Effects of Jet-to-Jet Spacing of Air-Jet Vortex Generators in Shock-Induced Flow-Separation Control

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Abstract
Experiments were carried out to assess the influence of spanwise spacing between adjacent orifices of an air-jet vortex-generator (AJVG) array on their separation-control effectiveness. The array was applied to a 24° compression-ramp-induced shock-wave / turbulent boundary-layer interaction at $M_\infty = 2.52$ and $Re_\theta = 8225$. Three spanwise oriented AJVG arrays of small, intermediate, and large jet spacings were studied. Their influence on the mean-flow organisation and turbulence quantities was assessed using flow visualisations and planar particle image velocimetry across multiple measurement planes. The streamwise vortices induced by the AJVGs incited different control effects depending on the degree of interaction between adjacent vortices. The array with intermediate spacing achieved the most favourable effects with reductions in separation length and area of about 25% and 52%, respectively. This reduction was brought about by the formation of stable, interacting streamwise-elongated coherent vortices downstream of jet injection and the associated entrainment of high-momentum fluid. The smallest jet spacing incites vortex interactions to adverse strength, breaking up the coherent structures and even increasing separation. The AJVGs with the largest spacing display characteristics similar to single jets in crossflow, with only a local modification of the separation region. Turbulent quantities are amplified both by the jets and the separation-inducing shock; AJVG control reduces the amplification across the shock-wave/boundary-layer interaction and the intermediate jet spacing is most effective also here.

Keywords Shock-wave/boundary-layer interaction · Air-jet vortex generators · Flow control · Jet-to-jet spacing

1 Introduction
Aerospace-transportation systems and air-breathing propulsion systems are subjected to persistent occurrence of shock-wave/boundary-layer interactions (SWBLIs), which can be a crucial factor when designing transonic airfoils, supersonic engine inlets, over-expanded
rocket engine nozzles, control surfaces of hypersonic vehicles, et cetera. The boundary-layer can separate from the surface, when it is subjected to a strong pressure rise imposed by the shock wave. This phenomenon can adversely impact the aerodynamic performance of the vehicle, incite thermal and pressure loads on the surface, promote turbulence amplification etc. A common feature in SWBLIs is the low-frequency unsteadiness of the shock/separation-bubble system (Clemens and Narayanaswamy 2014), which can be a source of pronounced vibrations when coupled to the structural resonant frequencies. Therefore, SWBLIs are extensively investigated in literature, both experimentally and using high-fidelity simulations, in an attempt to understand its structure and dynamics. The results are well-documented in a number of review articles (Clemens and Narayanaswamy 2014; Dolling 2001; Delery and Marvin 1986; Smits and Dussauge 1996; Andreopoulos et al. 2000; Babinsky and Harvey 2011; Dupont et al. 2006; Gaitonde 2015).

To mitigate the associated adverse effects, several active (Harloff and Smith 1996; Saito et al. 2008; Narayanaswamy et al. 2012) and passive (Qin et al. 2007; Pearcey 1961; Lin 2002; Holden and Babinsky 2007; Blinde et al. 2009; Schreyer et al. 2011) flow-control strategies have been proposed and studied. These methods aim at reducing or preventing flow separation and modifying the unsteadiness due to SWBLIs. One notable approach is to use small, sub-boundary-layer mechanical vanes or ramps to deflect the incoming boundary-layer and generate streamwise vortices downstream (see e.g. Babinsky et al. 2009). These streamwise vortices alter the boundary-layer characteristics by redistributing the momentum within the boundary-layer and bringing the high-momentum fluid from the outer regions of the boundary-layer closer to the wall. This reduces the boundary-layer shape factor and enhances its resistance to separation. In addition to reducing the separation length, micro-ramps have also been shown to stabilise the shock motion and reduce its unsteadiness (Blinde et al. 2009; Verma et al. 2012; Giepman et al. 2014). Despite their favourable influence on shock-induced separation, their physical presence on the surface generates parasitic drag. Moreover, their geometries are optimised for particular flow conditions and they cannot be switched off when not needed—which may be a large fraction of the flight trajectory.

To overcome these disadvantages, the focus has slowly started shifting towards air-jet vortex generators (AJVGs), where small air jets injected into the boundary-layer act as vortex generators. AJVGs were introduced by Wallis (1952) and first applied to suppress shock-induced separation by Wallis and Stuart (1958). The effectiveness of AJVGs is similar to that of traditional mechanical vortex generators (VGs) (Pearcey 1961; Pearcey et al. 1993). This is unsurprising, as mechanical micro-VGs and AJVGs share a similar working principle. The interaction of the injected jets with the incoming crossflow results in the formation of a system of streamwise vortices (Sebastian et al. 2020). As for mechanical VGs, these streamwise vortices redistribute the momentum within the boundary-layer and increase the momentum close to the wall, thereby also reducing separation.

