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Shock-vortex shear-layer interaction in the transonic flow around a supercritical airfoil at high Reynolds number in buffet conditions

Damien Szubert [a,*], Fernando Grossi [a], Antonio Jimenez Garcia [a], Yannick Hoarau [b], Julian C.R. Hunt [c], Marianna Braza [a]

[a] Institut de Mécanique des Fluides de Toulouse, UMR No 5502 CNRS-INPT-UPS, Allée du Prof. Camille Soula, F-31400 Toulouse, France
[b] Laboratoire ICUBE, UMR No 7357, Strasbourg, France
[c] Department of Earth Sciences, University College London, London WC1E 6BT, UK

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ABSTRACT

This paper provides a conceptual analysis and a computational model for how the unsteady 'buffeting' phenomenon develops in transonic, low incidence flow around a supercritical aerofoil, the OAT15A, at Reynolds number of 3.3 million. It is shown how a low-frequency buffet mode is amplified in the shock-wave region and then develops upstream and downstream interaction with the alternating von Kármán eddies in the wake past the trailing-edge as well as with the shear-layer, Kelvin–Helmholtz vortices. These interactions are tracked by wavelet analysis, autoregressive (AR) modelling and by Proper Orthogonal Decomposition. The frequency modulation of the trailing-edge instability modes is shown in the spectra and in the wall-pressure fluctuations. The amplitude modulation of the buffet and von Kármán modes has been also quantified by POD analysis. The thinning of the shear layers, both at the outer edge of the turbulent boundary layers and the wake, caused by an 'eddy-blocking' mechanism is modelled by stochastic forcing of the turbulent kinetic energy and dissipation, by small-scale straining of the higher-order POD modes. The benefits from thinning the shear-layers by taking into account the interfacial dynamics are clearly shown in the velocity profiles, and wall pressure distribution in comparison with the experimental data.

1. Introduction

Understanding the various mechanisms related to buffet instabilities in the transonic flow around a supercritical airfoil is the main objective of this paper. A detailed physical analysis is developed for the interactions between shock waves and the boundary layer over the aerofoil, as well as between wake vortices and the shock waves. A further complexity arises from the interactions between the wake vortices near the trailing edge and the fluctuating sheared interface that bounds the wake flow. Pioneering studies of Levy (1978) and Seegmiller et al. (1978), made evidence of a shock unsteadiness characterised by a low-frequency and high-amplitude, in the Mach number range 0.7–0.8 corresponding to aircraft's cruise-speed. Several experimental

* Corresponding author.

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and numerical studies have been devoted to this flow phenomenon and its impact on the aerodynamic forces: McDevitt et al. (1976), Jacquin et al. (2005, 2009) and Brunet (2003).

Whereas the majority of the studies devoted to the transonic interaction deal with the high-Reynolds number range, the physical mechanisms of the buffet onset can be studied more easily in the lower Reynolds number range, allowing for Direct Numerical Simulation. For a NACA0012 airfoil, (Bouhadji and Braza, 2003a, 2003b) have analysed the successive states of the unsteadiness due to the compressibility effects in the Mach number range 0.3–1.0 by 2D and 3D Navier–Stokes simulations. The buffet instability was analysed in association with the von Kármán vortex shedding in the Mach number range 0.75–0.85, as well as the suppression of the buffet form Mach numbers beyond 0.85. The buffet mode has also been analysed by DNS of Bourdet et al. (2003), who used in addition the Stuart-Landau model (Landau, 1944) in order to quantify the linear and non-linear parts of the buffet instability.

These studies showed the sharp rise of the drag coefficient as the Mach number increases in the range 0.7–0.8, as well as the interaction of the shock wave with the von Kármán wake instability downstream of the trailing-edge. It was shown that this instability was formed in the wake and propagated towards the trailing-edge beyond a low-subsonic critical value of the Mach number, of order 0.2, for a NACA0012 airfoil at zero incidence and Reynolds number of 10 000 (Bouhadji, 1998). This instability (mode I) persists within the whole transonic speed interval, up to Mach number of order 0.85, independently on the appearance of the buffet. This second instability (mode II) was found to appear in the interval 0.75–0.8 and to strongly interact with mode I, where the buffet was sustained by mode I. Experimental evidence of mode I was made by the Schlieren visualisations of D.W. Holder (Fung, 2002), Fig. 7.

