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Testing in Aerodynamics Research at ONERA: the Example of the Transonic Buffet

The paper reviews research conducted at ONERA over the last thirty years on the transonic buffet. We first present the transonic buffet phenomenon and we explain its importance for aeronautical applications. Then, a distinction is made between the 2D buffet produced by an airfoil and the 3D buffet that characterizes swept wings of finite span. The 2D buffet amounts to a pure oscillation of the shock phase-locked with the detachment and reattachment of the boundary layer downstream, whereas the 3D buffet takes the form of a pocket of broadband perturbations located in a limited portion of the wing. We recall that these mechanisms were first studied in the 1980s through a series of tests conducted in the transonic wind tunnel ONERA T2 at Toulouse and in the large transonic wind tunnel ONERA S2Ma at Modane. Since this pioneering work, progress in the measurement techniques has led to the constitution of a comprehensive database of the 2D buffet that we describe. This database, obtained in the wind tunnel ONERA S3Ch at Meudon, has been extensively used to validate various CFD tools, with the latter being used in turn to investigate the buffet physics. We illustrate this collaboration between simulation and physics by recalling that a linear stability analysis of accurate Reynolds-Averaged-Navier-Stokes (RANS) solutions made it possible to prove that the buffet on a 2D airfoil stems from a global instability mechanism. We also review more recent tests done in the case of a laminar airfoil, which reveal very distinct behaviors of the buffet flow. This illustrates how sensitive the buffet is to the nature of the boundary layer. The last section of the paper gives a short overview of advanced simulations for these different test cases. In the conclusion, we list research perspectives, which include some more general topics such as data assimilation.

Introduction

In fundamental science, testing is often aimed at confirming, improving, or disproving the predictions of a given theory¹. In aerodynamics, there is no new theory to be tested a priori, the basic equations (Navier-Stokes) having been established for a long time and still providing satisfactory results. Nevertheless, this science faces a fundamental obstacle, which is turbulence. Turbulence is an unavoidable consequence of the non-linear structure of the fluid mechanics equations, which produces a cascade of flow scales down to the limits of the continuum, constantly challenging the experiment, metrology and computation, see [2]. Since the 1980s, the advent of Computational

Fluid Dynamics (CFD) has deeply transformed aerodynamic engineering, which now relies heavily on computations. There is a consensus today that a critical area in this field is the ability to adequately predict viscous turbulent flows with the possible presence of a boundary layer transition and flow separation [3]. As CFD progresses, experiments become scarce and more comprehensive. However, they remain unavoidable for exploring the borders of the parameter space that they previously secured. Thus, testing will long remain essential to CFD, the success of which still depends on the best compromise between efficient software, physical knowledge and reliable measurement availability. The case of the transonic buffet described in this paper provides a good illustration of the collaboration between these various research domains, which has shaped thirty years of aerodynamics in an institution like ONERA.

¹ At the time of the 70th anniversary of ONERA, an emblematic example is the satellite MICROSCOPE launched by Soyuz on April 29th 2016 from the French Guiana Space Center, and which contains some world-class ONERA technologies. This satellite is aimed at improving the confirmation of the equivalence between inertial mass and gravitational mass, an important verification of Einstein's relativistic theory of gravitation, see [1].

Transonic buffet

When seeking a subject that could illustrate the role of testing in aerospace research in this 70th anniversary volume launched by ONERA, the transonic buffet came as a natural choice. This is because this topic illustrates well how aerodynamics has progressed over the last twenty years, thanks to advances in flow diagnostic techniques and fruitful cooperation between theory and numerical simulation. It is also relevant to question the future of wind tunnels. Buffet refers to an aerodynamic excitation leading to unsteady forces. Transonic buffet refers to cases where a shock wave is involved; it is characterized by self-sustained displacements of the shock wave location and periodic boundary-layer separation downstream from the shock. This occurs, for instance, on the upper surface of a highly loaded airfoil, i.e., when the flow Mach number and the airfoil angle of attack are both sufficiently large. As far as aeronautical applications are concerned, transonic buffet is one of the most important compressibility-based problems that limit the load capacity and efficiency of cruising aircraft. It can develop in all flow regions where shock waves are present, i.e., on airframe lifting surfaces and on rotating blades. Its control could enlarge flight envelopes and lead to significant energy savings. Conducting relevant research in that domain calls for controlling complex experiments in high-speed wind tunnels, but it also requires mastering advanced metrologies, advanced fluid mechanics software and cutting-edge theoretical approaches in compressible flow physics. Significant efforts have been made by the aeronautical community on the topic, especially at ONERA, which devoted both fundamental and applied type research in every relevant domain to this problem, such as flow stability, unsteady CFD and experiments in transonic/supersonic facilities. This article is aimed at presenting a synthetic view of the research conducted at ONERA in this field since the mid-1980s. The first set of described test cases concerned a 2D supercritical airfoil. We start with cases where the 2D transonic buffet develops under purely turbulent conditions, which is naturally the case on real aircraft but which necessitate a transition tripping of the airfoil boundary layers tested in wind tunnels. The buffet flow in that case takes the form of a single and global flow oscillation, of which the onset and structure turned out to be predictable by linear hydrodynamic stability, as detailed below. We then consider the case where the boundary layer is laminar, a subject of current investigations and an important issue for the topic of laminar wing aircraft. Recent results, which confirm

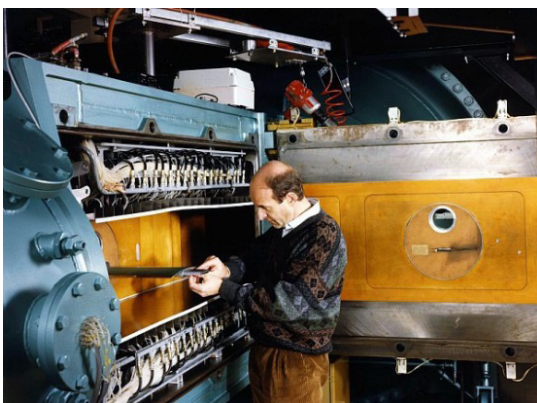
pioneering work conducted in the 1980s, reveal that the 2D laminar buffet is less severe than the turbulent one. Finally, turbulent buffet on 3D airfoils have been also documented several times at ONERA. In this case, the buffet develops in a limited portion of the wing. The physics of this buffet is complex and remains largely a matter of questioning.

