

# High-Speed PIV Measurements of Transonic Shock-Buffet Control on a Supercritical Airfoil with Air-Jet Vortex Generators

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## ABSTRACT

This study investigates the control of transonic buffet instability over a two-dimensional OAT15A supercritical wing model using air-jet vortex generators (AJVGs). For this, high repetition rate particle image velocimetry (PIV) measurements were conducted in both the streamwise/wall-normal and streamwise/spanwise planes at 5 kHz in the Trisonic Wind Tunnel Munich under buffet conditions within the range  $0.74 \leq M_\infty \leq 0.76$  and  $4.5^\circ \leq \alpha \leq 5.5^\circ$ . These measurements were conducted on an OAT15A wing model onto which a row of 37 AJVGs with a purely spanwise inclination of  $45^\circ$  was incorporated at  $0.20c$  from the leading edge. The results show that the uncontrolled flow at  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$  exhibits a pronounced buffet mode at  $f_b = 112.30 \text{ Hz} \pm 2.44 \text{ Hz}$  ( $St_b = 0.068$ ), characterised by large-amplitude shock motion and periodic growth and collapse of the downstream separated region. Under jet actuation at the same aerodynamic conditions, this instability is substantially mitigated, with the mean shock position shifting downstream by up to  $0.091c$  (measured at a chord-normal distance of  $\hat{y} = 0.10c$ ), and the standard deviation of the shock motion decreasing by approximately 68% with respect to the uncontrolled baseline case. A spectral analysis of shock motion also reveals a reduction of nearly 98% in the power spectral density associated with the dominant buffet mode. Furthermore, statistical analysis of the reverse-flow region demonstrates a strong suppression of large-scale separation events and with corresponding increased likelihood of small/diminishing reverse flow regions. Analysis based on Spectral POD further affirms the attenuation of the dominant buffet mode. Parametric investigations across multiple jet-injection pressures and aerodynamic conditions show that AJVG actuation consistently stabilises the interaction and suppresses buffet without introducing major disturbances into the outer flow.

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## 1. Introduction

Modern commercial aircraft operate in the transonic flow regime, where local flow velocities on the suction side of a supercritical wing can exceed the sonic limit and terminate in a shock wave. Although the resulting flow field is typically stable, it can become highly unsteady for certain combinations of angle of attack ( $\alpha$ ), Mach number ( $M_\infty$ ), and Reynolds number ( $Re_\infty$ ). This dynamic flow instability, commonly referred to as *transonic buffet*, manifests as a large-scale, self-sustained periodic oscillation of the shock wave, accompanied by pronounced variations in shock strength

and periodic thickening and thinning of the downstream shock-induced separation (McDevitt et al., 1976; Jacquin et al., 2009; Iovnovich and Raveh, 2012). This dynamic flow phenomenon can lead to substantial lift oscillations, strong fluctuating aerodynamic loads on the airframe accompanied by intense vibrations (buffeting), and a significant drag penalty (Giannelis et al., 2017). As a result, the operational envelope of the aircraft is restricted, and both safety and performance may be adversely affected. To advance the understanding of the flow phenomenon and its implications for flight performance, numerous experimental and computational studies have been conducted (see, for example, Jacquin et al. (2009); Crouch et al. (2009); Iovnovich and Raveh (2012); Hartmann et al. (2013); D'Aguanno et al. (2021); Accorinti et al. (2022); Schauerte and Schreyer (2023)), and detailed reviews of previous work are available in Lee (2001) and Giannelis et al. (2017).

Given the strongly detrimental impact of transonic buffet on the stability, performance, and reliability of modern civil aircraft, the development of suitable control strategies to delay or mitigate its onset is of critical importance. In this context, several active and passive control approaches for rigid wings have been explored in the literature (see Giannelis et al. (2017) for an overview). Owing to the highly dynamic nature of this phenomenon, these efforts have largely focused on either dampening the oscillation of the shock–separation system (e.g. using shock-control bumps (Bruce and Colliss, 2014)) or disrupting the acoustic feedback mechanism proposed by Lee (2001) (e.g. using trailing-edge deflectors (Caruana et al., 2005)). Another comparatively simple yet effective strategy is the installation of vortex generators upstream of the shock wave (Caruana et al., 2003). The streamwise vortices generated by these devices redistribute momentum within the boundary layer and improve its resistance to shock-induced separation; consequently, separated-flow instabilities have been shown to be greatly reduced (Caruana et al., 2003).

The above methods, though effective, rely on mechanical devices placed on the surface of the airfoil contour and are typically designed and optimised for a specific flow condition, while incurring unwanted parasitic drag under all other operating conditions. To circumvent this limitation, air-jet vortex generators (AJVGs) can be implemented (Wallis, 1952). Similar to their mechanical counterparts, AJVGs generate streamwise vortices through the interaction of an air jet injected into the crossflow (Kähler et al., 2007; Ali and Alvi, 2015; Sebastian et al., 2020). In addition to possessing effectiveness comparable to that of mechanical vortex generators, they can be flexibly operated or switched off when not required, thereby avoiding additional drag penalties. AJVGs have previously been employed successfully to mitigate shock-induced separation and its associated unsteadiness at higher Mach numbers, while investigating the influence of key geometric and jet parameters. These include the effects of jet diameter ( $d_{\text{jet}}$ ) (Szwaba, 2013), jet-to-jet spacing ( $D$ ) (Ramaswamy and Schreyer, 2022; Verma and Manisankar, 2019), jet-injection pressure ( $p_{\text{pl}}$ ) (Sebastian et al., 2023; Verma and Manisankar, 2019), jet-orifice shape (Ramaswamy and Schreyer, 2023, 2026), and jet-exit velocity profile (Ramaswamy et al., 2023), amongst others.

A demonstration of the ability of AJVGs to mitigate transonic shock buffet was carried out by Molton et al. (2013) at  $M_\infty = 0.82$  and a chord-based Reynolds number of  $Re_c = 2.5 \times 10^6$ , where AJVGs successfully delayed buffet onset. However, these investigations were conducted

on a swept-wing configuration, in which the buffet mechanisms are more complex and spectrally broader (Dandois, 2016). Investigations of AJVG-based buffet control over two-dimensional wings, for which a stronger and more isolated low-frequency spectral peak has been reported, are generally lacking. Furthermore, since the study of Molton et al. (2013), our understanding of both AJVG parameters and transonic buffet over two-dimensional airfoils has improved considerably (see the corresponding discussion above). It is therefore important to revisit and thoroughly investigate the role of optimally configured AJVGs in controlling transonic buffet over two-dimensional wings using state-of-the-art optical measurement techniques.

In this study, a single row of air-jet vortex generators is employed to control transonic buffet over a two-dimensional rigid OAT15A wind-tunnel model. Time-resolved 2D–2C PIV measurements are carried out in both the streamwise–wall-normal ( $xy$ -PIV) and streamwise–spanwise ( $xz$ -PIV) planes to fully characterise the shock and separated-flow dynamics at various incoming Mach numbers ( $M_\infty$ ) and angles of attack ( $\alpha$ ) for which buffet is observed to occur. The results are compared with the undisturbed buffet behaviour over the OAT15A model, which serves as the uncontrolled baseline case.

## 2. Wind tunnel facility and airfoil model

The experiments for this investigation were carried out in the Trisonic Wind Tunnel Munich (TWM) at the Bundeswehr University Munich. The facility is a blowdown wind tunnel with a rectangular test section measuring 0.300 m in width and 0.675 m in height upstream of the model. Downstream of the model, the test-section height increases symmetrically to 0.700 m in order to compensate for the displacement effect of the growing tunnel boundary layer along the 1.7 m long test section. Two compressors with a total capacity of 600 kW pressurise storage tanks with a combined capacity of approximately 360 m<sup>3</sup> up to 20 bar above ambient pressure. This configuration allows for a total run time of about 100 s under the conditions relevant to the present study. Prior to storage, the air is dehumidified using silica-gel-based dryers, reducing the dew point to approximately  $-40^\circ\text{C}$ .

During wind-tunnel operation, a hydraulically operated control valve is used to regulate the total pressure in the test section. Mach number control is achieved using an adjustable two-dimensional Laval nozzle upstream of the test section and a two-dimensional diffuser downstream. Optical access to the test section is provided by two circular windows on the side walls and a rectangular window on the top wall. Boundary-layer suction can be applied on the side walls to mitigate boundary-layer growth. Furthermore, the side-wall windows can be hydraulically actuated to set the desired angle of attack ( $\alpha$ ) of the wind-tunnel model within the test section.

**Table 1.** Summary of investigated aerodynamic conditions

| $p_0$ [bar] | $T_0$ [K] | $M_\infty$  | $\alpha$  | $Re_\infty$ [m <sup>-1</sup> ]        |
|-------------|-----------|-------------|-----------|---------------------------------------|
| 1.5         | 293       | 0.74 – 0.76 | 4.5 - 5.5 | $19.8 \times 10^6 - 20.1 \times 10^6$ |

For the present measurements, the Laval nozzle was fully opened and the downstream diffuser was adjusted to achieve transonic Mach numbers in the test section. The total pressure was set to  $p_0 = 1.5$  bar, and measurements were acquired once the total temperature reached  $T_0 = 293$  K. Under conditions relevant to the present study, the freestream turbulence intensity lies between 1.1% and 1.4%. The reported Mach numbers were measured at a distance of 639.5 mm, upstream of the model leading edge of the wind tunnel model at  $\alpha = 0^\circ$ .

