Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology.

A. Lepage, A. Geeraert, J. Dandois, V. Brunet, P. Molton, F. Ternoy, J.B. Dor, E. Coustols

▶ **To cite this version:**

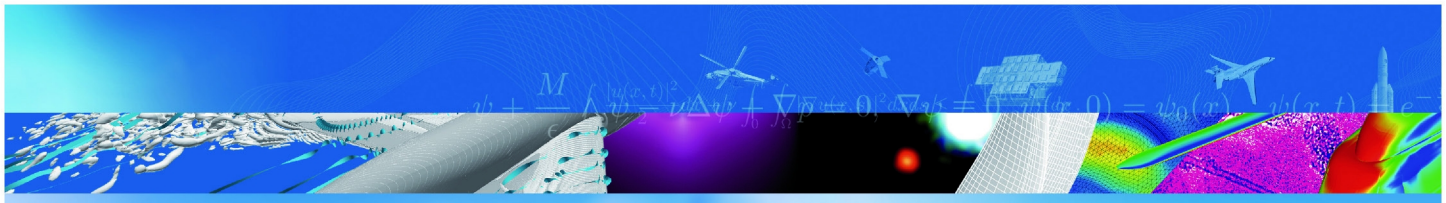
A. Lepage, A. Geeraert, J. Dandois, V. Brunet, P. Molton, et al.. Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology.. 3rd GDR symposium "Flow Separation Control", Nov 2013, LILLE, France. hal-01057666

HAL Id: hal-01057666
https://onera.hal.science/hal-01057666

Submitted on 25 Aug 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



T I R É À P A R T

Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology.

A. Lepage, A. Geeraert, J. Dandois, V. Brunet,
P. Molton, F. Ternoy, J.B. Dor, E. Coustols

3rd GDR symposium
"Flow Separation Control"
LILLE, FRANCE
7-8 novembre 2013

TP 2014-25

ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology.

Contrôle du tremblement transonique d'une voilure turbulente à l'aide d'actionneurs fluidiques. 2ème partie : Investigation expérimentale d'une méthodologie boucle fermée.

par

A. Lepage, A. Geeraert, J. Dandois, V. Brunet, P. Molton, F. Ternoy, J.B. Dor, E. Coustols

Résumé traduit :

L'objectif de cet article est de donner un aperçu des travaux réalisés dans le cadre du projet BUFET'N Co, projet de recherche fédérateur interne à l'ONERA, qui vise à étudier et à contrôler expérimentalement le phénomène de tremblement se développant sur une voilure 3D turbulente pour des conditions transsoniques. Cet article résume les principales investigations qui ont conduit à la définition d'une méthodologie de contrôle boucle fermée et sa mise en œuvre expérimentale. Plusieurs campagnes d'essais en soufflerie ont permis de caractériser l'instabilité aérodynamique de tremblement et d'étudier l'efficacité de dispositifs de contrôle fluidique, conçus et fabriqués au sein de l'ONERA. L'analyse des bases de données boucles ouvertes (fluctuations de pressions pariétales) a permis de montrer leurs effets sur les caractéristiques classiques du tremblement, en particulier sur la position du choc ou les décollements sur l'extrados d'une voilure. A partir de ces résultats, une méthodologie de contrôle boucle fermée basée sur une approche quasi-stationnaire a été définie et différentes architectures ont été testées pour différents paramètres tels que le type de signal d'entrée, la fonction objectif utilisée, la méthode d'ajustement du gain de boucle … Toutes les méthodes boucles fermées ont été implémentées sur un calculateur dSPACE déterminant en temps réel la commande des actionneurs fluidiques à partir des données de pression instationnaire. L'efficacité en matière de retard d'entrée en tremblement ou de limitations de ces effets a été démontrée à la fois lors d'essais en soufflerie de type recherche ou industrielle.