The effectiveness of separation control is influenced by a number of parameters. Earlier studies on AJVG jet-injection orientation (Wallis 1952; Wallis and Stuart 1958; Johnston and Nishi 1990) observed better effectiveness for arrays of spanwise-inclined jets in comparison to transversely-injected jets. A spanwise orientation of air jets was first proposed and tested by Wallis and Stuart (1958) to control shock-induced boundary-layer separation at transonic flow conditions. Johnston and Nishi (1990) further tested air jets of various orientations and highlighted the improved effectiveness of skewed jets. This prompted several investigations where a spanwise-inclined orientation of air-jets was adopted to successfully control shock-induced separation in the transonic and supersonic flow regimes (Szwaba 2005, 2013, 2011; Souverein and Debiève
2010; Ramaswamy et al. 2020; Ramaswamy and Schreyer 2021). Subsequent large-eddy simulations (LESs) of an analogous spanwise-inclined jet configuration in a supersonic crossflow (Sebastian et al. 2020)—which have been conducted to better understand the flow physics behind the improved control effectiveness—attributed the favourable performance to lower jet-penetration depths and a delayed vortex lift-off downstream. Investigations of the influence of jet-orifice diameter ($d_{jet}$) (Szwaba 2013) have shown that small orifice diameters of less than 25% of the boundary-layer thickness ($\delta$) are most effective. Furthermore, the jet-to-freestream momentum flux ratio (J), which can be controlled by varying the air-jet injection pressure ratio ($APR = P_{oj}/P_o$) plays a prominent role in characterising the AJVG performance. Studies exploring the influence of injection pressure (Verma and Manisankar 2012; Verma et al. 2015; Ramaswamy et al. 2020) and hence the momentum-flux ratio have established that an optimal control effectiveness can be attained with a jet-injection pressure ($P_{oj}$) equal to or slightly greater than the wind tunnel stagnation pressure ($P_o$); i.e., at $APR \approx 1$. Prior to such parametric studies, Szwaba (2005) also showed that AJVGs operating at $APR = 1$ showed an improved performance. This simplifies a potential AJVG installation, nullifying the necessity for energy-intensive pressure-supply systems.

For deeper insight into the flow organisation around AJVGs—and thereby its impact on separated flow—literature on the jet-in-crossflow phenomenon is helpful. The flow topology and vortical structures induced by single jets in supersonic crossflow have been widely investigated [see Mahesh (2013) for a summary]. Sebastian et al. (2020) reported the only study (to the authors’ knowledge) on the flow field around a single spanwise-inclined jet in a supersonic crossflow, investigating a configuration similar to the arrangement used for AJVG control described above. They observed the formation of an asymmetric system of vortices, dominated by a major counter-rotating vortex pair, where the clockwise-rotating vortex (induced above the jet) is stronger and sustains for a longer downstream distance. Also, investigations of arrays of jets in supersonic crossflow, which are of particular relevance to our investigation, are scarce. Ali and Alvi (2015) studied the flow fields around transversely-injecting jet arrays into a supersonic crossflow at Mach 1.5 using particle image velocimetry (PIV). They observed a strong dependence of the strength of the jet-induced shock and the streamwise vorticity downstream of injection on the spacing between the jets in the array. Counter-rotating pairs of streamwise vortices are generated downstream of each jet orifice. The induced vortex pairs remain coherent and maintain a spanwise extent in the order of the spacing between adjacent jets for spacings larger than $\sim 10d_{jet}$. For small jet spacings ($\sim 5d_{jet}$), the spacing is smaller than the spanwise extent of the counter-rotating vortex pairs, leading to strong jet/jet interactions and subsequent breakup and diffusion of vorticity (Ali and Alvi 2015).