Pioneering work

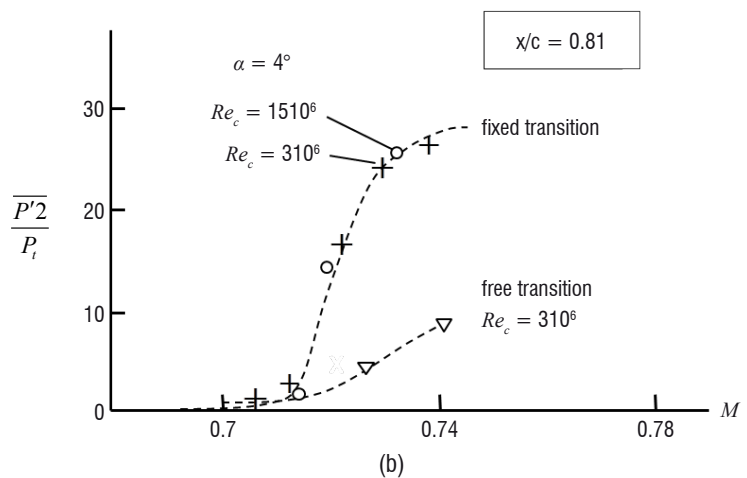
Pioneering experimental studies were conducted since the mid-1980s by the Aeroelasticity and Structural Dynamics Department and by the Aerodynamics and Energetics Models Department of ONERA. The first team studied a transonic airfoil named RA16SC1 in the ONERA S3Ma wind tunnel [4] from 1984 to 1987. In the same period, the second team launched a series of experiments at ONERA-Toulouse in the Cryogenic Induction Tunnel ONERA T2 on two models, the RA16SC1 and the OAT15A airfoils, see [5]. This team also coordinated a campaign on the 3D buffet on a swept wing in 2000 in the S2Ma wind tunnel at ONERA-Modane, see a review in [7]. Steady and unsteady pressure transducers on the model surfaces were used to characterize these different flows. Part of these experiments did not focus particularly on the flow physics, but rather on the control of the buffet by open-loop or closed-loop strategies. Also, the instrumentation used at that time was too modest to appraise the physics with enough detail, or for the building up of a sufficiently comprehensive database for fine CFD-experiment confrontations. Nonetheless, nearly all of the key elements regarding the buffeting phenomenon were already available at the end of these early works, and almost all of the bases of the subsequent work done at ONERA on the topic were developed at that time.

Airfoil buffet

A first example of those pioneering contributions is shown in Figure 1 which was extracted from an experiment on the 2D transonic buffet conducted in the ONERA T2 wind tunnel in the mid 1980's [5]. "T2" was a transonic wind tunnel with a test section that was 0.39 m wide and 0.37 m tall, equipped with 2D adaptive walls, see Figure 2(a). The tunnel was cryogenic and pressurized, operating within a total temperature range from 300 K to 100 K and within a total pressure range from 1.5 bars to 4 bars². The model was a supercritical OAT15A of 0.15 m chord length, designed for cryogenic flows and equipped



(a)



(b)

Figure 1 – (a) Airfoil buffet experiment on the OAT15A airfoil in the cryogenic induction tunnel T2 at ONERA-DMAE, (b) pressure fluctuation variance on the downstream upper side ($x/c = 0.81$) of the airfoil for an angle of attack $\alpha = 4^\circ$: effects of the Mach number, the Reynolds number and the boundary layer state from [5].

² The T2 tunnel closed in the 2000s due to lack of funding and activity.

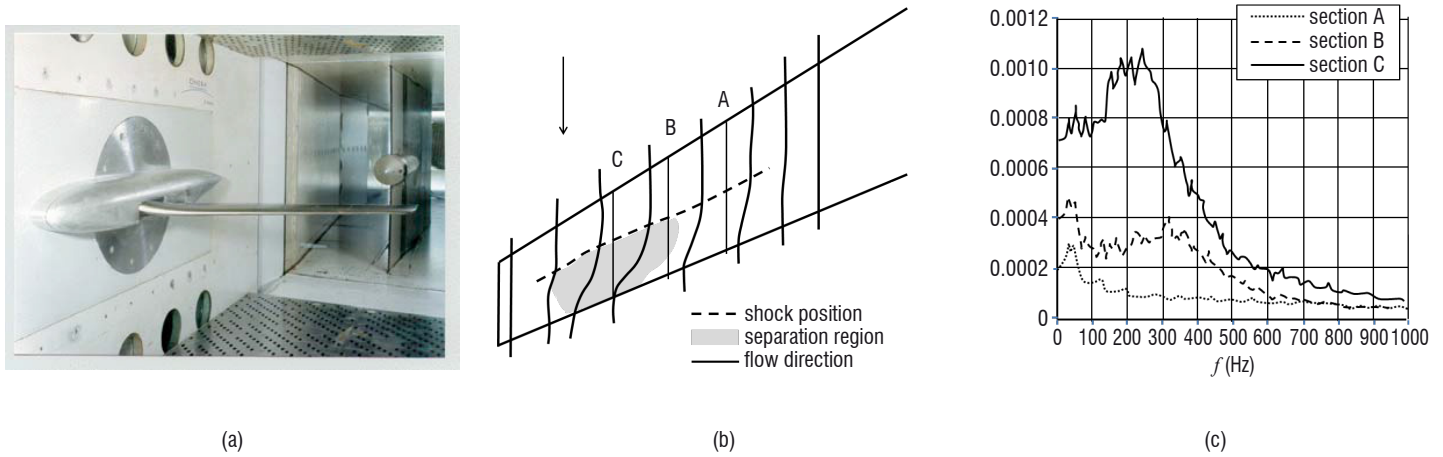


Figure 2 – (a) 3D buffet experiments on a 3D model in the S2MA tunnel. Case $M_0 = 0.82$, $\alpha = 3.7^\circ$, $Re_{cm} = 8.3 \cdot 10^6$: (b) mean surface flow organization with separation area, (c) spectrum of the shock position deduced from unsteady pressure measurements in three sections of the wing, [7].

with a single transducer to measure the unsteady wall pressure on the downstream part of the upper side, at 81% of the chord. Figure 1(b) shows the variations with the Mach number of the pressure-fluctuation variance for a fixed angle of attack equal to 4° . Two different states of the upper boundary layer flow were considered: a natural transition case and a forced transition one obtained by adding a tripping device on the upstream suction side. In the first case, the boundary layer is assumed to be laminar (at least down to the shock location); in the second case, the boundary layer is turbulent. Even though no specific diagnostic was applied to prove these assertions, they look reasonable. The figure shows that when the boundary layer is turbulent, the transonic buffet is characterized by a sudden increase of the pressure fluctuations, here around $M = 0.72$ for this particular airfoil and angle of attack ($\alpha = 4^\circ$). Analyses of the corresponding signal have shown that the pressure fluctuations are characterized by a single frequency close to 100 Hz, see [5]. However, Figure 1(b) also shows two other important results. The first concerns the negligible influence of a variation by a factor five of the Reynolds number on the turbulent boundary layer cases. This suggests that the underlying dynamics is essentially fixed by the mean turbulent flow. It took two decades to confirm that the onset of the transonic buffet actually results from a single global instability mode of the mean turbulent flow, see below. The second interesting result found in Figure 1 is the absence of any clear buffet when a natural transition is considered. As shown also later on, this radical change in the flow properties in the case of a laminar boundary layer is the subject of active research today. Concerning CFD, the methods used at that time to compute such flows were unsteady viscous-inviscid interaction methods, see [6].