NB : Ce Tiré à part fait référence au Document d'Accompagnement de Publication DADS13039

Transonic Buffet Control on 3D Turbulent Wings using Fluidic Devices. Part 2: an experimental investigation of a closed loop methodology

Arnaud LEPAGE[1], Arnaud GEERAERT[1], Julien DANDOIS[2], Vincent BRUNET[2], Pascal MOLTON[3], FredericTERNOY[4], Jean Bernard DOR[5] and Eric COUSTOLS[5]

ONERA – The French Aerospace Lab
[1] Aeroelasticity and Structural Dynamics Department, Châtillon, FRANCE, 92320
[2] Applied Aerodynamics Department, Meudon, FRANCE, 92190
[3] Fundamental and Experimental Aerodynamics Department, Meudon, FRANCE, 92190
[4] Model Design and Manufacturing Department, Lille, FRANCE, 59000
[5] Aerodynamics and Energetics Modeling Departement, Toulouse, FRANCE, 31000

Abstract:

The presented paper aims at giving an overview of the work performed in the ONERA's internal research project BUFET'N Co addressing the experimental characterization and the control of the buffet phenomenon on 3D turbulent wings in transonic flow conditions. This paper summarizes the main investigations leading to the definition of a closed loop methodology of buffet control and its experimental demonstration. Several wind tunnel tests campaigns enabled to characterize the buffet aerodynamic instability and to study the efficiency of fluidic control devices designed and manufactured by ONERA. The analyses of the open loop databases (wall pressure fluctuations) demonstrated the effects on the usual buffet characteristics, especially on the shock location and the separation areas on the wing suction side. Using these results, a closed loop control methodology based on a quasi-static approach was defined and several architectures were tested for various parameters such as the input signal, the objective function, the tuning of the feedback gain... All closed loop methods were implemented on a dSPACE device calculating in real time the fluidic actuators command from the unsteady pressure sensors data. The efficiency of delaying the buffet onset or limiting its effects was demonstrated using the quasi-static closed loop approach and tested in both research and industrial wind tunnel environment.

Résumé:

L'objectif de cet article est de donner un aperçu des travaux réalisés dans le cadre du projet BUFET'N Co, projet de recherche fédérateur interne à l'ONERA, qui vise à étudier et à contrôler expérimentalement le phénomène de tremblement se développant sur une voilure 3D turbulente pour des conditions transsoniques. Cet article résume les principales investigations qui ont conduit à la définition d'une méthodologie de contrôle boucle fermée et sa mise en œuvre expérimentale. Plusieurs campagnes d'essais en soufflerie ont permis de caractériser l'instabilité aérodynamique de tremblement et d'étudier l'efficacité de dispositifs de contrôle fluidique, conçus et fabriqués au sein de l'ONERA. L'analyse des bases de données boucles ouvertes (fluctuations de pressions pariétales) a permis de montrer leurs effets sur les caractéristiques classiques du tremblement, en particulier sur la position du choc ou les décollements sur l'extrados d'une voilure. A partir de ces résultats, une méthodologie de contrôle boucle fermée basée sur une approche quasi-

stationnaire a été définie et différentes architectures ont été testées pour différents paramètres tels que le type de signal d'entrée, la fonction objectif utilisée, la méthode d'ajustement du gain de boucle … Toutes les méthodes boucles fermées ont été implémentées sur un calculateur dSPACE déterminant en temps réel la commande des actionneurs fluidiques à partir des données de pression instationnaire. L'efficacité en matière de retard d'entrée en tremblement ou de limitations de ces effets a été démontrée à la fois lors d'essais en soufflerie de type recherche ou industrielle.

Key words:

Transonic Flow; Fludic Vortex Generator ; Buffet Control ; Closed Loop.

1 Introduction

For modern civil aircrafts, the buffet phenomenon remains today a problem of outstanding importance for aircraft designers. In transonic flow, the "buffet" phenomenon refers to a strong shock wave / turbulent boundary layer interaction and massive flow separations located on the upper side of wings at high Mach number and/or high angle of attack. The aircraft structural response to the aerodynamic excitation is called "buffeting" and may decrease passenger comfort, increase structural fatigue and affect the aircraft manoeuvrability. The buffet onset is usually defined by a pilot seat acceleration level and this limit determines the flight envelope in terms of lift coefficient - Mach number boundaries: a 30% margin is required for the cruise lift coefficient.