Flow-visualization-based studies on separation control with AJVG arrays (Ramaswamy et al. 2020; Verma and Manisankar 2019) (which use spanwise-inclined injection) provided evidence of similar variations in 3D vortex structure for varying jet spacing and reported the direct consequences of such variations on the flow-control effectiveness. At very large jet spacings ($\sim 25d_{jet}$), the jets in the array seem to not interact with their respective neighbours and show characteristics equivalent to single jets in crossflow. The control effectiveness in such configurations was observed to be quite weak. When the jet spacing is reduced to moderate lengths ($\sim 7 - 13d_{jet}$), the interaction between the jets improves and consequently results in a better control effectiveness [e.g. $\sim 10\%$ separation-length reduction for $8d_{jet}$ (Ramaswamy and Schreyer 2021)]. When the jets are placed too close together ($\sim 4d_{jet}$), however, the control effectiveness decreases and the separation length even increases compared with the uncontrolled baseline interaction.
An improved understanding of the flow around spanwise-inclined AJVGs with varying jet-spacings, as well as their effects on shock-induced separation, is essential to better explain the observed differences in control effectiveness. It is of course also a prerequisite for the development of improved control setups. To achieve this objective, direct velocity measurements with detailed turbulence data along the entire length of the interaction domain are crucial, yet notably scarce in literature (Souverein and Debiève 2010; Ramaswamy and Schreyer 2021). With this incentive, we employ 2D-2C PIV at different streamwise/wall-normal and streamwise/spanwise planes to investigate the effect of AJVG arrays with three different jet spacings on a 24° compression-ramp-induced SWBLI.

The experimental setup and conditions are provided in Sect. 2, followed by a discussion of the measurement uncertainty in Sect. 3. The results are presented and discussed in Sect. 4, followed by concluding remarks in Sect. 5.

## 2 Experimental Setup

### 2.1 Trisonic Wind Tunnel Facility

The experiments for this study were conducted in the trisonic wind-tunnel facility, equipped with the supersonic test section, at the Institute of Aerodynamics, RWTH Aachen University. It is an intermittently operating in-draft facility driven by 4 × 95 m³ vacuum tanks, which is supplied by a 165 m³ reservoir balloon filled with dry air. The stagnation conditions in the balloon correspond to the laboratory ambient conditions. Upon disengaging the fast-acting valve, a stable flow time of ∼ 2.5 seconds is ensured in the test section. Optical access to the 400 mm × 400 mm test section is provided by three circular quartz windows - two on each side of the test section and one on the top wall. The chosen free-stream Mach number $M_\infty = 2.52$ corresponds to a free-stream unit Reynolds number of $Re_\infty = 9.62 \times 10^6 m^{-1}$. The free-stream properties are summarised in Table 1, where $U_\infty$ is the free-stream velocity and $P_o$ and $T_o$ are the stagnation pressure and temperature of the facility, respectively.

### 2.2 Flat-Plate and Compression-Ramp Model

A 24° compression-ramp was installed 69.5δ downstream of the leading edge of a flat-plate model that spans the entire width of the wind-tunnel test section (see Fig. 1). A uniform turbulent boundary-layer with a thickness of $\delta = 10.4$ mm at $4.5\delta$ upstream of the ramp-corner (Ramaswamy and Schreyer 2021) was ensured by placing a zig-zag trip ∼ 1δ downstream of the leading edge of the flat plate. The maximum height of the ramp was restricted to 16 mm to prevent wind-tunnel blockage and breakdown of the flow, thereby resulting in a ramp-surface length of 3.78δ.

| $M_\infty$ | $U_\infty$ | $Re_\infty$ | $P_o$ | $T_o$ | Humidity |
|-----------|------------|-------------|-------|-------|----------|
| 2.52 ± 0.6% | 581.2 m/s | $9.6 \times 10^6 m^{-1} \pm 2.8\%$ | 99.49 kPa ± 1.42% | 297 K ± 1.15% | 4 – 6% |

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The AJVG array is installed 7.69δ upstream of the ramp corner via a modular insert. The air jets are injected through circular orifices with diameters of $d_{jet} = 0.1\delta$ in the AJVG array. The jets are pitched at an angle of $\theta = 45^\circ$ with respect to the flat-plate surface and skewed at an angle of $\phi = -90^\circ$ with respect to the freestream, resulting in a purely spanwise injection. Fixing the origin of the coordinate system at the ramp-corner along the model centreline, this implies that the jets are injected along the negative Z axis. This spanwise inclination of the AJVGs was adopted due to its favourable performance for flow control purposes (see Sect. 1) and for comparability with earlier studies (Wallis and Stuart 1958; Souverein and Debiève 2010; Szwaba 2005, 2011, 2013; Ramaswamy and Schreyer 2021). The air-jets are supplied with the institute pressure supply via a plenum inside the flat plate and the jet-stagnation conditions were monitored using a WIKA S-20 pressure transducer and a J-type thermocouple. For the measurements of the baseline case, a clean insert without any holes was used.