In an earlier study (Ramaswamy et al., 2025), buffet behaviour was characterised over a wide range of  $M_\infty/\alpha$  combinations, and conditions exhibiting large-scale self-sustained buffet oscillations were identified using an in-house-built focusing Schlieren system (Ibarra et al., 2025). The present study focuses on Mach numbers between 0.74 and 0.76 and angles of attack between  $4.5^\circ$  and  $5.5^\circ$  selected from those studies. A summary of the aerodynamic conditions investigated is provided in Table 1.

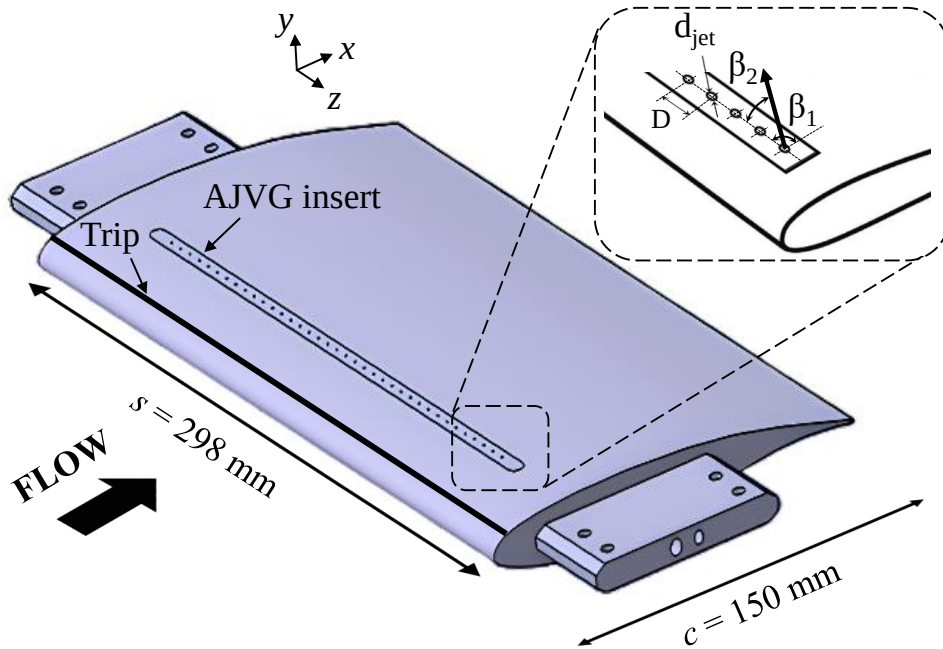


**Figure 1.** OAT15A wind tunnel model with the AJVG insert. The schematic on the top right shows the major AJVG geometric parameters. Image not to scale

For the wind-tunnel model, a two-dimensional extrusion of ONERA's OAT15A supercritical airfoil was milled from aluminium (see Fig. 1). This profile was selected due to its status as a de facto benchmark, having been extensively studied at various facilities over the past decades (Jacquin et al., 2009; Accorinti et al., 2022; D'Aguanno et al., 2021; Schauerte and Schreyer, 2023). The wind-tunnel model has a chord length of  $c = 150$  mm and a span of  $s = 298$  mm. A small gap of 1 mm exists between the model and the side walls on either side and is filled with soft rubber to limit damage to the optical windows and to avoid gap flows that could alter the flow topology on the suction side of the airfoil. The resulting aspect ratio of  $AR = 2$  offers a balanced compromise between approximating a quasi-two-dimensional flow field in the baseline case and enabling the acquisition of high-quality experimental data. To achieve a fully-developed turbulent flow state,

the boundary layer is tripped at  $0.073c$  using a two-dimensional strip with a height of  $60\ \mu\text{m}$  on both the suction and pressure sides of the airfoil.

To control the occurrence of transonic buffet, an array of 37 AJVGs is placed symmetrically about the model centreline at  $0.20c$  from the leading edge of the model. The subfigure in Fig. 1 illustrates the main AJVG parameters. Each jet orifice has a circular cross-section with a diameter of  $d_{\text{jet}} = 0.7\ \text{mm}$ , and the jet-to-jet spacing between adjacent orifices is  $D = 8.57d_{\text{jet}}$ ; the AJVGs thus cover the central 72.4% of the span of the wind-tunnel model to generate a 2D flow condition on average. All jets in the array have a pitch angle of  $\beta_2 = 45^\circ$  and are skewed at  $\beta_1 = 90^\circ$  with respect to the freestream flow; they therefore inject purely in the spanwise direction at a  $45^\circ$  inclination. Such spanwise-inclined jets exhibit lower jet penetration and generate streamwise vortices that persist over a longer downstream distance (Sebastian et al., 2020) compared with transversely injected jets. They are therefore more favourable for flow-control applications and have been adopted to control shock-induced separation in several studies reported in the literature (Wallis, 1952; Szwaba, 2013; Souverein and Debiève, 2010; Ramaswamy and Schreyer, 2021; Sebastian et al., 2023). Uniform and steady jet injection is ensured by incorporating a pressure plenum beneath the AJVGs into the model, which is supplied by an external independent air reservoir.

For the present investigations, three different plenum pressures ( $p_{\text{pl}}$ ) were considered, varying within the range  $1\ p_0 \leq p_{\text{pl}} \leq 2.33\ p_0$ , where  $p_0$  is the total pressure in the test section. The geometric and flow parameters of the AJVGs discussed above were selected based on previous parametric investigations of supersonic and transonic separation control (Ramaswamy and Schreyer, 2021, 2022; Verma and Manisankar, 2019; Sebastian et al., 2023; Szwaba, 2013). A summary of the major AJVG parameters considered in the present study is provided in Table 2. Assuming sonic conditions at the jet exit, the corresponding momentum-flux ratios ( $J$ ) and momentum coefficients ( $C_\mu$ ) for the selected pressure ratios are also listed in the table.

**Table 2.** AJVG conditions

| $d_{\text{jet}}$ | $D$                  | $\beta_1$  | $\beta_2$  | $p_{\text{pl}}$ | $p_{\text{pl}}/p_0$ | $J$  | $C_\mu$ |
|------------------|----------------------|------------|------------|-----------------|---------------------|------|---------|
| 0.7 mm           | $8.57d_{\text{jet}}$ | $90^\circ$ | $45^\circ$ | 1.5 bars        | 1.00                | 1.06 | 0.0009  |
|                  |                      |            |            | 2.5 bars        | 1.67                | 1.77 | 0.0015  |
|                  |                      |            |            | 3.5 bars        | 2.33                | 2.47 | 0.0021  |

### 3. PIV measurement setup

To examine the flow field, two-dimensional, two-component high-repetition-rate PIV measurements were carried out in two planes, namely the streamwise–wall-normal ( $xy$ -PIV) and streamwise–spanwise ( $xz$ -PIV) plane. For both cases, LaVision’s PTU and Davis 11.2 software package were used for image acquisition and synchronisation.

For the  $xy$ -PIV measurements, a dual-pulse Nd:YAG high-speed laser (wavelength 532 nm) from

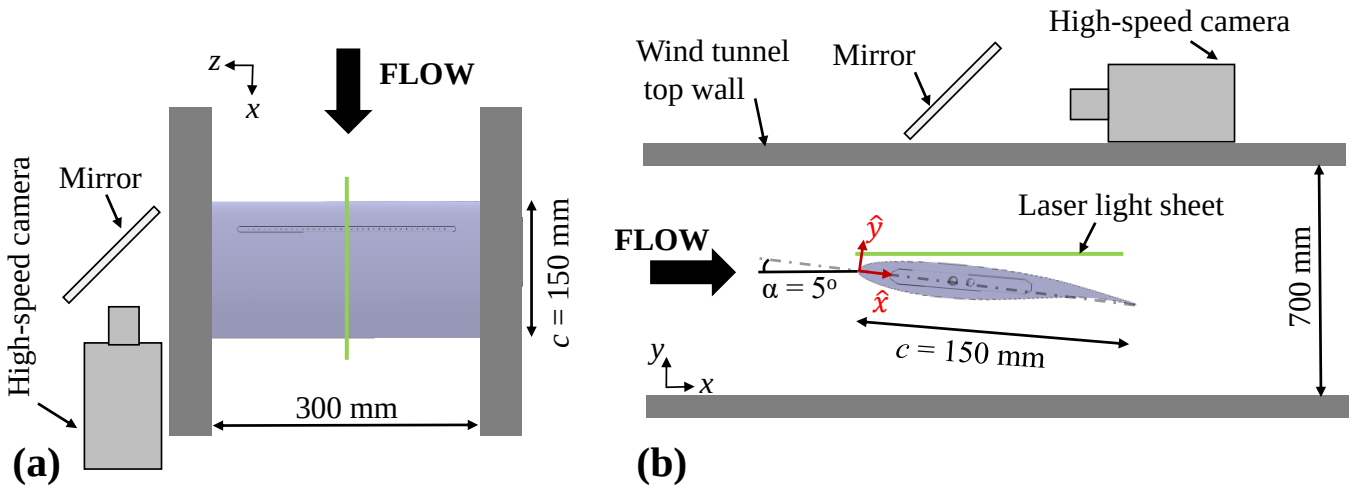


**Figure 2.** Schematic of the (a)  $xy$ -PIV as seen from the top-view, and (b)  $xz$ -PIV setup as seen from the side view. Not to scale.