To get a better knowledge of buffet and to investigate the efficiency of innovative buffet control devices, ONERA took part recently in several projects, national or collaborative research activities (the EU-funded AVERT and Clean Sky projects). At the same time, ONERA launched an internal multi-disciplinary research project (BUFET'N Co – [1]), with the objective to realize the buffet control of 3D turbulent wings in transonic flow conditions and its demonstration during wind tunnel (WT) tests. A special focus was to investigate buffet control thanks to a closed loop methodology and the use of fluidic devices. Therefore, several wind tunnel tests were carried out in the framework of these projects and a large amount of measurements was acquired on two models and in various flow conditions before buffet onset and in buffet conditions. Several classical and innovative devices have been designed, manufactured and tested by ONERA (mechanical vortex generator, fluidic vortex generator, synthetic jet actuator and fluidic trailing edge devices). During the WT tests, the control devices behaviours and their efficiency to decrease the buffet effects or to postpone the buffet onset have been precisely investigated [2]. The analyses of the open loop (OL) databases allowed to identify the best actuator for the realization of the active buffet alleviation based on a closed loop (CL) control approach. Consequently, this paper summarizes the main investigations leading to the definition of a CL methodology of buffet control using fluidic VG actuator and its experimental demonstration.

2 Wind Tunnel Tests Campaigns

In order to obtain a reference experimental database, a global roadmap has been decomposed in several wind tunnel tests. The first experimental setup has been tested in the S3Ch research transonic wind tunnel located in the ONERA Meudon Center within the objective to improve the 3D turbulent buffet understanding and to test the efficiency of several actuators. The second phase of the WT tests has been performed in the in the industrial S2Ma wind tunnel of the ONERA Modane-Avrieux Center. This wind tunnel enables to test larger models with specific measurement and test conditions: global effort balance measurements, continuous variation of the angle of attack and adjustment of the WT stagnation pressure. These characteristics have allowed to extend the parametric analysis of the buffet and to estimate the performances of the various control actuators.

FIG. 1 – Models in the S3Ch (left) and S2Ma (right) WT test sections

An overview of models installed in the WT test sections is depicted in Figure 1. Both wing models represented a "generic" civil transport aircraft composed of a swept wing and a fuselage. A peniche was used to extract the model from the influence of the WT wall boundary layer. The aerodynamic shapes are based on the supercritical ONERA OAT15A airfoil. For the S3Ch test (respectively S2MA), the chord varies from 0.24m at the root to 0.2 m at the tip over a 0.704m span (respectively from 0.450m at the root to 0.225 m at the tip over a 1.225m span). The wing models have been equipped mainly with accelerometers to identify the structural responses and steady and unsteady pressure sensors for the aerodynamic characterization. The results presented in this paper give a global and combined overview of the two WT tests.

3 Open Loop Database

3.1 The Buffet Phenomenon

This phenomenon has been experimentally studied for many years [3], but it is still not completely explained. Data from the state of art indicated that the global mechanisms of the buffet instability for 2D configurations are now well understood. In transonic flow, the sudden recompression on the upper side of wing generates shock waves which interfere with the boundary layer leading to a potential occurrence of a flow separation. With an increase of Mach number or angle of attack, the flow separation may increase in size and spread from the shock foot to the trailing edge. The shock location oscillates dynamically and modulates the flow separation area. The aerodynamic instability is mainly described by a harmonic behaviour, which frequency and amplitude depend on the shape of the airfoil and on the aerodynamic conditions of the flow. For 3D configurations, the shock wave / boundary layer interactions are also involved in the buffet mechanism but in a wide frequency band rather than a particular frequency. In fact, the geometrical parameters of the wing are various (sweep angle, aspect ratio, twist law, span-wise effects…) and lead the 3D buffet. Although the global effects of 2D and 3D buffet are identical on the wings performances (decrease of lift), the physical phenomena involved in the 3D case are more complex and required a specific attention in the view of closed loop control.

In this study, only the aerodynamic part of the measurement is considered, and the response of the structure of the model of the aircraft (buffeting) was acquired but not taken into account in the control approach. Therefore the main information on the buffet status (before, onset or in buffet) was based on the analysis of the unsteady pressure sensors data.