3D buffet

3D buffet refers to flows over transonic swept wings. As illustrated below, the 3D buffet strongly differs from the 2D airfoil buffet. As mentioned in the introduction, early studies were devoted to this problem at ONERA in the early 2000s (see a review in [7]). They were based on the use of a 3D half wing/fuselage body similar to a civil transport aircraft. At that time, the model was designed with the help of viscous-inviscid coupling computations. Its principal dimensions are 1.25 m spanwise and between 0.25 and 0.45 m chordwise. The model was equipped with 6 accelerometers, 60 steady and 103 unsteady pressure transducers, and the global efforts were measured by means of a 6-component wall balance. It was tested in 2000 in the

ONERA S2MA facility. "S2Ma" is a transonic or supersonic, pressurized closed circuit wind tunnel with a test section that is 1.77 m tall, 1.75 m wide and 3.75 m long, equipped with fixed top and bottom perforated walls, see Figure 2(a). The tests were performed with a mean aerodynamic chord Reynolds number of $Re_{cm} = 8.3 \cdot 10^6$ and free stream Mach numbers between 0.80 and 0.84. Figure 2(b) and (c) illustrate the main properties found for the 3D buffet flow on the upper side of the model wing, here for $M_0 = 0.82$ and $\alpha = 3.7^\circ$. This flow differs from that of a 2D airfoil in two main points: (i) the buffet develops in a restricted portion of the wing, here around 75% of the span, where a finite area separated region appears; this leads to a corrugation of the mean shock in that region, see Figure 10(a); (ii) the dynamics of this buffet is no longer modal but rather broadband. In the case of Figure 2(c), energetic frequencies arise at around 200 Hz. Once normalized by the mean chord length, this corresponds to a Strouhal number $St = fc_m/U_\infty = 0.24$, which is nearly three times larger than that obtained on a 2D airfoil. More detailed investigations have shown that at that Mach number the shock location became displaced over less than 5% of the chord in Section C identified in Figure 2(b) when the buffet was established. Consequently, in comparison with the 2D buffet phenomenon, the shock location is less displaced for 3D buffeting.

A second campaign was conducted ten years later, in 2010, using the same model and the same facility. As reported in [8], thanks to a deeper pressure signal analysis some progress has been made on the physics of the 3D buffet, which consists in the combination of the streamwise oscillation of the shock location, like the 2D buffet with the phenomenon of "stall cells" (named "buffet cells" by Iovnovich *et al.* [9]). These "stall cells" are clearly evidenced by the presence of a spanwise wavelength at the shock location. On a swept wing, these stall cells are convected towards the wing tip. The 3D buffet frequency increases with the sweep angle from $St = 0.07$ in 2D to $St = 0.26$ for a 30° sweep.

The physics of the turbulent airfoil buffet

We now focus on the period since the early 2000s, when detailed experiments, including flow characterization by means of advanced optical methods, were made possible on a 2D airfoil and where CFD had made significant progress.

Mean flow and dynamics

A fully documented experiment on the topic was conducted at ONERA in the mid-2000s in the continuous closed-circuit transonic wind tunnel S3Ch of the Fundamental and Experimental Aerodynamics Department at Meudon, [10]. The test section of the S3Ch wind tunnel is 0.76 m tall and 0.8 m wide equipped with 2D adaptive top and bottom walls like the T2 wind tunnel in Toulouse, see Figure 3(a). As in the previous work conducted in the T2 wind tunnel, a tripped supercritical airfoil OAT15A was again considered for studying turbulent regimes. Here, the model had a chord length of 0.23 m and a 0.8 m width (actually the width of the wind tunnel). This gives $AR \approx 3.4$ for the aspect ratio. This was sufficient to avoid any 3D effects due to interactions of the airfoil flow with the boundary layers of the wind tunnel side walls, which were a source of concern during the T2 experiments for which $AR \approx 2.6$. In the S3Ch experiment, surface flow visualizations proved that the flow was perfectly 2D over a large portion of the model [10]. The average chord-based Reynolds number was $Re_c = 310^6$ with laminar-turbulent transition fixed on the airfoil by means of a Carborundum strip located at $x/c = 7\%$ from the leading edge. The Mach number M_0 was varied between 0.70 and 0.75 and the flow incidence α , controlled by means of deformable walls, could be varied between 2.5° to 3.9° . The measurements comprised surface flow visualizations by oil and sublimating products, steady and unsteady pressure (68 pressure taps and 36 unsteady Kulite™ pressure transducers in the central section of the wing), flow-field characterizations by Schlieren films, and velocity fields by means of a two-component laser-Doppler velocimeter. As revealed by the pressure spectra of Figure 3(b), measured at $x/c = 0.8$ for $M = 0.73$, the onset of the buffet occurs for an angle of attack $AOA = 3.2^\circ$ and it is characterized by flow oscillations that induce very energetic and harmonic pressure oscillations. These oscillations are felt over the entire range of transducers on the upper surface, from the shock foot down

to the trailing edge, revealing the global character of the phenomenon. The frequency of the phenomenon is $f \approx 70$ Hz giving a chord-based Strouhal number $St = fc/U_\infty = 0.068$. Similar low frequencies were obtained previously in other airfoil buffet flows: a value of $St \approx 0.081$ was found by Lee [11] for a supercritical airfoil, and McDevitt and Okuno [12] found $St \approx 0.045$ for a NACA0012 airfoil. This variability in the transonic buffet Strouhal number indicates that the chord is not the only length scale involved; others, such as the mean shock position, the boundary layer thicknesses or the shock interaction region sizes can be also considered, but no consensus has yet emerged today. The value $\alpha = 3.5^\circ$ was selected for a full characterization of the unsteady velocity field with Laser-Doppler velocimetry. A phase-averaged technique has been applied to this data. The technique can separate the "coherent" motion, related to a periodic excitation (possibly a global mode, see below), from the random fluctuating part.

A component of the velocity, $u(\underline{x}, t)$ for instance, is decomposed into three contributions, $u(\underline{x}, t) = \bar{u}(\underline{x}) + \tilde{u}(\underline{x}, t) + u''(\underline{x}, t)$, where $\bar{u}(\underline{x})$ is the temporal-average, $\tilde{u}(\underline{x}, t)$ is the cyclic component and $u''(\underline{x}, t)$ is a random fluctuating component. The phase-averaged velocity is defined as $\langle u(\underline{x}, t) \rangle = \bar{u}(\underline{x}) + \tilde{u}(\underline{x}, t)$, the remaining fluctuating component u'' being a residue characterizing events that are not in phase with the reference signal. In the present case, the reference signal has been chosen as the pressure signal measured by the Kulite™ transducer located close to the mean shock location. Phase averages of the longitudinal and vertical components of the velocity (u, v) were then determined following a procedure described in [10]. The structure of the phase-averaged longitudinal velocity flow $\langle u(\underline{x}, t) \rangle = \bar{u}(\underline{x}) + \tilde{u}(\underline{x}, t)$ is illustrated in Figure 3(c) and (d), which shows two phases (among the 20 covering the buffeting flow period) corresponding to the extreme locations of the oscillating shock, respectively. The oscillation of the shock phase-locked with the oscillating of the shear layer downstream is shown.