Numerical simulations in the high-Re range (Grossi et al., 2012b; Jimenez-Garcia, 2012), regarding a supercritical airfoil, the OAT15A, introduced a splitter-plate at the trailing edge, which suppressed the von Kármán mode. It was shown that in the cases where the von Kármán mode was remote (downstream of a critical length of the splitter plate), the buffet mode was considerably attenuated and disappeared. Therefore, it is worthwhile analysing the interaction of these two modes in the high-Reynolds number regimes for aerodynamics applications. In particular, there is little knowledge of this kind of interaction in the state of the art with regard to the high-Re range as well as more generally, of the trailing-edge dynamics feedback effect towards the shock-wave/boundary-layer interaction region (SWBLI) upstream of the trailing-edge. Lee (1990) reported a schematic explanation of the buffet interaction with Kutta waves coming from the trailing-edge, without a quantification of this interaction. Furthermore, it is worthwhile mentioning that the SWBLI is followed by separation of the boundary layer and by the formation of *thin* shear layers at the edges of the boundary layers and in the wake, where local Kelvin–Helmholtz (K–H) instabilities are observed.

In order to compute the interactions and feedback between the shear-layer and trailing-edge instabilities with the upwind shock-buffet mode, new methods are needed. These have to overcome the tendency of the shear layers to thicken downstream of the SWBLI, because of the turbulent shear stress modelling near the interface is usually approximated by employing eddy-viscosity concepts based on equilibrium turbulence hypotheses and direct cascade. In the flow physics however, upscale phenomena occur that increase the energy of the turbulence spectrum from intermediate range towards the lower wavenumbers (Braza et al., 2006). These mechanisms are not yet sufficiently taken into account in the modelling equations. However, theoretical analysis (Hunt et al., 2008) and experimental studies (e.g. Ishihara et al., 2015) show that these stresses are generated by the inhomogeneous small-scale motions in the turbulent region near the interface and thence increase the local "conditional" shear and "eddy blocking effect" within the interfacial layer (Fig. 1). This influence of small scales on the whole flow is effectively an "upscale" process. The local turbulence adjacent to the interface tends to reduce the Kelvin–Helmholtz instability modes of the interface (Dritschel et al., 1991).

A new approach for modelling the interface regions is needed, which can be based on recent numerical and experimental research into turbulent interfacial shear flows, on the outer edges of jets, wakes and the outer parts of boundary layers with thickness L. The thin randomly moving interfaces which separate regions of strong and weak turbulence have a thickness $\ell(\ll L)$. This general property of turbulent flows was in fact suggested and discussed by Prandtl in 1905, though he did not take it further once he became interested in the mixing length model of the mean properties of turbulent shear flows (see Bodenschatz and Eckert, 2011; Taveira and da Silva, 2014). Within these layers, the average shear (or in 2-dimensions the gradient of shear) is much stronger than that in the adjacent turbulent shear flows. At very high Reynolds numbers Re, determined by L and the *R.M.S.*, turbulent velocity u_o, the thickness ℓ of these interface layers is of the order of the Taylor microscale ℓ_V (i.e $L\,\mathrm{Re}^{-1/2}$), but within them very thin elongated vortices form with a thickness ℓ_V of the order of the Kolmogorov microscale (i.e. $\ell_V \sim L\,\mathrm{Re}^{-3/4}$, Eames and Flor, 2011). Numerical simulations show that these sharp interfaces occur even in complex turbulent flows, such as flows over aircraft wings (Braza, 2011).

These interfaces have their own mean local dynamics that keep the mean gradients at the interface at a maximum, through eddy blocking and enhanced vortex stretching (Hunt et al., 2008). Similar bounding interfaces also occur at the edges of patches of turbulence, such as puffs or vortex rings (Holzner et al., 2008). These intensely sheared layers interact with the motions outside the layers by blocking external eddies (through shear sheltering), which leads to a balance between sharpening of the velocity gradients in the layer and the tendency to diffuse outwards (Hunt et al., 2008). The typical spacing between the interfacial layers is of order of the "dissipation integral length scale" (Hunt et al., 2014).

Thus, the overall high-Re dynamics of the interface has to be modelled in order to correctly represent the turbulent transfers through the rotational–irrotational regions either side of these interfaces that have to be kept thin. This modelling has to include the complex interactions between the developing instability modes and the fine-scale turbulence. It is necessary to have a comprehensive turbulence model that should include the effects of the low-frequency organized motion