3.2 Fluidic Vortex Generator Actuator

The results presented in this paper deal only with the "fluidic Vortex Generator (VG) actuator" type as far as these actuator characteristics gave the best compromise in terms of efficiency on buffet control between performance and controllability for CL applications. The fluidic VG consist of small nozzles generating a supersonic flow [4]. The main principle is to add momentum and kinetic energy to the turbulent boundary layer which develops upstream of the shock, in order to decrease or suppress the appearance of separated unsteady flows. A more detailed description on the fluidic actuators in terms of geometry, location, blowing characteristics … is given in the associated paper [5]. For the S3Ch model (respectively S2Ma), 25 (50) fluidic VG were located at 25.5% (15%) chord length and positioned between 50 and 84% (46 and 89%) of the span. Main outcomes from all WT tests have demonstrated the VG efficiency for various continuous flow rates [6].

In the view of CL control, a real time command was required to control the VG actuators. Therefore, the functioning was driven by an analogic signal which level fixed the VG opening and the resulting flow rate. As the transonic buffet phenomenon refers always to a strong shock wave / turbulent boundary layer interaction, it seemed very relevant to check the ability to control the shock location with the fluidic VG. During the OL tests, specific test points were especially dedicated to this purpose. Typical results are shown in figure 2 and refer to a low frequency command imposed to fluidic VG. The analysis of the unsteady pressure sensors located on the chord at 75% of the span gives the shock location for each time sample. The envelop and the time evolution of the shock location fluctuations are described in figure 2. For this test point, the shock oscillated mainly at the frequency of the actuators command with a 7% chordwise amplitude between the uncontrolled location and controlled locations.

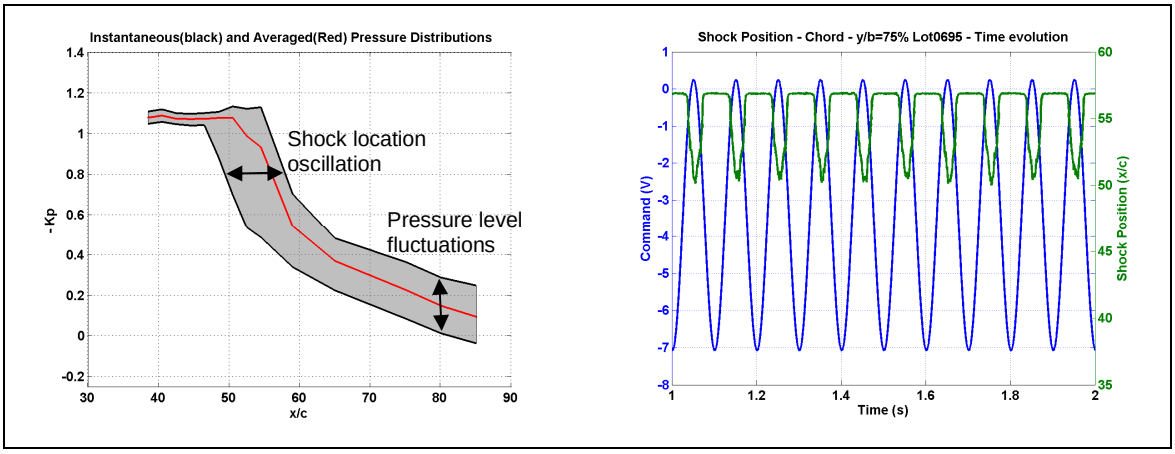


FIG. 2 – Wall pressure coefficient distributions (left) and temporal evolutions of the shock location and command (right) – Flow rate (f = 10Hz)= 4 + 4 sin(ωt) g/s – WT @ S2Ma – M = 0.82 Pi = 0.6 Bar and Angle of attack = 3° (after the buffet onset)

Very fine time-frequency analyses allowed to determine the operational frequency bandwidth of the actuator which covers largely the 3D buffet frequency range. However the lack of significant frequency identified in the 3D buffet phenomenon has led to the impossibility or inexpediency to apply an ideal CL approach (i.e. control of the dynamical behaviour of the flow-model system). Starting from these conclusions, the strategy was reoriented to realize CL control of the buffet phenomena thanks to a quasi-static approach aiming at adapting the averaged mass flow rate to the aerodynamic conditions.