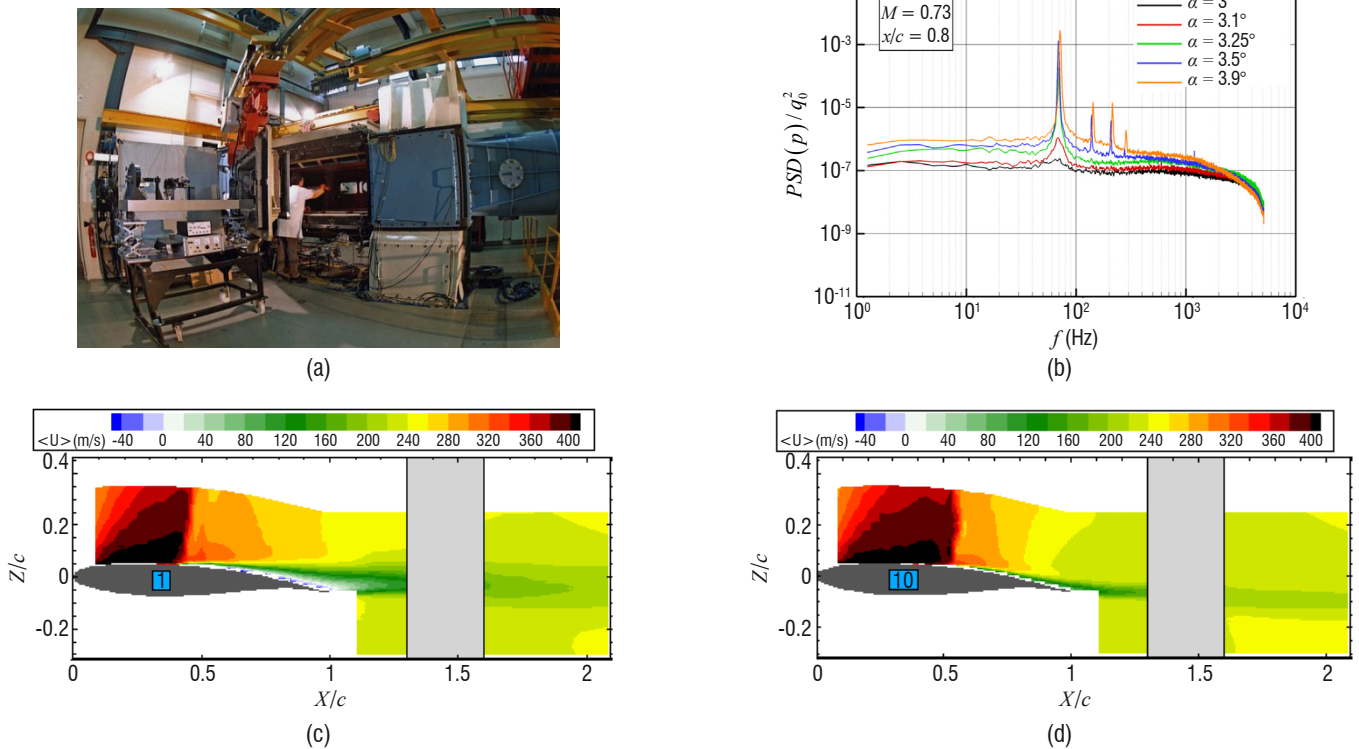


Figure 3 – (a) Airfoil buffet experiment on the OAT15A airfoil in the S3Ch wind tunnel at ONERA-DAFE, (b) Pressure power spectra at $x/c = 0.8$ for different angles of attack, (c) LDV phase-averaged longitudinal velocity $\langle u(\underline{x}, t) \rangle = \bar{u}(\underline{x}) + \tilde{u}(\underline{x}, t)$ (see text) with shock upstream (phase 1/20), (d) with shock downstream (phase 10/20) (from [10]).

A global instability mechanism

As shown by Crouch *et al.* [13], both the onset conditions and the spatial and temporal structure of the buffet flow on 2D airfoils appear to be well described by a global-stability approach. This milestone, at the crossroads of theoretical fluid mechanics and computational sciences, was achieved thanks to the rising of CFD in the 2000s. A short synthesis of the accomplishments of ONERA in this field applied to transonic buffet will be made later. The theoretical framework of the analysis of Reference [13] were the unsteady Reynolds Averaged Navier-Stokes equations (URANS). The main ingredients of this theory are the following. Consider the Navier-Stokes equations governing the flow dynamics in the form $\partial_t q = R(q)$, where the state vector $q = (\rho, \underline{u}, T, \nu)^T$ represents the aerodynamics (i.e., the density, the velocity field, the internal energy and the viscosity fields). Let q_0 denote a base flow, meaning an equilibrium point such that $R(q_0) = 0$, and let q' denote superimposed small perturbations; the latter are governed by $\partial_t q' = A(q')$, where A is the Jacobian operator linked to the R by the relation $A = \partial R / \partial q_{q=q_0}$. The perturbation is then sought in the form of normal modes $q'(x, t) = \hat{q}(x) \exp\{(\sigma + i\omega)t\}$, where σ and ω represent the temporal growth rate and the frequency of the global mode \hat{q} , respectively. When $\sigma > 0$ (resp. < 0), the base flow is unstable (resp. stable). Substituting q' leads to an eigenvalue problem for $\lambda = \sigma + i\omega$, which is written as $A\hat{q} = \lambda\hat{q}$. When the Reynolds number is large, the flow is fully unsteady and it is usually turbulent. A choice must be made for the base flow q_0 . After splitting the total flow q into a steady-state flow \bar{q} and an

unsteady perturbation q' , an approximation of q_0 by \bar{q} can be proposed. The steady-state flow \bar{q} is a solution of the Reynolds Averaged Navier-Stokes equations (RANS) $RANS(\bar{q}) = 0$. This calls for a turbulent model to close additional turbulent flux terms, i.e., the averaged Reynolds stresses. Using an eddy viscosity formulation for this model, the global stability analysis described above can finally be applied to the state vector $q = \bar{q} + q'$ with $\bar{q} = (\bar{\rho}, \bar{u}, \bar{T}, \bar{\nu})^T$ and $q' = (\rho', \underline{u}', T', \nu')^T$, where $\bar{\nu} = \bar{\nu} + \bar{\nu}'$ is the eddy viscosity. The ability of an eddy-viscosity formulation of the turbulence model to reproduce such an unsteady separated flow as close as possible to the test case was proven by Thierry and Coustols [14]. Crouch *et al.* [13] used a combination of the global mode analysis of the RANS equations with the Spalart-Allmaras turbulence formulation of the eddy viscosity (RANS-SA) and successfully tested the method with the NACA0012 airfoil database of McDevitt and Okuno [12]. The periodic behavior of the flow illustrated in Figure 3 suggests that a transonic buffet flow should be dominated by a single normal mode. This was confirmed by the theory, further applications to the ONERA-OAT15A airfoil having led to the same conclusion, see Sartor *et al.* [14]. Some of the latter authors' findings are reproduced in Figure 4. Figure 4(a) shows the base flow horizontal velocity field, a solution of the RANS-SA equations for $M_0 = 0.73$ and $\alpha = 3.5^\circ$, and Figure 6(b) shows the eigenvalue spectra obtained for various angles of attack. The theory predicts a destabilization of a single mode of frequency $f = 77$ Hz for an angle slightly larger than $\alpha = 3.25^\circ$, against $f \approx 70$ Hz and $\alpha = 3.1^\circ$ in the experiment. Interestingly, when α is increased further (up to very large angles, such as 7°),