Photonics Industries was used as the light source. The laser delivers a pulse energy of 15 mJ per pulse when operating at 10 kHz and has a pulse width of approximately 200 ns. A combination of lenses and mirrors was used to form a thin light sheet that illuminated the suction side of the airfoil along the model centreline in the  $xy$  plane (see Fig. 2a). Owing to the symmetric nature of the model, this light sheet also passed through the central jet orifice of the AJVG array.

The light sheet illuminated di-ethyl-hexyl-sebacate (DEHS) tracer particles, which were introduced upstream of the wind-tunnel settling chamber using four PIVTEC seeding generators. The illuminated particles were visualised through the side windows using a Phantom V2640 high-speed camera via a mirror placed at  $45^\circ$  (see Fig. 2a). The camera was equipped with a Zeiss Distagon 35 mm lens set to  $f/2$ , together with a  $2\times$  Teleplus Pro teleconverter, resulting in an effective field of view of  $1.32c \times 0.82c$  and a spatial resolution of 10.26 px/mm.

To further characterise the spanwise dynamics of the shock wave, high-speed PIV measurements were also carried out in the  $xz$  plane, as depicted schematically in Fig. 2b. For this configuration, the laser light was shaped into a sheet to illuminate a plane located at a height of  $0.074c$  above the leading edge of the wing at  $5^\circ$ . A second Phantom V2640 high-speed camera, equipped with a Zeiss Milvus 50 mm lens set to  $f/2.8$  and positioned above the test section, was used to visualise the illuminated DEHS particles via a mirror placed at  $45^\circ$ . The field of view covers  $1.08c \times 1.55c$  and spans the central  $\sim 80\%$  of the wind-tunnel model; it therefore encompasses the entire spanwise extent of the AJVG array.

For both measurement campaigns, 15,000 image pairs were acquired at 5 kHz, resulting in a total acquisition duration of 3 s, which is well above the  $\mathcal{O}(100 \text{ Hz})$  buffet frequency expected for the cases tested here (Accorinti et al., 2022). A pulse separation time of  $4 \mu\text{s}$  resulted in maximum particle-image displacements of up to 11 px and 15 px for the  $xz$ -PIV and  $xy$ -PIV datasets, respectively, in regions where the flow velocities reached approximately 400 m/s.

The acquired images were first pre-processed to account for minor model and camera/lens vibrations, followed by the application of a sliding minimum filter in time with a filter length of five images and a sliding background subtraction with a kernel size of 16 px to improve image contrast. Processing of the particle images was carried out using Davis's FlowMaster platform with a multi-pass interrogation algorithm. Final interrogation-window sizes of 16 px  $\times$  16 px with 50% overlap were used for both datasets. A universal outlier-detection method (Westerweel and Scarano, 2005), with  $\sigma = 2$  in a  $5 \times 5$  neighbourhood, was employed to identify and replace spurious vectors. For all test cases, more than 98% of the vectors were found to be valid in most instantaneous fields. The resulting vector fields were further processed in MATLAB to obtain velocity statistics. Although the velocity fields were acquired in the wind-tunnel world coordinate system  $(x, y, z)$ , the flow fields presented in the subsequent sections are resolved and shown in the chord-parallel and chord-normal coordinate systems,  $\hat{x}, \hat{y}, z$  (see Fig. 2b), for all investigated angles of attack ( $\alpha$ ) and Mach numbers ( $M_\infty$ ).

#### 4. Uncontrolled transonic buffet over an OAT15A wing

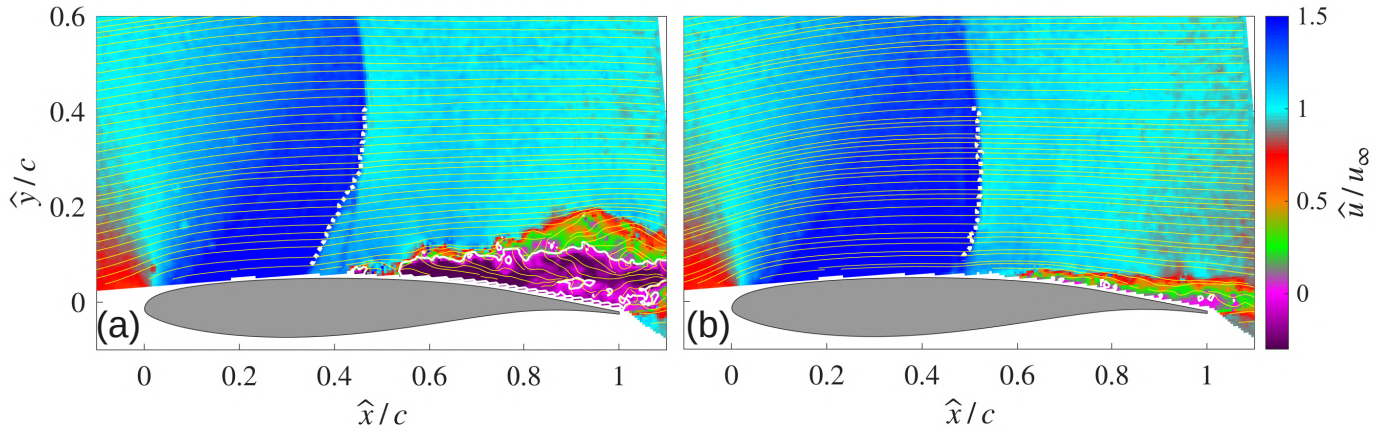


**Figure 3.** Instantaneous PIV images from  $xy$ -PIV at the (a) most upstream and (b) most downstream shock position of the uncontrolled case.  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$ . White solid lines show the  $\hat{u} = 0$  contour and white dotted lines trace the shock position.

In this section, the undisturbed transonic buffet over an OAT15A wing is first characterised to gain an understanding of the highly unsteady flow field to be controlled. This is illustrated in Fig. 3, where instantaneous PIV snapshots from an exemplary buffet cycle are presented with the shock wave at its most upstream position (Fig. 3a) and its most downstream position (Fig. 3b), both under established buffet conditions ( $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$ ). For each instantaneous image, the vertical extent of the shock position, identified as the location of minimum chord-parallel velocity gradient ( $\partial \hat{u} / \partial \hat{x}$ ) within the range  $0.08 \leq \hat{y}/c \leq 0.42$ , and the reverse-flow area ( $A_{\text{rev}}$ ) enclosed by  $\hat{u} = 0$  were also extracted. These are presented as white dotted lines and solid white lines, respectively, in Fig. 3.

In both instances, flow acceleration to supersonic velocities is observed over the wing, terminating

in a shock wave. At its most upstream location (Fig. 3a), the shock exhibits a more oblique orientation, and a large separated-flow region is observed downstream of its location. Furthermore, a prominent  $\lambda$ -shaped shock structure is visible close to the wall below  $\hat{y}/c \leq 0.23$ . As the flow field evolves throughout the buffet cycle, the shock moves downstream and reaches its most downstream location in Fig. 3b; here, the shock wave is more normal with respect to the surface, and the downstream flow field is nearly attached. Between these two extremes, the shock wave translates by a distance of  $\Delta\hat{x} = -0.12c$  (measured at  $\hat{y}/c = 0.10$ ), while the reverse-flow area decreases by  $\Delta A_{\text{rev}} = 0.041c^2$ , highlighting the highly unsteady nature of this phenomenon.

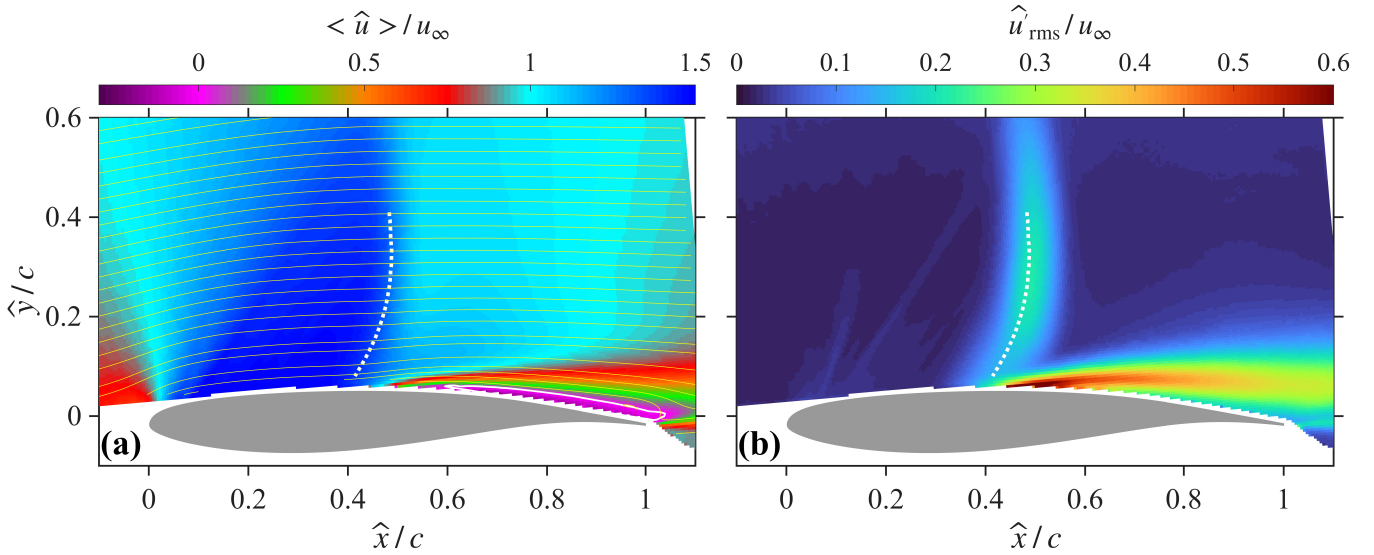


**Figure 4.** (a) Mean chord-parallel and (b) root-mean-squared values of chord-parallel fluctuating components of the uncontrolled buffet from *xy*-PIV at  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$ .