3.3 Typical wall pressure results

The figure 3 presents the steady and unsteady pressure results acquired during S2Ma tests at the most equipped section (y/b = 75%) and for a continuous variation of angle of attack through the visualization of the steady pressure coefficient and RMS value distributions. Up to an angle closed to buffet onset, the mean shock position is moving backwards and the "supersonic plateau" level increases. Then, with an increase of angle of attack, the shock is moving upwards, its oscillation amplitude increases and a separation occurs just upstream of the trailing edge. The distribution of RMS values is perfectly consistent with the pressure coefficients distribution. Considering unsteady pressure transducer located near the trailing edge, the pressure coefficient and the RMS value remain mainly constant for low angle of attack. Then both criteria indicate clearly the occurring of a separated area which intensity increases strongly at very high angle of attack.

These behaviours of shock location and flow separation at the trailing edge are typically characteristic of the buffet phenomenon and have been chosen as potential inputs to be used in the different control strategies.

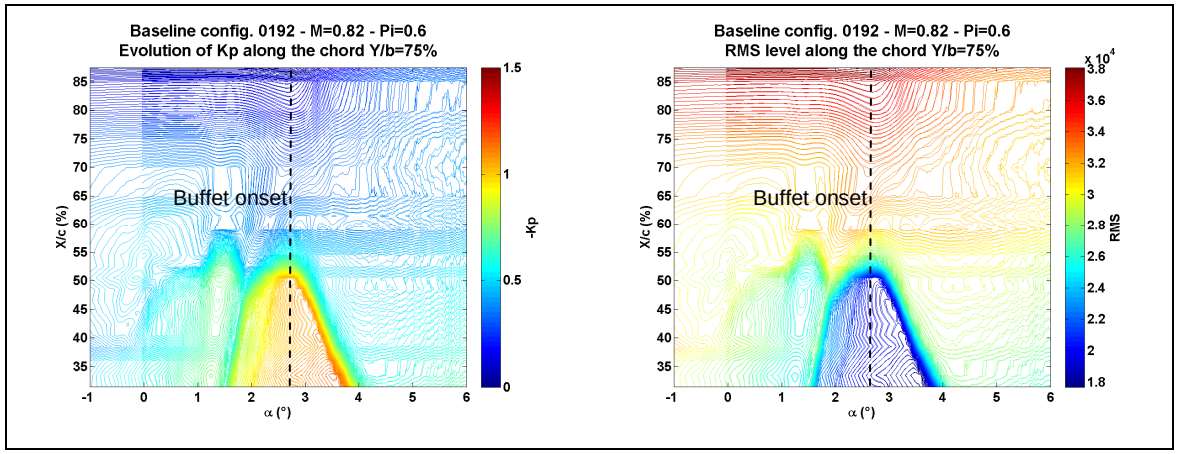


FIG. 3 –Wall pressure coefficient (left) and RMS value (right) distributions for a continuous variation of angle of attack – WT @ S2Ma – M = 0.82, Pi = 0.6 Bar, Re = 2.83 10^6

4 Principles and demonstration of the closed loop control of transonic buffet

4.1 The quasi-static approach

The general principle of a classical feedback loop is represented in figure 4. The output of the system observed by the sensors is compared to the reference input and the error signal is passed into a compensator and applied to the system. The design problem consists in finding the appropriate compensator such that the closed-loop system is stable and behaves in the appropriate manner.

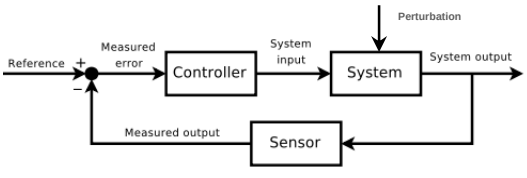


FIG. 4 – Principle scheme of feedback control

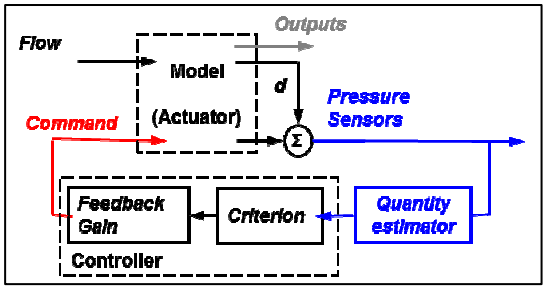


FIG. 5 – Bloc diagram of the Buffet control loop

The application of a feedback control for buffet phenomena alleviation can be associated to a disturbance rejection strategy. In this case, no reference input is applied to the system, the control architecture aims at minimizing its response to a specific perturbation. For the proposed CL approach, the quasi steadiness property results from the fact that the system output is passed into an integrator block in order to estimate a specific criterion (RMS value, averaged value) over a "long time" (few seconds) . According to the typical results presented in the 3.3 paragraph, the main control parameters are described in table 1 and depend on the signal and the objective function used in the CL.