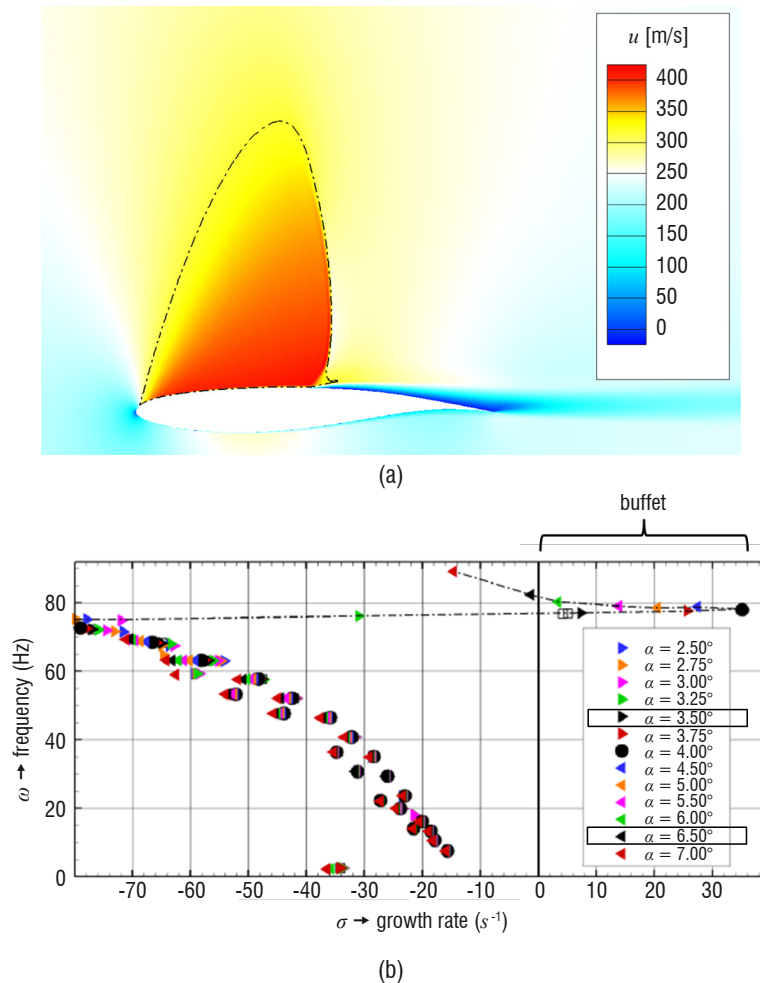


Figure 4 – Buffet at Mach number $M = 0.73$ (tripped supercritical airfoil OAT15A) – Global stability analysis: (a) RANS-SA horizontal velocity field for $\alpha = 3.5^\circ$, (b) eigenvalue spectra for various angles of attack, [15].

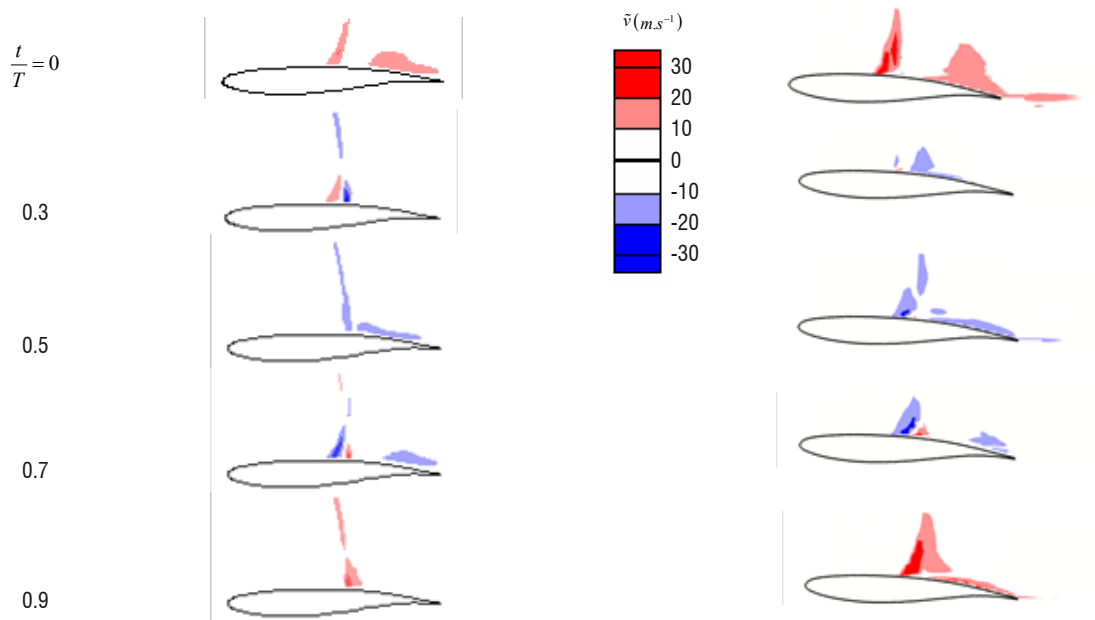


Figure 5 - Buffet at $(M_0, \alpha) = (0.73, 3.5^\circ)$ (tripped supercritical airfoil OAT15A) - Unsteady vertical velocity fluctuations. Left: computation (global mode), right: experiment (cyclic component of the vertical velocity $\tilde{v}(\underline{x}, t)$), [16].

the fully-detached flow obtained is no longer buffeting; this suggests that a periodic reattachment of the downstream flow is a key feature to obtain a buffet flow.

In the framework of the global stability theory recalled above, when the dynamics are dominated by a single global mode the latter should correspond to the cyclic component \tilde{q} of a triple decomposition. This was emphasized by Crouch *et al.* [15] by comparing the structure of the global mode q' of the RANS-SA flow with the cyclic component \tilde{q} of the OAT15A flow described in Figure 3(c) and (d). Figure 5 shows the vertical-velocity fluctuations using contours chosen to allow a direct comparison of the two flow-fields.

