of the test chamber, we have concluded that a test at Mach 0.76 at 1 degree incidence was relevant for the buffeting case of interest, with minimum interference from the solid walls.

3. Experimental and Numerical Results

3.1 Numerical Results

All numerical simulations were performed using DxUNSp CFD platform. The solver is using unstructured tetrahedral meshes, explicit 4 order Runge Kutta time integration scheme with global time step strategy. The system is able to dynamically adapt meshes using local flowfield indicators, mainly local Mach number. The simulations were started in a hybrid approach, using an initial global simulation for the global tunnel (Figure 8, 1 million points, shock located in the second throat as requested by the wind tunnel operation) in first phase in order to assess the farfield boundary conditions. Then we have used a fine mesh for the domain of the solid wall test section, with special treatment on the solid walls and the model surface. Here the detailed mesh was based on 5 million points.

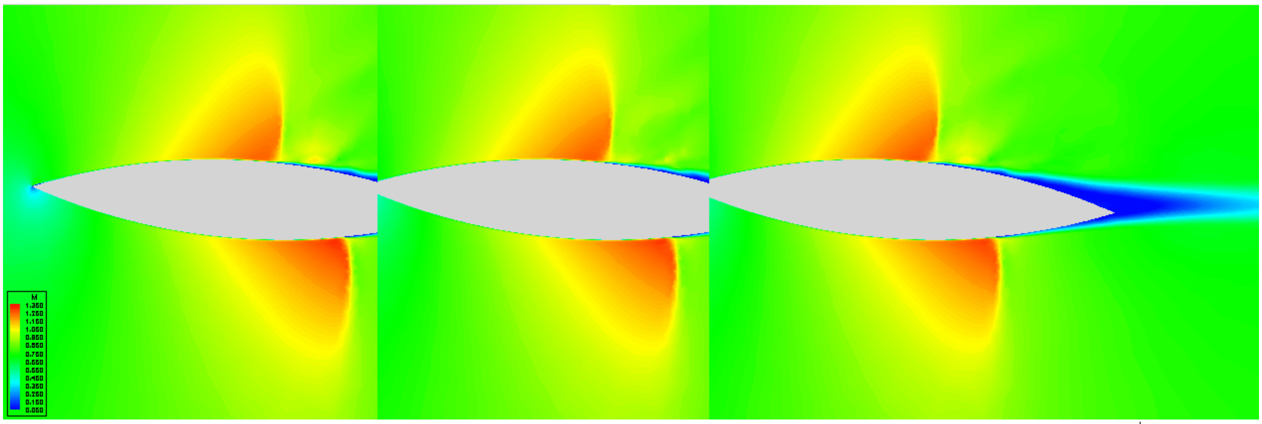

Figure 9 : Numerical simulation for buffeting control (Mach = 0.75, 3.5 deg, Reynolds = 11 mil, F^+=5)

Numerical computations were used in step 1 to reproduce a buffeting flow configuration in the tunnel, for airfoil at 3.5 incidence, Mach = 0.75 and Reynolds = 11 mil. (Figure 4), and then to enable the use of the SJ actuators for buffeting alleviation. The reduced frequency of the oscillation was 0.455, which is in good agreement with other experimental and numerical data. Then, a steady flow configuration was achieved using F^+=5 (f=1500 Hz) for the actuators. This result is presented for a reference section located 40% spanwise in Figure 9

This numerical result proved the feasibility of the buffeting alleviation with SJ. It was then considered as a reference case for wind tunnel testing and assessment using the setup presented in Section 2.

3.2 Experimental results

Experiments in this paper are related only to the solid wall test section of INCAS supersonic wind tunnel. The flow configuration was selected so that a minimum interference with the solid walls was indicated by the schlieren pictures and from pressure information on the walls. This regime was corresponding to Mach = 0.762, aprox. Reynolds = 8 mil., incidence 1 degree (uncorrected). This is somehow equivalent to the numerical case presented.

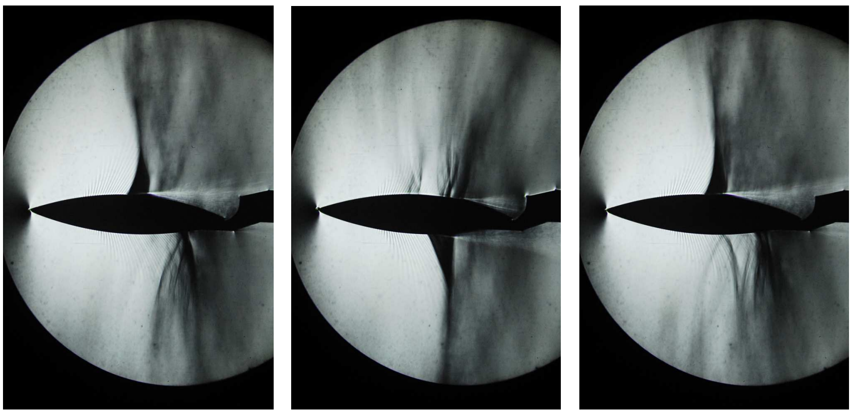

Figure 10 : Schlieren images for buffeting and controled flow (Mach = 0.76, 1 deg., Reynolds 8 mil., F^+=5)