Criterion / Sensor	RMS value	Mean value
Trailing edge Pressure signal	Minimization *(See section 4.3)*	Maximization
Shock location signal	Minimization	Maximization *(See section 4.4)*

TAB 1 - Control configurations tested during WT test campaign

The two lines of table 1 correspond respectively to a specific strategy. The first one is based on the signal of an unsteady pressure sensor located near the trailing edge. The use of these data in the feedback loop leads to an action on the flow separation phenomena in the sensor area. The second strategy is based on a shock location signal and should allow an effect on the shock wave instability phenomena. The two closed loop control architectures were first tested in the S3Ch wind tunnel for a unique aerodynamic condition: M=0.82, Pi=1 bar and angle of attack of 3° (closed to buffet onset). Moreover, for each case, the feedback gain was tuned manually.

4.2 Real-time control system

All of the methods were implemented by the ONERA on a real time dSPACE device which was comprised of several processors and Input/Output boards interlinked for fast internal communication and data exchange. The I/O interface was composed of a maximum of 15 analog inputs and 18 analog outputs. A dedicated computer was used for creating, compiling and implementing Simulink models in the processor boards and a real-time man/machine interface was developed to monitor the signals and change control/command parameters.

The schematic control architecture is shown in figure 5. The control laws were based on unsteady pressure data and used in a SISO configuration (i.e. Single Input Single Output) or MISO (i.e. Multi Input Single Output). All of the fluidic VG were therefore driven synchronously by a unique command signal.

4.3 Quasi-steady control of the RMS value of a trailing edge unsteady pressure sensor

The main results are plotted from figure 6 to figure 8. Starting from the uncontrolled configuration, the pressure fluctuations level (estimated through the RMS value) were very high. The command of the fluidic VG was determined proportionally to this signal through the CL. As the efficiency of the control modified the signal RMS value, the leading actuation command was adjusted in the same way. After a rise time and settling time, the control command converged to a fixed value.

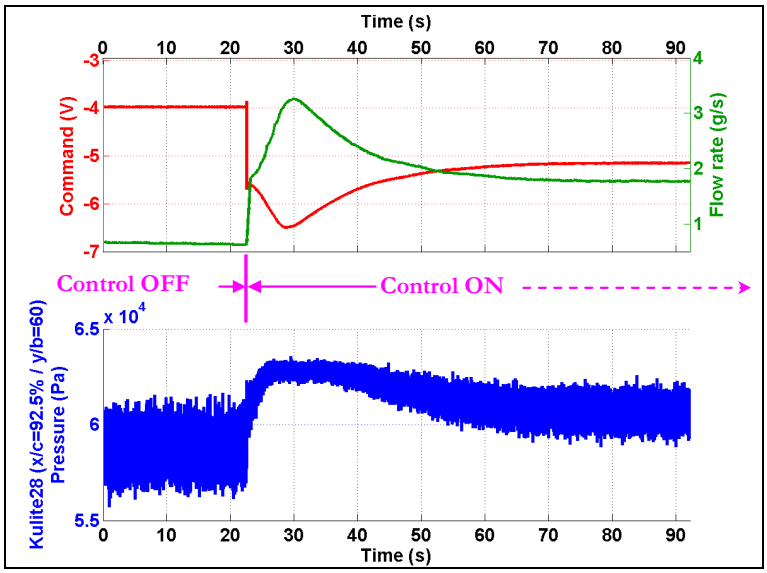


FIG. 6 – Time evolutions of command, flow and pressure signals
WT @ S3Ch – M = 0.82, Pi = 1 Bar and angle of attack of 3°

The temporal evolution of the pressure distribution (-Kp and RMS) along the chord located at 60% of span are detailed in figure 7. The CL was activated after 20s. After a transient state, the reduction of the RMS value of the unsteady pressure fluctuations were clearly visible at the trailing edge indicating that the flow separation has been suppressed. At the same time, pressure coefficient and RMS distributions indicated that the shock location moved more downstream.