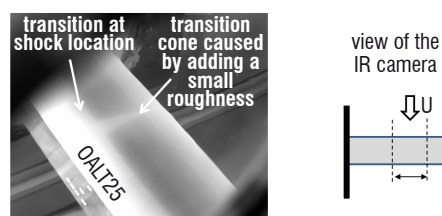
Laminar airfoil buffet

Laminar versus turbulent mean flows

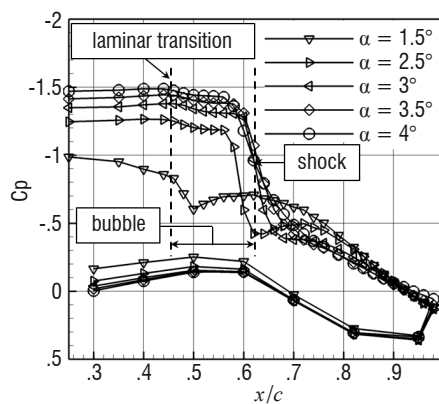
The experiments described above were reproduced recently in the same facility (ONERA S3Ch), using an OALT25 airfoil designed to promote a laminar boundary layer ahead of the shock wave in the absence of tripping, see [17]. The chord length and the span of the OALT25 airfoil are identical to those of the OAT15A, their relative thicknesses being very close (12.18% compared to 12.3%). The Mach number M_0 was varied between 0.70 and 0.75 and the flow incidence α between 1.5° and 4° . The same experimental protocols and techniques were used, LDV being replaced by PIV, with the addition of thermographic diagnostics obtained by using an Infra-Red (IR) camera to check that the upstream laminar flow was 2D and free from any spurious transition up to the shock. Given that the adaptive walls prevent a direct view from above, the IR camera is installed outside the test section and provides a limited view through the side windows of approximately a quarter of the span. Figure 6(b) shows an IR photo, where the change from dark to light grey indicates a transition. A transition cone caused by an added small roughness is also visible. The photo shows that the transition is 2D (at least in the observed region) and that it is caused by the shock. Figure 6(c) then shows the pressure coefficient C_p -distributions provided by pressure taps located in the central section



(a)



(b)



(c)

Figure 6 – (a) Airfoil buffet experiment on the supercritical OALT25 airfoil without stripping (natural transition) in the S3Ch wind tunnel at ONERA-DAFE, (b) IR image for $M_0 = 0.73$ (see text), (c) Mean pressure coefficient, [17].

of the wing at $25\% \leq x/c \leq 100\%$ for $M_0 = 0.73$ and for different angles of attack. It shows that a shock forms for and settles at a position of approximately 60% of the chord length when α is increased. It can be noted that the C_p curves of Figure 6(b) are marked by a slight compression ahead of the shock, at about 40% of the chord. This feature is absent in the case where the boundary layer is turbulent, as in the OAT15A data commented earlier, as well as in the present experiments when transition was forced. The most likely reason for this is the existence of a laminar separation bubble under the shock foot. This bubble forms as soon as the compression occurs, as a result of the little resilience of a laminar boundary layer to an adverse pressure gradient. The presence of a laminar bubble was confirmed with the help of numerical RANS results, where the laminar-turbulent transition in the boundary layer was accounted for by means of a dedicated criterion, [17]. These experiments reveal that the dynamics of the laminar airfoil buffet flow differ radically from those of a turbulent airfoil. First, the spreading of the C_p - recompression region due to shock unsteadiness in Figure 6(b) shows that, in the laminar regime, the shock oscillation

amplitude does not exceed 5% of the chord length against 20% in the case of the turbulent OAT15A airfoil, see Figure 3(c)-(d).

Importantly, this suggests that the laminar buffet is less severe than the turbulent buffet. Tripping the boundary layer on this airfoil confirmed these conclusions. This is shown in Figure 7, where the global footprint of the shock obtained in the laminar case is compared to the turbulent case obtained with forced transition at 7% of the chord for $(M_0, \alpha) = (0.735, 4^\circ)$. These pictures were obtained by taking the minimum pixel intensity over a set of images that compose the Schlieren movies. The extent of the shock movements in the turbulent case represents about 24% of the chord, while in the laminar case the amplitude of the shock movement does not exceed 5% of the chord (the vertical extent of the dark turbulent shear layer region behind the shock is the mark of the periodic separated flow). The evolution of the flow dynamics towards buffeting was then analyzed by inspecting pressure spectra at increasing angles of attack for a given Mach number, here $M_0 = 0.735$. Figure 8(a) and (b) show the pressure



Figure 7 – Buffet at $M_0 = 0.73$ (supercritical airfoil OALT25) – Minimum intensity projection of the Schlieren movies for $(M_0, \alpha) = (0.735, 4^\circ)$: (a) forced transition cases (7%) and (b) natural transition cases, [17].