From the experimental investigation for the model without controls, a periodic oscillation associated to buffeting was identified with an approximate global frequency f = 49 Hz (first 2 images in Figure 10). This value is in good agreement with data from literature, mainly with experiments reported by McDevitt ([1], [2]). Since in this phase of the experiments no information from transducers located inside the model was available, the frequency evaluation was based only on the interpretation of the digital schlieren images.

The experiments with SJ controls were relevant for the possibility of using such arrays of devices in order to stabilize the oscillations of the shock. A quasy steady flow configuration was achieved using 12 SJ devices, at f = 1500 Hz operated in phase. The schlieren images gave a first confirmation (third image in Figure 10). This result was confirmed also by the reduced oscillation as recorded by the special transducer introduced into the model in this phase of the experiments.

4. Further Investigations and Conclusions

4.1 UFAST Project

This work was performed with relation to the EU FP6 project UFAST. The major goals of this project are related to a higher and deeper understanding of the mechanisms of SWBLI, where buffeting flows are considered as one of the selected relevant phenomena. The usage of the advanced numerical techniques are considered in strong correlation with detailed experiments using state of the art tools and instruments.

4.2 Some Conclusions

A major finding from present investigation is based on the capability of predicting buffeting flows using URANS computations for 3D configurations. This is a very demanding computational effort and results are very sensitive to boundary conditions and blockage effects. At the same time, using numerical simulations for the SJ actuators combined with a hybrid approach for the global overall simulation proved to be a feasible attempt to achieve buffeting alleviation numerically.

In a concentrated effort to assess the numerical findings, wind tunnel tests for the biconvex airfoil 18% were performed at INCAS supersonic wind tunnel. The buffeting phenomenon was accurately simulated and extensive data were provided for cross-correlation with numerical simulations. The use of SJ for buffeting alleviation also proved to be successful and this work will further be investigated in UFAST project in order to produce active flow control laws for SWBLI.

References

[1] McDevitt, J.B. Levy, L.L. and Deiwert, G.S. “Transonic flow about a thick circular-arc airfoil,” *AIAA Journal*, Vol.14, No.5, 1976, pp.606-613.

[2] McDevitt, J.B., “Supercritical flow about a thick circular-arc airfoil”. *NASA-TM-78549*, *National Aeronautics and Space Administration*, January 1979.

[3] Tijdeman, H., “Investigation of the transonic flow around oscillation airfoils”, *NLR TR 77090 U*, National Aerospace Laboratory, The Netherlands, 1977.

[4] Mabey, D.G., “Oscillatory flows from shock induced separations on biconvex airfoils of varying thickness in ventilated wind tunnels.” *AGARD CP-296*, France, 14-19 Sept. 1980, pp.11.1-14.

[5] Levy L.L. “Experimental and computational steady and unsteady transonic flows about a thick airfoil,” *AIAA Journal*, Vol.16, No.6, 1978, pp.564-572.

[6] Edwards, J.W. “Transonic shock oscillations calculated with a new interactive boundary layer coupling method” *AIAA-93-0777*.

[7] Rumsey, C. L., Sanetrik, M. D., Biedron, R. T., Melson, and Parlette, E. B., “Efficiency and Accuracy of Time-Accurate Turbulent Navier–Stokes Computation,” *Computers and Fluids*, Vol. 25, No. 2, 1996, pp. 217–236

[8] Girodroux-Lavigne, P., and LeBalleur, J. C., “Time Consistent Computation of Transonic Buffet over Airfoils,” *Proceedings of the 16th Congress of the International Council of the Aeronautical Sciences*, 1988, pp. 779–787.

[9] – Nae C., “Flow Solver and Anisotropic Mesh Adaptation using a Change of Metric based on Flow Variables”, *AIAA Paper 2000-2250*

[10] Gortz S., Möller J., “Recursive Projection Method for Efficient Unsteady CFD Simulations”, *ECCOMAS 2004*, 2004

[11] Nae C., “Numerical Simulation of the Synthetic Jet Actuator”, ICA 0.266, *ICAS 2000*, Harrogate, UK, 2000

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