In order to analyse the global flow behaviour at pronounced buffet conditions ( $M_\infty = 0.755$ ;  $\alpha = 4.5^\circ$ ) in greater detail, the time-averaged chord-parallel velocity ( $\hat{u}/u_\infty$ ) and the rms of the fluctuating chord-parallel velocity component ( $\hat{u}'_{\text{rms}}/u_\infty$ ), as measured by *xy*-PIV, are presented in Figs. 4a and 4b, respectively. The estimated mean shock position (white dotted lines) and the mean reverse-flow area (solid white lines) are also superimposed on the figures. Unlike the instantaneous frames presented earlier, the chord-parallel velocities are smeared at the shock location due to the oscillatory nature of the shock wave. Nevertheless, the flow exhibits a time-averaged separated region with a mean reverse-flow area of  $A_{\text{rev}} = 0.007c^2$  (see Fig. 4a). Consequently, a large streamwise extent of fluctuating chord-parallel velocity is observed in the vicinity of the shock wave and the separated shear layer (see Fig. 4b).

Furthermore, *xz*-PIV was employed to assess the spanwise variation of the flow field, and the resulting velocity statistics at  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$  are presented over the central  $\sim 80\%$  of the span in Fig. 5. Note that the velocities  $u, w$  are resolved and presented in the wind-tunnel coordinate system due to the absence of the vertical velocity component required for coordinate rotation. However, the spatial coordinates are presented in the chord-parallel reference frame ( $\hat{x}$ ) to facilitate comparison of the identified shock position with the *xy*-PIV measurements. In addition

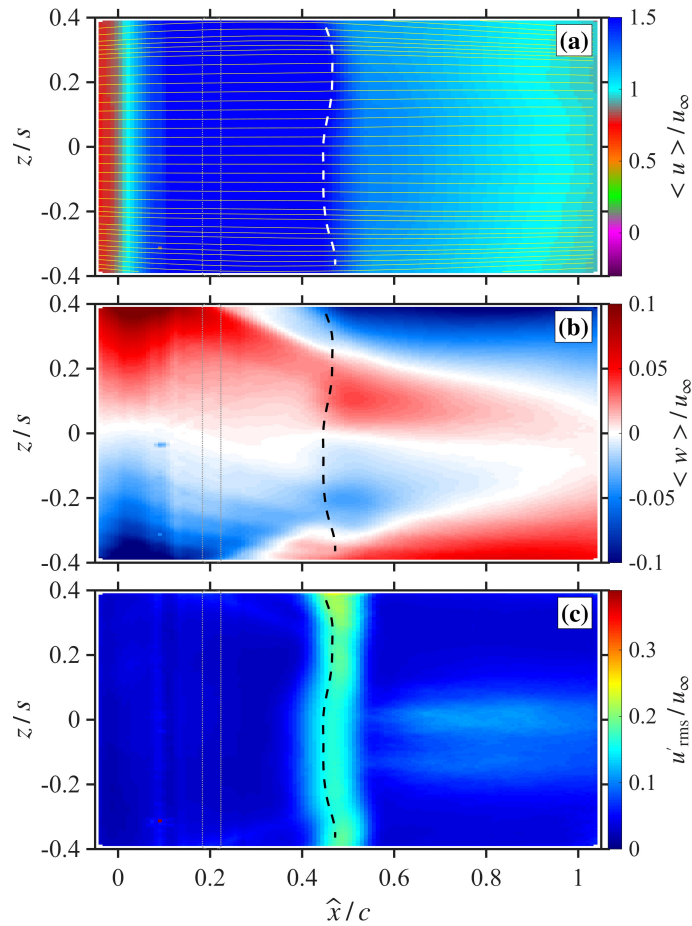


**Figure 5.** (a) Mean streamwise velocity, (b) mean spanwise velocity and (c) root-mean-squared values of streamwise fluctuating components of the uncontrolled buffet from  $xz$ -PIV at  $M_\infty = 0.755$  and  $\alpha = 4.49^\circ$ .

to the mean shock location (black dashed lines), the location of the modular insert is also depicted as dotted lines at  $\hat{x}/c = 0.20$ ; for the uncontrolled baseline case reported here, a clean insert without jet orifices was used.

The results show a quasi-two-dimensional flow field across the span, as evident from the mean streamwise velocity component presented in Fig. 5a. Nevertheless, examination of the mean spanwise velocity component (see Fig. 5b) reveals a measurable influence of the side-wall boundary layers on the flow behaviour. The mean spanwise velocity field indicates a convergence of the flow towards the model centreline ( $z/s = 0$ ), as evidenced by the opposing signs of the spanwise velocity component on either side of  $z/s \approx 0$  in Fig. 5b. Consequently, the buffet phenomenon is strongest in this region, exhibiting more intense shock motion and intermittent penetration of the separated boundary layer into the  $xz$ -PIV measurement domain. Evidence of this can be observed in the elevated magnitude of  $u'_{\text{rms}}/u_\infty$  at  $\hat{x} \geq 0.6$  and within the range  $-0.2 \leq z/s \leq 0.2$ , as well as in the more upstream mean shock position near  $z/s \approx 0$  in Fig. 5c, compared with other spanwise locations. The results also show that the presence of the baseline insert, which contains no jet orifices, at  $\hat{x}/c = 0.20$  does not produce any significant modification of the outer flow upstream of the shock wave.

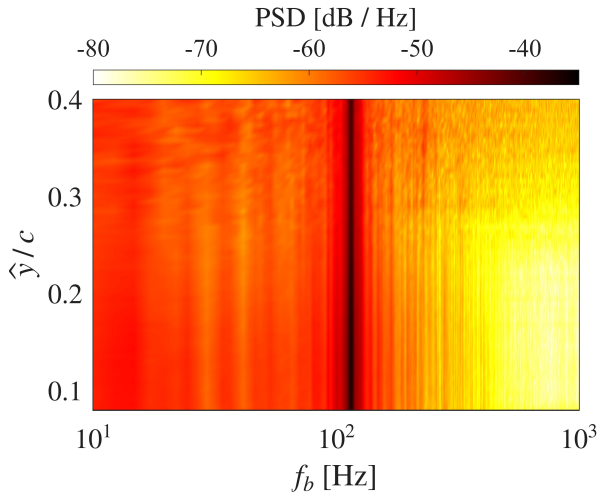


**Figure 6.** PSD maps of shock-motion at  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$  along  $\hat{y}$  from  $xy$ -PIV

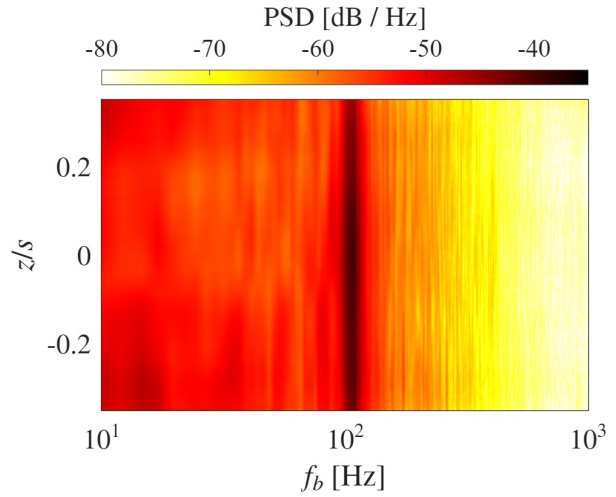


**Figure 7.** PSD maps of shock-motion at  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$  along  $z$  from  $xz$ -PIV

Having obtained a statistical characterisation of the flow field under transonic buffet conditions, the extracted instantaneous shock locations across the span and along the vertical direction are now used to assess the spectral characteristics of the shock motion. To this end, power spectral densities (PSD) of the detected shock locations across  $z/s$  and along  $\hat{y}/c$  were computed using the Welch method (Welch, 1967), with a window size of 2048 samples, 50% overlap, and a frequency resolution of  $\Delta f = 2.44$  Hz.

Fig. 6 shows the PSD distribution of the shock position as a function of chord-normal distance ( $\hat{y}/c$ ), as obtained from the  $xy$ -PIV measurements. A corresponding distribution across the span from the  $xz$ -PIV measurements is presented in Fig. 7. In both cases, the flow conditions correspond to  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$ , representative of pronounced buffet conditions. The results clearly reveal a strong and coherent buffet frequency across both the spanwise and chord-normal directions. Integrating the PSD distributions along both directions yields a buffet peak frequency of  $f_b = 112.30 \text{ Hz} \pm 2.44 \text{ Hz}$ . The corresponding chord-based Strouhal number is  $St_b = f_b \cdot c/u_\infty = 0.068$ , which is in excellent agreement with the results reported for the same airfoil geometry by Jacquin et al. (2009) ( $St_b = 0.067$ ), D'Aguanno et al. (2021) ( $St_b = 0.070$ ), Accorinti et al. (2022) ( $St_b = 0.074$ ), and Schauerte and Schreyer (2023) ( $St_b = 0.071$ ).