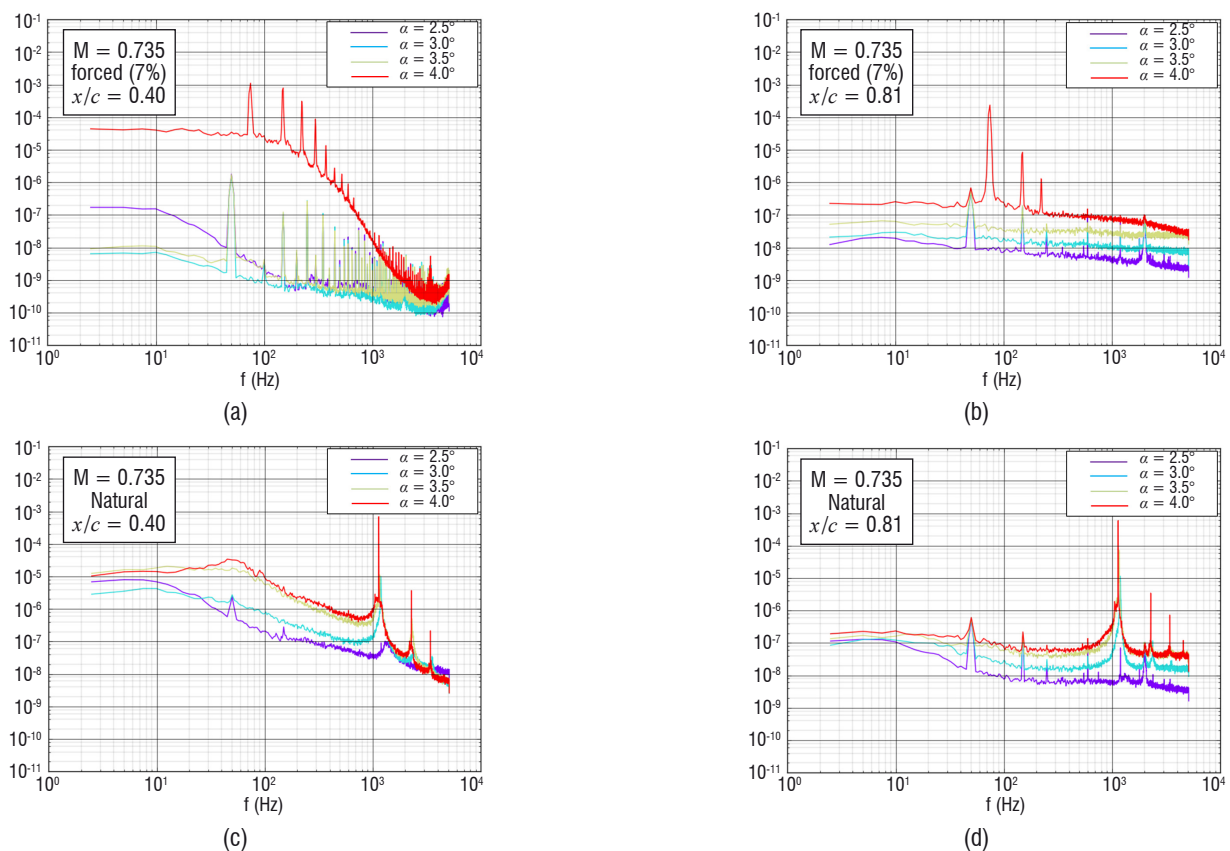


Figure 8 – Buffet at $M_0 = 0.735$ (supercritical airfoil OALT25) – Spectra of the pressure fluctuations for a selection of angles of attack α : (a) $x/c = 0.40$, turbulent case (tripping 7%), (b) $x/c = 0.85$, turbulent case (tripping 7%), (c) $x/c = 0.40$, laminar case, (d) $x/c = 0.85$, laminar case, [17].

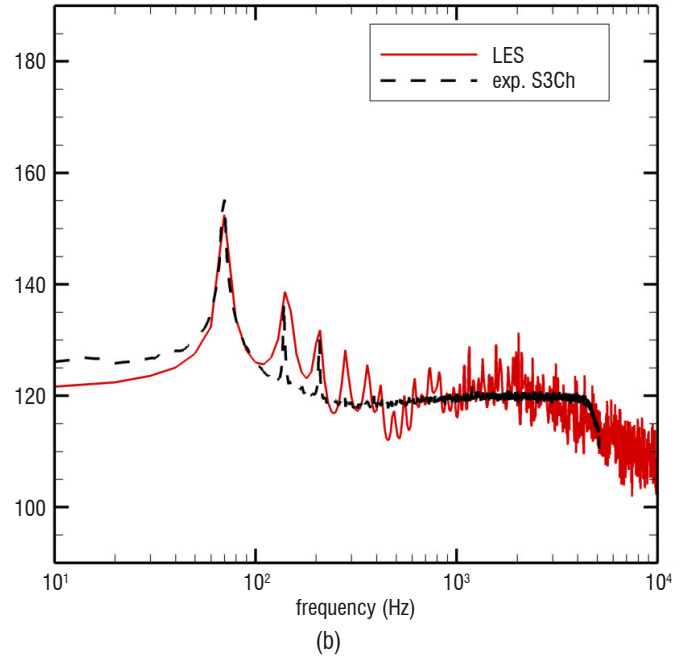
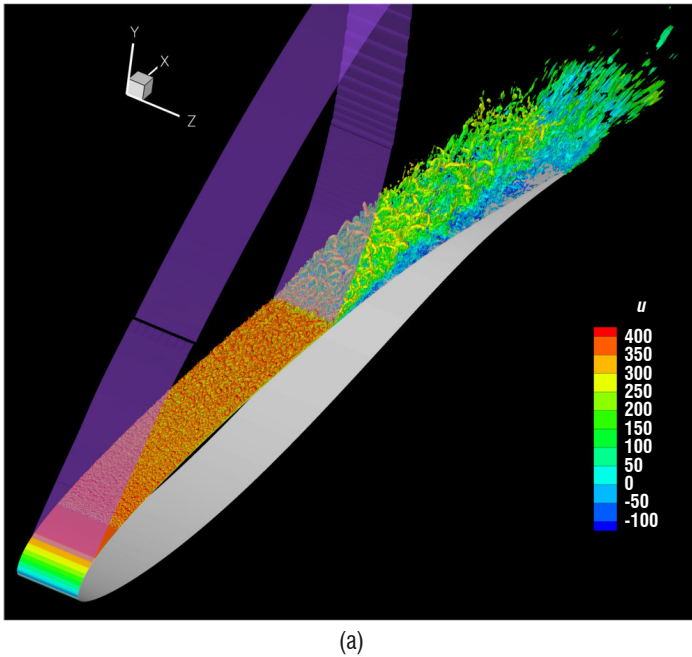


Figure 9 – LES of the buffet flow at Mach number $M = 0.73$ (tripped supercritical airfoil OAT15A) – (a) An iso-value of the Q criteria colored by the longitudinal velocity and one iso-value of the pressure (purple) to mark the shock location, (b) PSD of pressure fluctuations (SPL in dB) at $x/c=0.9$ [19].

spectra obtained in the tripped boundary layer case at $x/c = 40\%$ (close to the mean shock position at $x/c = 60\%$) and at $x/c = 81\%$; Figure 8(c) and (d) show the pressure spectra in the natural transition case, at $x/c = 60\%$ (at the mean shock position) and at $x/c = 81\%$. The turbulent case at a high angle of attack ($\alpha > 3.5^\circ$) exhibits buffet at 75 Hz, a value very close to that found in the OAT15A experiment. The global nature of the phenomenon is evidenced again by the presence of the same mode at $x/c = 0.40$ in Figure 8(a) and at $x/c = 0.81$ in Figure 8(b). As shown in Figure 8(c)-(d), when the transition is set free the flow behaves very distinctly, exhibiting a global buffeting frequency that is an order of magnitude higher, at about 1130 Hz (incidentally, this corresponds to a chord-based normalized frequency $St = f c / U_\infty \approx 1$). This reinforces the conclusion that a laminar buffet is less severe than a turbulent buffet. Low-frequency unsteadiness is felt at $x/c = 0.40$, see Figure 8(c), but it is not modal and it is not retrieved further downstream, see Figure 8(d)³.

This energetic footprint should be related to the dynamics of the laminar separation bubble identified in Figure 6(b). These results are promising for aeronautical applications, because they suggest that more laminar aircraft could combine two advantages: less drag, due to delayed transition, and a larger flight envelope, thanks to a less severe buffet⁴.