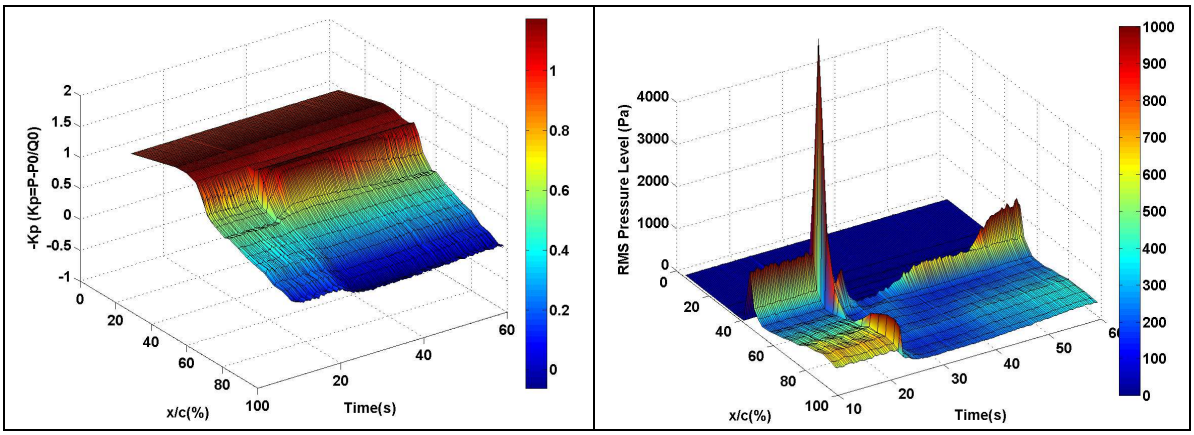


FIG. 7 - Pressure coefficient distribution (left) and RMS value distribution (right) @ y/b = 60%. - WT @ S3Ch – M = 0.82, Pi = 1 Bar and angle of attack of 3°

The transient state, observed after the control has been switched on, coincided with the conclusions of cases with low flow rate [5]. Previous tests performed with continuous flow rate indicated that, for low momentum coefficient values, the action of fluidic VG actuators on buffet could be the opposite of the desired effect: increase of RMS pressure levels, expansion of the flow detachment …

4.4 Quasi-steady control of the averaged value of a "Shock location sensor"

In this second approach, 10 unsteady pressure sensors were monitored continuously in order to estimate the shock location. The function of the "quantity estimator block" (figure 5) was to estimate the shock location in real time. The resulting signal was used as input of the controller. The main results are plotted on the following figure. As for the previous case, the evolution of the fluidic VG command was clearly proportional to the chosen signal. With a small gain value, the actual command might result to an inefficient fluidic VG command or might converge to the desirable output slowly. However, with a large control gain, the actual output might reach the (maximum) saturation value or may never converge (i.e. the controller-plant system oscillates). At the end of the test point, the control efficiency showed that the shock location moved of 10% in chord downstream. The RMS fluctuations of shock location (but also of the unsteady pressure at the trailing edge) were clearly decreased.