## 5. Effect of control

Having characterised the undisturbed transonic buffet phenomenon, this section investigates the effects of jet actuation on the spatio-temporal behaviour of the flow field. All results correspond to  $M_\infty = 0.756$  and  $\alpha = 4.5^\circ$ , comparable to the uncontrolled case presented in Sec. 4, with the jets actuated at  $p_{pl} = p_0$ .

### 5.1. Shock and separation bubble behaviour

To assess the direct impact of jet actuation on buffet, the instantaneous chord-parallel velocity along  $\hat{x}/c$  was extracted at  $\hat{y}/c = 0.10$  and plotted as a function of time in Fig. 8 for both the uncontrolled and AJVG-controlled cases. For the controlled case presented here, the jets are actuated with a plenum pressure equal to the wind-tunnel stagnation pressure ( $p_{pl} = p_0$ ). The mean shock position is indicated by a solid white line, whilst the chordwise extent of the shock motion is characterised by dashed white lines representing the region within  $\pm 1\sigma$  of the mean position. The uncontrolled case (Fig. 8a) clearly depicts a quasi-periodic motion of the shock wave and the downstream shear layer, with a period of approximately  $\sim 9$  ms. Upon jet actuation (see Fig. 8b), they impart a minor disturbance to the outer flow, visible as a weak jet-induced deceleration directly downstream of  $\hat{x} = 0.2c$ . Nevertheless, the flow appears to recover rapidly, and no large-scale modification of the outer flow is introduced by the jets. Furthermore, the momentum redistribution induced by the jets favourably alters the buffet behaviour by shifting the mean shock position downstream by nearly 21% and reducing the standard deviation of the shock motion by approximately 68%.

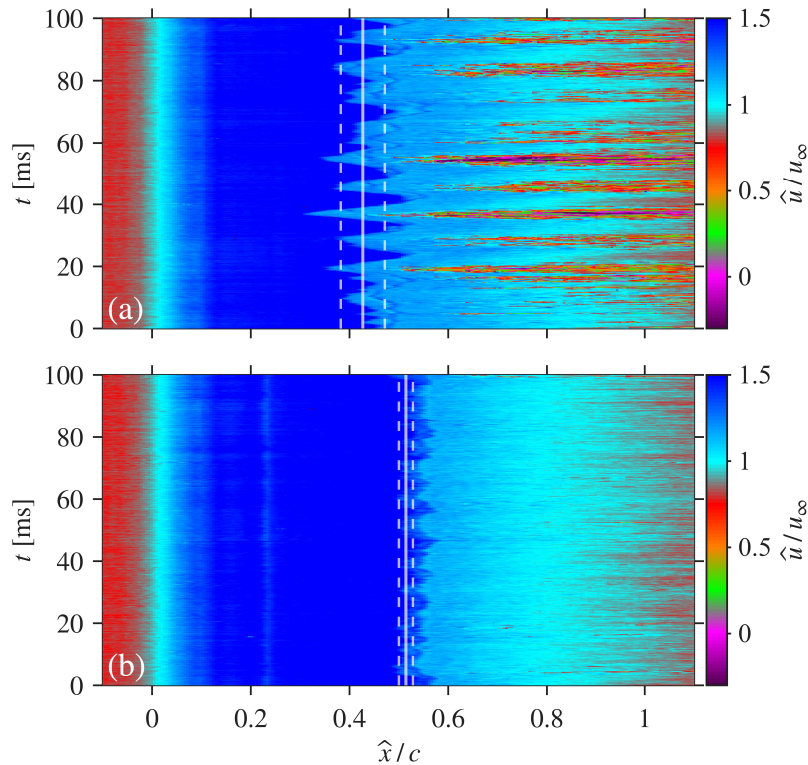


**Figure 8.** Chord-parallel streamwise velocity as a function of  $\hat{x}/c$  and time at a constant  $\hat{y}/c = 0.10$  for the (a) uncontrolled flowfield and (b) AJVG-controlled flowfield at  $p_{pl} = p_0$ .  $M_\infty = 0.756$  and  $\alpha = 4.5^\circ$ .

To further quantify the favourable effects of the jets, the spectral content of the shock motion is assessed for both the uncontrolled and AJVG-controlled interactions (with  $p_{pl} = p_0$ ) under identical incoming conditions ( $M_\infty = 0.755$ ;  $\alpha = 4.5^\circ$ ). Figure 9 shows the spanwise-integrated power spectral density (PSD) of the shock motion obtained from  $xz$ -PIV for the two cases on a logarithmic

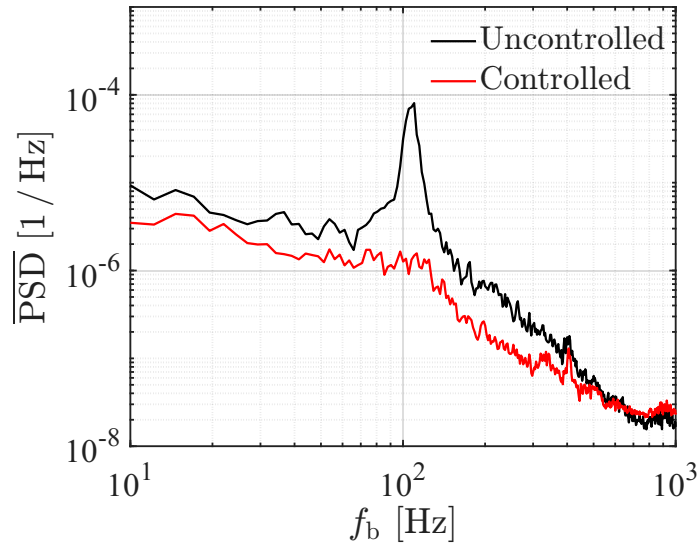


**Figure 9.** Spanwise-integrated PSD of shock location from  $xz$ -PIV for the uncontrolled and AJVG-controlled case at  $p_{pl} = p_0$ ,  $M_\infty = 0.755$  and  $\alpha = 4.5^\circ$ .

scale. The dominant peak associated with buffet is clearly visible for the uncontrolled case at  $f_b = 109.80$  Hz, which is exactly  $1 \Delta f$  lower than the integrated value reported earlier and therefore lies within the uncertainty limits of the spectral estimation. With the application of control, this dominant peak is significantly suppressed, exhibiting a nearly 98% reduction in the  $\overline{\text{PSD}}$  of the dominant buffet peak. A minor peak is observed at  $f = 4 \times 10^2$  Hz for the controlled case, which most likely corresponds to residual shock motion. Nevertheless, the corresponding  $\overline{\text{PSD}}$  is nearly 2.8 orders of magnitude lower than that of the dominant buffet peak in the uncontrolled case, highlighting the stabilising effect of the jets on the interaction.

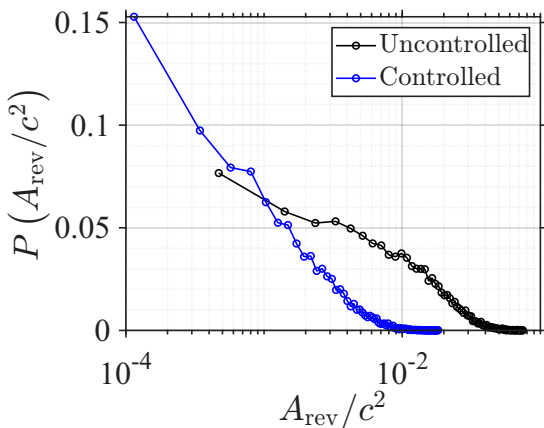


**Figure 10.** Probability of reverse flow area ( $A_{rev}$ ) from  $xy$ -PIV for the uncontrolled and AJVG-controlled case at  $p_{pl} = p_0$ ,  $M_\infty = 0.756$  &  $\alpha = 4.5^\circ$ .

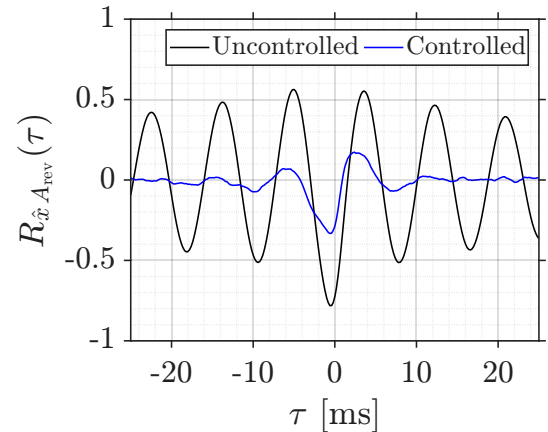


**Figure 11.** Cross-correlation in time between  $\hat{x}$  at  $\hat{y} = 0.10c$  and  $A_{rev}$  for the uncontrolled and AJVG-controlled cases at  $p_{pl} = p_0$ ,  $M_\infty = 0.756$  &  $\alpha = 4.5^\circ$ .

To further quantify the separated-flow behaviour, the probability distribution of the normalised reverse-flow area  $P(A_{rev}/c^2)$  for the uncontrolled and controlled configurations is presented in

Fig. 10, for the same flow conditions as in the preceding figures ( $M_\infty = 0.756$ ;  $\alpha = 4.5^\circ$ ;  $p_{pl} = p_0$ ). For both configurations, the highest probability occurs at  $A_{rev} \leq 5 \times 10^{-4} c^2$ . With jet actuation, however, this probability increases by nearly 50%, indicating a substantially greater occurrence of very small or nearly vanishing separated regions. In addition, the occurrence of larger separation bubbles ( $A_{rev} \geq 5 \times 10^{-3} c^2$ ) is significantly diminished under controlled conditions, suggesting the suppression of strong instantaneous or intermittent separation events.