A tribute to CFD

Although this review paper has primarily concerned testing, CFD has accompanied a large part of these experimental studies. After the cited pioneering works based on unsteady viscous-inviscid interac-

tion methods used to guide experiments in the 1980s [6], efficient Navier-Stokes solvers came into play at ONERA as in all other institutions. An example was given in Figure 4(a) based on the use of the ONERA software package for a compressible flow around complex geometries, named elsA [18], for which the above experiments were precious test cases. Reference was also made to studies on the role of the turbulent models in simulations of the transonic buffet by means of Unsteady Reynolds-Averaged-Navier-Stokes (URANS) solvers, [14]. Beyond RANS or URANS approaches, fully turbulent computations became the main challenge in the 2000s. Large Eddy Simulations (LES), Detached Eddy Simulation (DES) and hybrid techniques (ZDES) mixing RANS approaches (for the wall flows) and LES (in the detached regions) were confronted to those test cases. The capacity of a LES to capture the turbulent buffet of the 2D airfoil in Figure 3 is illustrated in Figure 9 [19]. This LES used 42 million cells to compute a domain width of 7.3% of the chord, see Figure 9(a). Figure 9(b) shows that the pressure spectrum obtained on the upper trailing edge at $x/c = 0.9$ compares well to the experiment. The LES method is currently being tested on the case with a natural transition described in Figures 6 to 8. The progress made compared to the 2010s are those provided by high-performance computing (HPC) optimization (code FastS). This leads to a reduction in the computation time by a factor between five and ten for this type of computation [20].

A full LES of a representative 3D aircraft geometry is largely beyond the reach of actual computers. However, the ZDES method can be used, as shown in Figure 10, where the 3D buffet flow in Figure 2 has been computed using 190 million cells, [21]. Results are in rather good agreement with wind tunnel tests, although the low-frequency fluctuations are slightly overestimated due to lack of duration of the computed signal compared with the wind tunnel data, see [21].

³ All of the data show the presence of a peak at $f = 50$ Hz with a small amplitude around $10^{-6} q_0^2$ (where q_0 denotes the dynamical pressure). It is an electrical artifact.

⁴ Other experiments were conducted in 2012 in the ONERA S2MA wind tunnel on laminar airfoils designed by Dassault-Aviation within the framework of JTI Clean Sky SFWA-ITD. The results, protected by privacy rules, are generally in line with the current research findings described in this chapter.

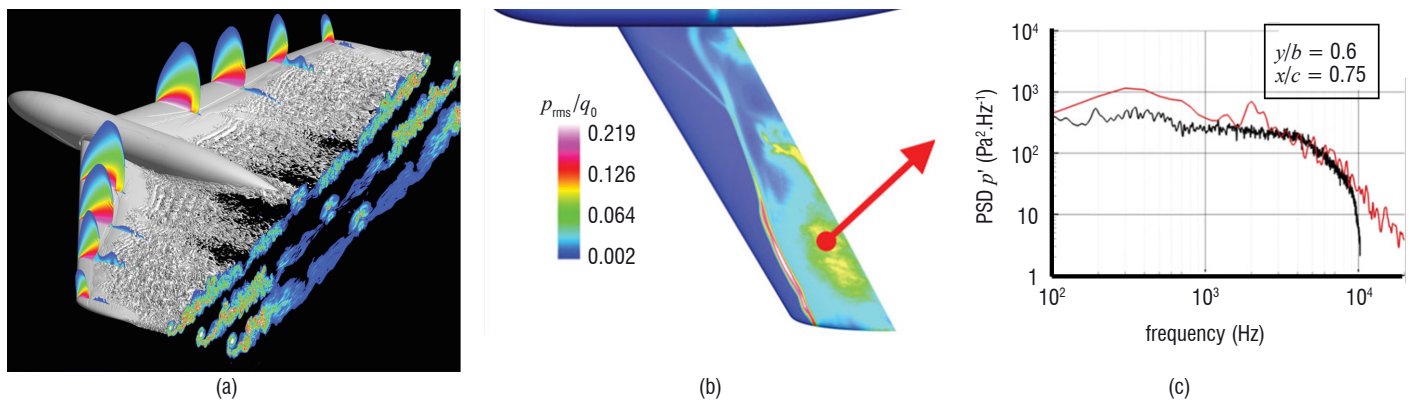


Figure 10 – ZDES of transonic buffet over a civil aircraft configuration ($Re_{mc} = 2.810^6$, $M = 0.82$) – (a) Isosurface of Q-criterion featuring the coherent structures resolved with ZDES and vorticity and Mach contours. (b) Pressure RMS fluctuations on the suction side, showing the location of the shock motion. (c) pressure spectrum at the location identified in (b), [21].

Buffet control

Interestingly, as mentioned above, it has been demonstrated that the transonic buffet is easy to control by open-loop or closed-loop strategies. Early investigations [4] were very successful in showing that vortex generators deployed upstream of the shock suppress the 2D buffet and that moving small flaps located at the trailing edge of a swept wing can significantly reduce the 3D buffet. Further investigations, including fluidic actuation tests, have confirmed the efficiency of such strategies. This topic is beyond the scope of this paper. The reader will find in [22] and [23] comprehensive reviews of various contributions by ONERA to buffet flow control.

Conclusion and perspectives

This article summarizes nearly three decades of research based on wind tunnel tests conducted by ONERA on the transonic buffet, an important basic phenomenon for aeronautical applications. Thanks to significant progress made since the 1980s, the case of a 2D airfoil in a fully turbulent regime is now better understood. The two next steps are: (i) understanding the sensitivity to the boundary layer state revealed by the most recent experiments, (ii) elucidating the transition mechanisms from 2D to 3D buffet. These objectives are now clearly within reach. The success of such researches will require the best possible utilization of the various wind tunnels and CFD platforms available at ONERA. This will otherwise require a strengthening of cross-interactions between simulation and experiment, in particular by considering data assimilation. We will end this review by addressing this challenging research perspective, to which the buffet problem

could contribute. Data assimilation is the process of incorporating observations into a mathematical model of a real system, by combining numerical, control and optimization methods (see [24]). Its objective for fluid mechanics is the combination of experimental and numerical analysis to obtain more reliable and more complete information for a real flow. Its applications to aerodynamics are only beginning and the transonic buffet appears to be particularly well suited for producing such techniques. Indeed, as seen above, the 2D buffet flow dynamics strongly depend on the state of the boundary layer in the region of the shock wave. However, in a wind tunnel, this region is too thin and too sensitive to be fully characterized conveniently by means of the available measurement techniques, especially in the laminar regime. Data assimilation techniques combining CFD models of variable complexity (from RANS to LES) with different turbulence and transition models and different sets of flow measurements can be tested carefully using the above described research environment. Extension of the method to the 3D buffet will have to deal with a reduced ability to control the experimental conditions and with the manipulation of a system of much larger dimensions. Meanwhile, adjoining data-driven techniques based on inverse modeling and machine learning can enable, for instance, the construction of accurate models of turbulence and transition, by allowing what is missing in the closure to be inferred and converting that inference into modeling knowledge [25]. Transonic buffet data would challenge such a machinery by physics that are altogether global, local, compressible and highly receptive to details in the shock boundary layer interaction region. To begin with, machine-learned transition and turbulence models, which could easily manage both turbulent and laminar 2D buffet flows, would constitute a breakthrough. All of these constitute promising subjects for the topic of testing in aerodynamics ■

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