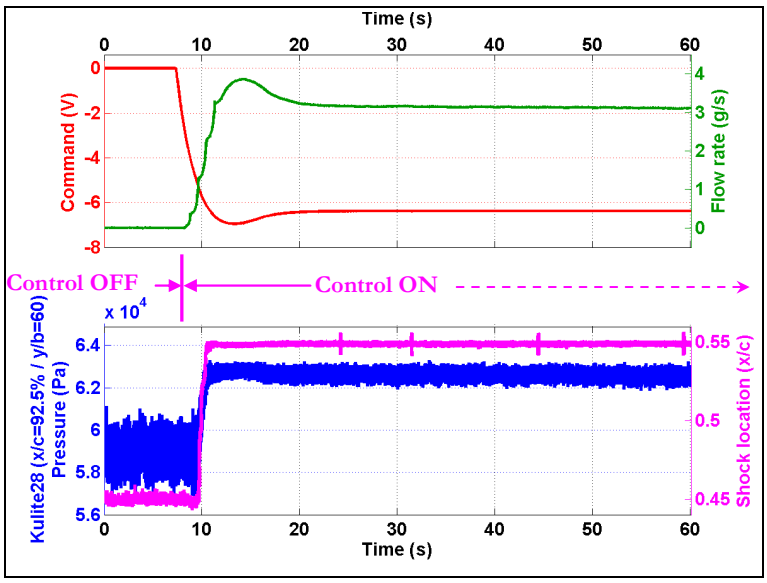


FIG 8 - Time evolutions of command, flow, pressure and shock location signals
WT @ S3Ch – M = 0.82, Pi = 1 Bar and angle of attack of 3°

5 Conclusions

The buffet phenomenon remains today a major phenomenon for aircraft since it limits their flight domain. In this paper, an experimental roadmap based on several wind tunnel tests has been conducted in order to get a better understanding of this phenomenon for 3D turbulent wing in transonic flow. Databases analyses were carried out to determine the steady and unsteady mechanisms involved in this flow instabilities. As the transonic buffet on the upper side of a wing is characterized by a shock motion and a massive flow separation, these latter have been used for the definition of active buffet alleviation strategy. Therefore fluidic vortex generators were used to limit the aerodynamic instability by decreasing the extent of separated area or to stabilize the shock location. The objective of this work was to demonstrate the feasibility of controlling the buffet using a closed loop based on a quasi-steady approach. Different approaches have been developed addressing the adjustment of the actuator flow rate thanks to a feedback command based on the real time estimation of the shock location or the flow separation level. Finally, the efficiency of delaying the buffet onset or limiting its effects was successfully demonstrated in both research and industrial wind tunnel environment.

Acknowledgements

The AVERT wind tunnel tests were conducted within the FP7 AVERT European project (Contract No.: AST5-CT-2006-030914), funded by EC and project partners (Airbus, Dassault Aviation and Alenia Aeronautica). The closed-loop buffet control tests in the S3Ch wind tunnel have received funding from the European Union's Seventh Framework Program (FP7/2007-2013) for the Clean Sky Joint Technology Initiative, under Grant Agreement CSJU-GAM-SFWA-2008-001.

This paper presents results from studies which have been supported by the ONERA Research Federator Project "BUFET'N Co" (collaboration between different several ONERA scientific departments, DAAP, DMAE, DADS, DAFE, DMS, DCSD). The authors are very grateful to the ONERA S3Ch and S2MA wind tunnel teams, who contributed to the success of these tests.

References

[1] E. Coustols, V. Brunet, R. Bur, D. Caruana & D. Sipp, 2009, "BUFET'N Co: A Joint ONERA Research Project devoted to Buffet Control on a Transonic 3D Wing using a Closed-Loop Approach", CEAS/KATNET II Conference, Bremen, Germany.

[2] P. Molton, J. Dandois, A. Lepage, V. Brunet & R. Bur, 2013, "Control of Buffet Phenomenon on a Transonic Swept Wing", AIAA Journal, Vol. 51, No. 4, pp.761-772.

[3] D. Caruana, A. Mignosi, M. Corrège, A. Le Pourhiet, A.M. Rodde , 2005, "Buffet and buffeting control in transonic flow", Aerospace Science and Technology, vol 9, pp 605–616

[4] F. Ternoy, J. Dandois, F. David and M. Pruvost, 2013, "Overview of Onera Actuators for active flow control", Aerospace Lab, vol. 6.

[5] J. Dandois, P. Molton, A. Lepage, A. Geeraert, V. Brunet, J.-B. Dor and E. Coustols, 2013, "Buffet Characterisation and Control for Turbulent Wings", Aerospace Lab, vol. 6.

[6] J. Dandois, J.-B. Dor, P. Molton, A. Lepage, F. Ternoy and E. Coustols, 2013, "Transonic Buffet Control on 3D turbulent wing using Fluidic Devices. Part 1 : Open loop study", The 3th GDR Symposium, Lille, nov. 2013.

ONERA
THE FRENCH AEROSPACE LAB

BP 72 - 29 avenue de la Division Leclerc - 92322 CHATILLON CEDEX - Tél. : +33 1 46 73 40 40 - Fax : +33 1 46 73 41 41

www.onera.fr