To examine the relationship between the shock motion and the separated region, the cross-correlation between the instantaneous shock position ( $\hat{x}$ ) at  $\hat{y} = 0.10c$  and the instantaneous reverse-flow area ( $A_{rev}$ ) is presented in Fig. 11. As expected, the uncontrolled case exhibits the highly coherent and periodic nature characteristic of transonic buffet, as evidenced by the oscillatory behaviour of the correlation coefficient. Furthermore, the peak correlation occurs when the two signals are out of phase with one another, i.e.  $A_{rev}$  reaches its maximum when the shock is located furthest upstream (and vice versa), which is typical of buffet behaviour. The maximum negative correlation coefficient is obtained at  $\tau = -0.4$  ms, indicating that variations in separation-bubble area precede changes in shock position.

With the application of control, the dynamics of the interaction appear to be fundamentally altered. Although the maximum correlation still occurs for out-of-phase signals, the controlled case exhibits significantly less coherence and loses its periodic character; the correlation coefficient decays to nearly zero for  $|\tau| \geq 10$  ms. Nevertheless, within these incoherent and intermittent, likely small-scale, separation events, the separation area continues to precede shock motion with approximately the same time delay as in the uncontrolled case.

## 5.2. Flowfield statistics

Fig. 12a presents the mean chord-parallel velocity field at  $M_\infty = 0.756$  and  $\alpha = 4.5^\circ$  under controlled conditions with  $p_{pl} = p_0$ . A weak jet-induced oblique shock is observed originating from  $\hat{x} = 0.2c$ . Nevertheless, the outer flow over the suction side of the airfoil is only marginally affected and recovers rapidly downstream of the jet-induced disturbance. The momentum redistribution introduced by the jets causes the shock to become less oblique and shift further downstream compared with the baseline case shown in Fig. 5a. Furthermore, despite the presence of instantaneous and intermittent shock-induced separation events, as discussed in Sec. 5.1, the mean flow field exhibits no persistent reverse-flow region under controlled conditions. Consequently, the rms of the chord-parallel velocity fluctuations (see Fig. 12b) is significantly reduced along both the shock and the separated shear layer compared with the uncontrolled case at the same flow conditions (see Fig. 5b).

Probing the  $xz$ -PIV measurements reveals similarly favourable effects across the span under controlled conditions. Figures 13a, 13b, and 13c present the mean streamwise velocity ( $\langle u \rangle / u_\infty$ ), mean spanwise velocity ( $\langle w \rangle / u_\infty$ ), and the rms of the streamwise velocity fluctuations ( $u'_{rms} / u_\infty$ ), respectively, for the controlled case with  $p_{pl} = p_0$  at  $M_\infty = 0.753$  and  $\alpha = 4.5^\circ$ . As also observed in

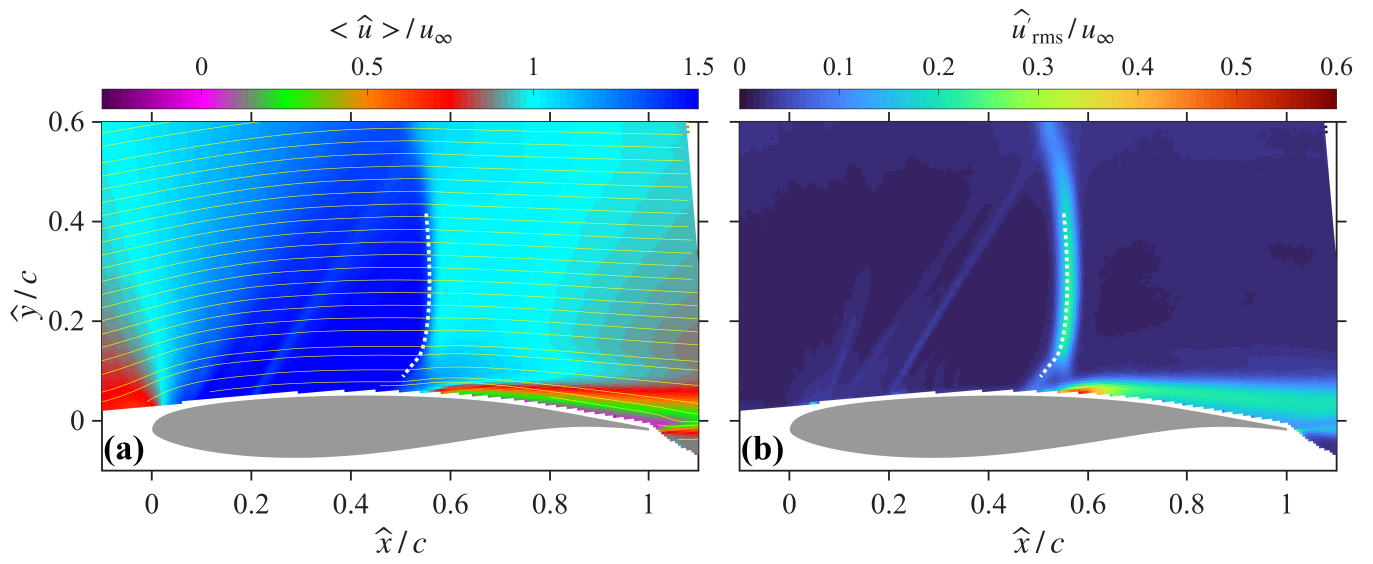


**Figure 12.** (a) Mean chord-parallel and (c) root-mean-squared values of chord-parallel fluctuating components from  $xy$ -PIV at  $M_\infty = 0.756$  and  $\alpha = 4.5^\circ$  and  $p_{\text{pl}} = p_0$ .

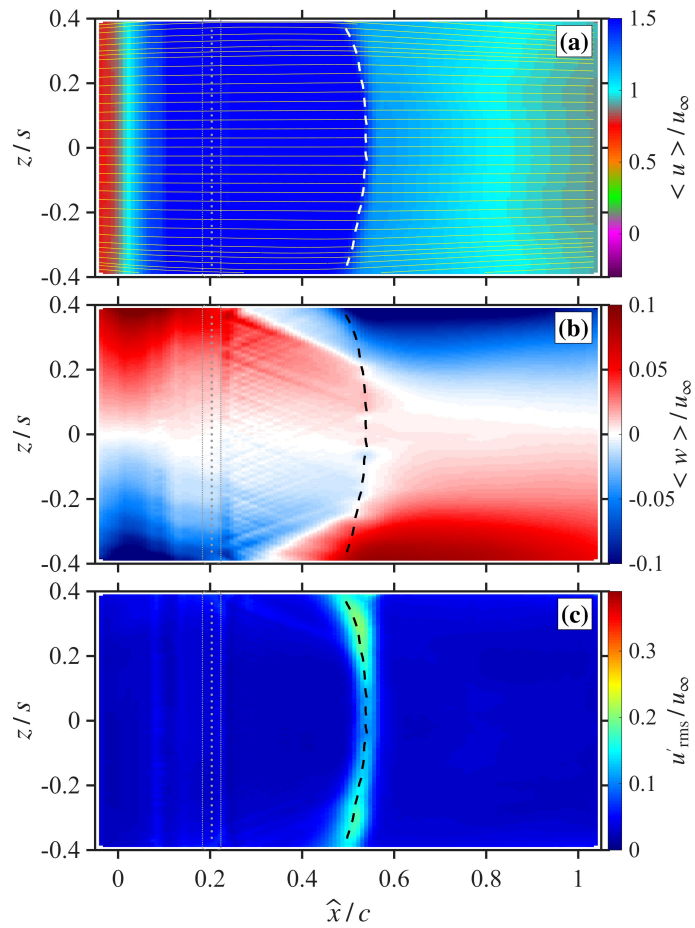


**Figure 13.** (a) Mean streamwise velocity, (b) mean spanwise velocity, and (c) root-mean-squared values of streamwise velocity fluctuations from  $xz$ -PIV.  $M_\infty = 0.753$ ,  $\alpha = 4.5^\circ$  and  $p_{\text{pl}} = p_0$

Fig. 5a, the jets located at  $\hat{x} = 0.2c$  do not introduce any major disturbances into the  $xz$ -PIV measurement plane. This further suggests that the beneficial influence of the jets in stabilising transonic buffet arises primarily from the energisation of the near-wall flow, rather than from large-scale alterations of the outer flow over the suction side. Consequently, any additional drag associated with jet actuation is also expected to remain minor.

The only discernible signature of the jets appears in the mean spanwise velocity field shown in Fig. 13b, where zig-zag-shaped footprints are observed extending downstream from the jet location at  $\hat{x} = 0.20c$ . These structures likely arise from interactions between adjacent jet-induced vortices. Indeed, the spanwise spacing between neighbouring jet orifices was specifically selected to promote such interactions, which have previously been shown to enhance the overall streamwise vorticity generated by the array (Ramaswamy and Schreyer, 2022; Sebastian et al., 2020). As a result of the associated near-wall momentum redistribution, the shock wave is displaced downstream across nearly the entire spanwise extent of the control array, spanning the central 80% of the model width, with an average shift of approximately  $0.07c$  relative to the uncontrolled baseline case (see Fig. 5).

As discussed in Sec. 5.1, the jets also stabilise the flow field. Consequently, there is a reduction in the streamwise extent of  $u'_{\text{rms}}/u_{\infty}$  along the shock location in Fig. 13c. Regions of elevated fluctuation intensity are primarily observed near  $|z/s| \approx 0.3$ , arising from the combined influence of AJVG edge effects and side-wall interactions with the shock wave. Furthermore, the reduced probability of large-scale reverse-flow regions under controlled conditions (see Fig. 10) results in the absence of the strong downstream velocity fluctuations that were observed behind the shock in the uncontrolled case shown in Fig. 5c.

### 5.3. Spectral POD

To further substantiate the above observations and obtain a comprehensive understanding of the jet influence on the overall flow field, spectral proper orthogonal decomposition (SPOD) was applied to the instantaneous chord-parallel velocity fluctuations obtained from the  $xy$ -PIV measurements for both the uncontrolled and AJVG-controlled interactions with  $p_{\text{pl}} = p_0$ . As before, the freestream conditions for both cases are  $M_{\infty} = 0.756$  and  $\alpha = 4.5^\circ$ . Unlike snapshot POD, SPOD enables the identification of spatio-temporally coherent modes associated with distinct frequencies (Schmidt and Colonius, 2020), making it particularly well suited for extracting the dominant dynamics from time-resolved PIV flow fields.

Figure 14 presents the eigenspectrum of the dominant first SPOD mode for both the uncontrolled and AJVG-controlled flow fields. For the uncontrolled case, a pronounced peak is observed at  $f_b = 114.7$  Hz, corresponding to the buffet mode, together with its first harmonic. This frequency is exactly  $1\Delta f$  above the integrated value reported in Sec. 4 and is in good agreement with the spectral results presented in Fig. 9.

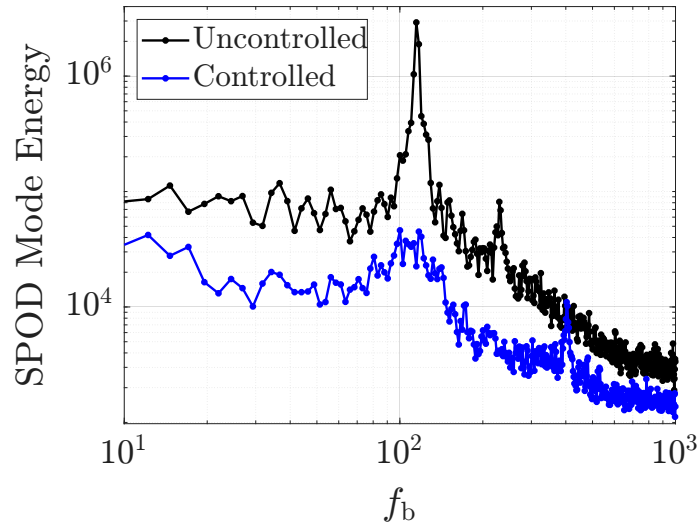


**Figure 14.** SPOD Eigenspectra of the leading mode for the uncontrolled and controlled case at  $p_{pl} = p_0$ .  
 $M_\infty = 0.756$ ;  $\alpha = 4.5^\circ$ .

Under controlled conditions, the modal energy of the first mode is generally lower across all frequencies, and more importantly, the dominant buffet peak disappears. A minor increase in energy is observed near  $f = 4 \times 10^2$  Hz, which likely corresponds to the residual shock motion and weak reverse-flow oscillations under jet actuation, as also identified in Fig. 9. However, as noted previously, the associated energy remains several orders of magnitude lower than that of the uncontrolled buffet mode, further confirming the effectiveness of jet actuation in suppressing the transonic buffet instability.

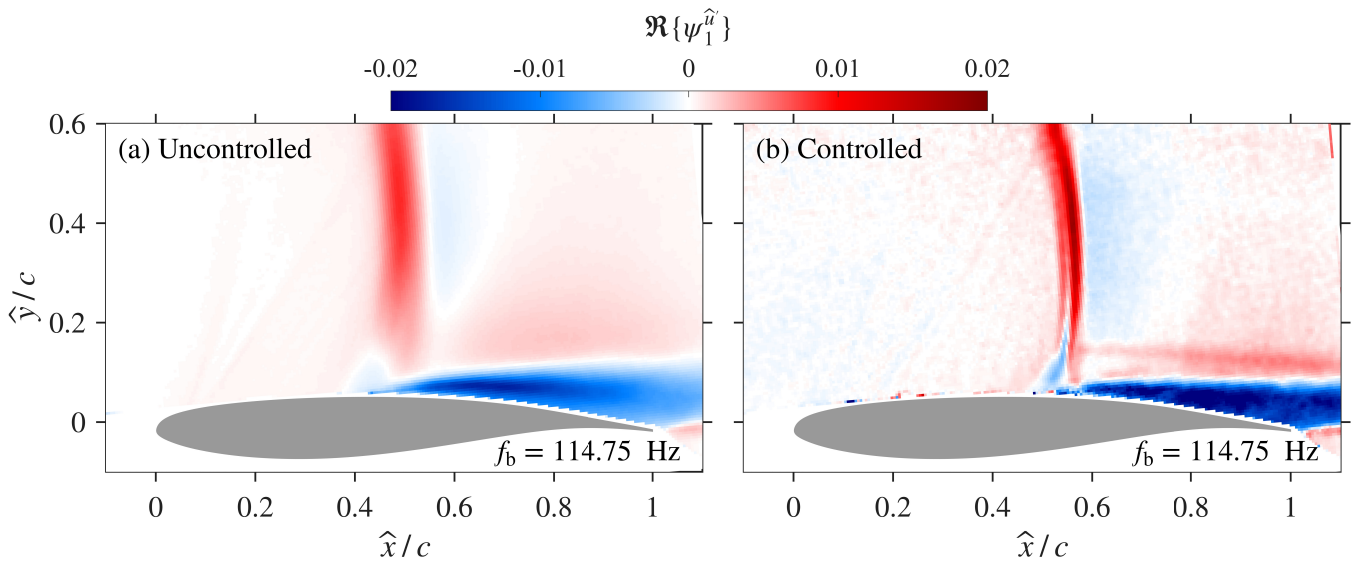


**Figure 15.** Real part of the leading SPOD mode shape of streamwise velocity fluctuations at  $f_b = 114.75$  Hz for the (a) uncontrolled and (b) controlled cases at  $p_{pl} = p_0$ .  $M_\infty = 0.756$ ;  $\alpha = 4.5^\circ$ .

This behaviour is further illustrated in Fig. 15, where the SPOD mode shapes at  $f = 114.75$  Hz are presented for both the uncontrolled (Fig. 15a) and AJVG-controlled interactions (Fig. 15b).

The application of control clearly reduces the amplitude of the shock-wave oscillation while simultaneously diminishing the extent of the reverse-flow region, thereby further demonstrating its favourable effect in suppressing transonic buffet.

## 6. Sensitivity of control to jet and aerodynamic conditions

Finally, this section examines the sensitivity of the control strategy to different jet-actuation and freestream conditions in order to obtain a broader understanding of buffet suppression across a wide parametric range. Figure 16 presents the spanwise-averaged shock-dynamics results for three jet-injection conditions ( $p_{pl} = p_0$ ,  $p_{pl} = 1.66p_0$ , and  $p_{pl} = 2.33p_0$ ) as a function of  $\alpha$  at fixed  $M_\infty = 0.752$  (Fig. 16a) and as a function of  $M_\infty$  at fixed  $\alpha = 5.0^\circ$  (Fig. 16b). The dominant buffet frequencies are indicated in the figure, where the marker size is proportional to the value of  $\overline{\text{PSD}}_{\text{max}}$ . Results for the uncontrolled baseline case under the same freestream conditions are also included, for which a clean insert without jet orifices was used.

As expected for transonic buffet, the dominant buffet frequency increases, while the corresponding  $\overline{\text{PSD}}_{\text{max}}$  values decrease with increasing  $\alpha$  and  $M_\infty$ . This behaviour indicates a gradual transition from peak-buffet conditions towards buffet-offset aerodynamic states. With the application of control, both the identified peak frequencies and their associated  $\overline{\text{PSD}}_{\text{max}}$  values are strongly suppressed across all investigated aerodynamic and jet-injection conditions.

These results demonstrate that (a) jet actuation effectively suppresses the buffet instability rather than merely shifting buffet to higher values of  $\alpha$  and  $M_\infty$ , and (b) a plenum pressure of  $p_{pl} = p_0$  is already sufficient for effective buffet mitigation, thereby eliminating the need for energy-intensive pressure-supply systems.

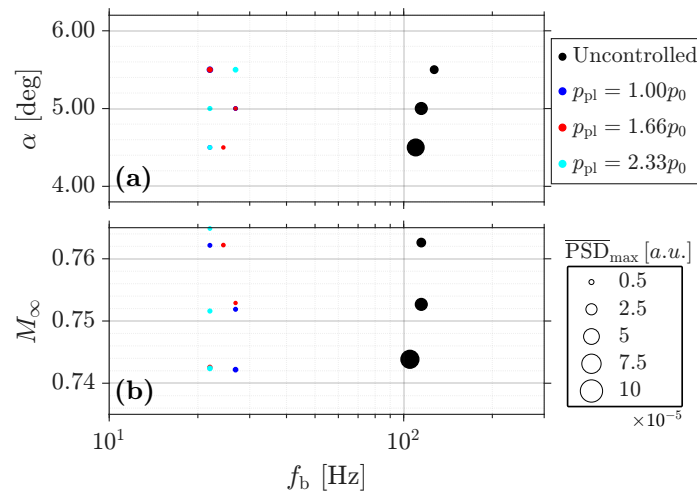


**Figure 16.** Shock dynamics as a function of (a) angle of attack ( $\alpha$ ) at a fixed  $M_\infty = 0.752$ , and (b) Mach number ( $M_\infty$ ) at a fixed  $\alpha = 5.0^\circ$  for the uncontrolled and AJVG-controlled interactions

To further emphasise the primary effects of varying injection pressure and incoming aerodynamic conditions, the change in the spanwise-averaged mean shock position ( $\Delta(\hat{x}/c)$ ) between the con-

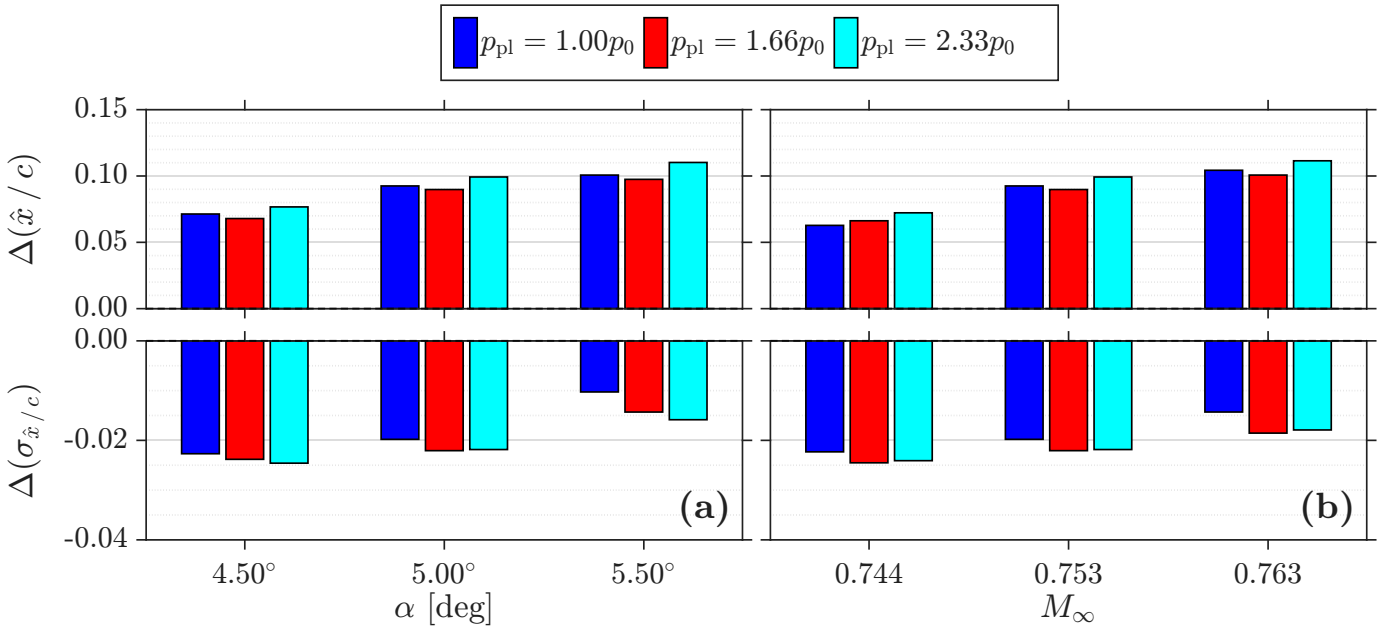


**Figure 17.** Comparison of change in shock position statistics for different jet-injection pressures as a function of (a)  $\alpha$  at  $M_\infty = 0.752$ , and (b)  $M_\infty$  at  $\alpha = 5.0^\circ$

trolled and uncontrolled cases, together with the corresponding change in the standard deviation of the shock motion ( $\Delta(\sigma_{\hat{x}/c})$ ), were extracted from the  $xz$ -PIV measurements using Eqs. 1 and 2. The resulting trends are presented in Fig. 17.

$$\Delta(\hat{x}/c) = [\hat{x}/c]_{\text{controlled}} - [\hat{x}/c]_{\text{uncontrolled}} \quad (1)$$

$$\Delta(\sigma_{\hat{x}/c}) = [\sigma_{\hat{x}/c}]_{\text{controlled}} - [\sigma_{\hat{x}/c}]_{\text{uncontrolled}} \quad (2)$$

As before, the results are presented as a function of  $\alpha$  at fixed  $M_\infty = 0.752$  in Fig. 17a and as a function of  $M_\infty$  at fixed  $\alpha = 5.0^\circ$  in Fig. 17b. Results for all three jet-injection pressures are included. Overall, the AJVGs are effective in shifting the spanwise-averaged mean shock position downstream while simultaneously reducing the standard deviation of the shock motion across all investigated cases. The downstream displacement of the shock corresponds to an increased extent of supersonic flow over the wing. Combined with the reduced reverse-flow regions observed downstream of the shock under controlled conditions, this suggests the potential for improved lift at identical aerodynamic conditions compared with the uncontrolled baseline case. Increasing  $\alpha$  and  $M_\infty$ , however, weakens the effectiveness of the jets in reducing shock unsteadiness at lower injection pressures. Nevertheless, the results show that this reduction in effectiveness can be recovered by increasing the jet-injection pressure, thereby highlighting the versatility of fluidic vortex generators for buffet control.

## 7. Summary and Conclusions

In this study, experiments were carried out to assess the effectiveness of air-jet vortex generators (AJVGs) in controlling the transonic buffet instability. For this purpose, a full-span wind-tunnel model based on ONERA's OAT15A geometry, with a chord length of  $c = 150$  mm, was manufactured from aluminium. A single row of 37 AJVGs was incorporated into the model at  $\hat{x} = 0.20c$  using a modular insert. The jet orifices have a diameter of  $d_{\text{jet}} = 0.70$  mm and are inclined spanwise at  $45^\circ$ . To interrogate the flow field, time-resolved particle image velocimetry (PIV) measurements at 5 kHz were carried out in the streamwise–wall-normal plane ( $xy$ -PIV) along the model centreline and in the streamwise–spanwise plane ( $xz$ -PIV) at a height of  $0.074c$  above the leading edge of the model at  $\alpha = 5.0^\circ$ .

Measurements of the uncontrolled transonic buffet reveal a distinct buffet mode at  $f_b = 112.30 \text{ Hz} \pm 2.44 \text{ Hz}$ , accompanied by large-amplitude shock motion and periodic growth and shrinkage of the downstream separated region. Side-wall effects from the wind tunnel were found to influence the two-dimensionality of the buffet phenomenon, with the strongest shock motion occurring near the model centreline and weakening slightly towards the spanwise edges.

With jet actuation at a plenum pressure equal to the wind-tunnel stagnation pressure, the flow field is substantially altered; at a chord-normal distance of  $\hat{y} = 0.1c$ , the mean shock position shifts downstream by nearly  $0.091c$ , while the standard deviation of the shock motion is reduced by approximately 68% (with respect to the uncontrolled case) for  $M_\infty = 0.756$  and  $\alpha = 4.5^\circ$ . In addition, the dominant buffet frequency observed in the baseline case is nearly suppressed completely, with a reduction of approximately 98% in the associated power spectral density. Characterisation of the reverse-flow area ( $A_{\text{rev}}$ ) shows that jet actuation increases the likelihood of smaller separated regions while simultaneously suppressing larger reverse-flow events. Furthermore, cross-correlation analysis between  $A_{\text{rev}}$  and the instantaneous shock position demonstrates that the periodic and coherent behaviour characteristic of uncontrolled buffet is replaced by intermittent and weakly coherent shock and separation dynamics under controlled conditions.

As a consequence, the mean flow field under controlled conditions exhibits no measurable persistent reverse-flow region, together with a substantial reduction in the rms of the velocity fluctuations. More importantly, the statistical flow-field contours do not reveal any major alteration of the outer flow due to jet actuation, thereby indicating that the favourable modification of buffet dynamics is primarily associated with changes in the near-wall flow behaviour. The dominant buffet mode of the uncontrolled case was also identified using spectral POD analysis and was found to be strongly attenuated under controlled conditions. The corresponding mode shapes reveal a substantial reduction in both the shock-wave oscillation amplitude and the extent of the reverse-flow region, further substantiating the beneficial influence of the jets on the buffet phenomenon.

Extending the analysis to higher Mach numbers ( $M_\infty$ ) and angles of attack ( $\alpha$ ) shows that AJVG actuation shifts the spanwise-averaged mean shock position downstream while simultaneously reducing the standard deviation of the shock motion across all investigated cases. Although the

effectiveness of the jets in suppressing shock unsteadiness decreases with increasing  $\alpha$  and  $M_\infty$ , this deterioration can be partially offset by increasing the jet-injection pressure.

In conclusion, the present investigation demonstrates that air-jet vortex generators constitute an effective and robust method for mitigating transonic buffet on the OAT15A aerofoil. The experimental results show that AJVG actuation substantially attenuates the dominant buffet mode, reduces shock-motion unsteadiness, and suppresses large-scale separated-flow dynamics. Furthermore, the findings indicate that the control mechanism operates primarily through favourable modification of the near-wall flow, whilst leaving the outer flow field largely unaffected. This suggests a beneficial aerodynamic outcome, potentially in the form of an improved lift-to-drag ratio under controlled conditions. Although the control authority diminishes at higher Mach numbers and angles of attack, part of this reduction can be compensated for by increasing the jet-injection pressure, highlighting the adaptability and practical potential of AJVG-based buffet control for future transonic aerodynamic applications.

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