In the present study, we focus on AJVGs with three different jet-to-jet spacings: $D = 4d_{jet}$, providing a case with very strong jet/jet interactions; $D = 25d_{jet}$ with very weak jet/jet interactions; and $D = 8d_{jet}$, the most control-effective jet spacing among the tested cases. These spacings were selected on the basis of an earlier parametric study Ramaswamy et al. (2020) and each represents the most distinct case of its respective category. Note that the measurements of the 25$d_{jet}$ inlet were performed on an AJVG array with a jet spacing of $D = 12.5d_{jet}$, where alternate holes were securely plugged from within the plenum. The flow field around the plugged holes was verified to not show any jet-induced structures, with and without cross flow. For all tested cases, the jet-injection pressure was equal to the wind-tunnel stagnation pressure, i.e. $APR = 1$. A schematic of the wind-tunnel model with the installed AJVG module is shown in Fig. 1 and the AJVG parameters with the relevant jet-properties are summarised in Table 2. The spacing between the orifices is used to label the cases; D4, D8, and D25 correspond to AJVG cases with $D = 4d_{jet}$, $D = 8d_{jet}$ and $D = 25d_{jet}$, respectively.
2.3 Flow Measurement and Data Processing Techniques

Prior to the detailed velocity-field measurements with PIV, flow visualizations were conducted to get an overview on the flow topologies in the investigated cases. Surface-flow features were tracked using an oil-flow visualisation technique, utilizing an oil mixture comprising of hydraulic oil, oelic acid and TiO$_2$ particles. The transient oil-images were recorded using a PCO pixelfly CCD camera at a resolution of $\sim 0.2$ mm/px. The flow visualisations reported in this article augment our previous investigation (Ramaswamy et al. 2020), where visualisation tools were used to study similar AJVG configurations, albeit with a reduced number of jet-orifices ($n = 15$) per array.

Two-dimensional two-component PIV measurements were carried out at selected locations along streamwise/wall-normal (WN planes) and streamwise/spanwise planes (WP planes).

For the WN-PIV, a Litron NANO-L pulsed Nd:YAG laser with a maximum single-pulse energy of 200 mJ was used to generate a thin light sheet of $\sim 1$ mm. The laser light illuminates the flow seeded with di-ethyl-hexyl-sebacate (DEHS), which was introduced into the reservoir balloon, after passing though a cyclone separator, prior to each run. Measurements of the particle diameter ($d_p$) and the corresponding response time ($\tau_p$) via an oblique shock-wave test, yielded $d_p = 0.7$ μm and $\tau_p = 2.6$ μs (Marquardt et al. 2019). In general, a particle Stokes number of $St < 1$ is required for the PIV particles to faithfully track the turbulent structures. The Stokes number for the current measurement is $\tau_p U_\infty / \delta = 0.14$, which according to Samimy and Lele (1991), should result in a slip velocity of less than 1.4%. The illuminated particles are imaged using four FlowSense EO 11M cameras (C1 - C4), arranged such that always two cameras observe a common field of view (FOV) (see Fig. 2b). This configuration was chosen to improve the acquisition rate and to record at high spacial resolution. Each FlowSense camera is equipped with a 4008 px $\times$ 2672 px CCD sensor and a Tamron SP AF 180mm f/3.5 objective. The camera pairs on each side of the wind tunnel are aligned such that the two cameras in each pair observe the same field of view. The setups use beam-splitter cubes and are arranged to within $\sim 5$ px accuracy. One pair of cameras (C3 & C4) records the jet-injection region and the subsequent modification of the boundary-layer downstream (FOV2 in Fig. 2a, $-9.8\delta \leq x \leq 0.7\delta$), while the other pair (C1 & C2) records a field of view farther downstream, focusing on the SWBLI and the related flow separation (FOV1 in Fig. 2a, $-4.5\delta \leq x \leq 4.5\delta$). This results in a field of view of $9\delta \times 6\delta$ (FOV1) at a resolution of 43 px/mm for cameras C1 and C2 and a slightly larger field of view of $10.5\delta \times 7\delta$ (FOV2) at 36.5 px/mm for cameras C3 and C4. The total effective and common field of view thus amounts to $12\delta \times 6\delta$.

FlowSense cameras record double-frame images at a maximum of 3Hz. To increase the acquisition rate, two sets of cameras (C1 & C3 and C2 & C4, respectively) were triggered.

| AJVG | Jet spacing (D) [mm] | No. of jets (n) | $\theta$ [deg] | $\phi$ [deg] | APR ($P_{oj}/P_o$) [-] | Momentum-flux ratio J [-] |
|------|---------------------|-----------------|---------------|-------------|---------------------|---------------------|
| D4   | 4                   | 23              |               |             |                     |                     |
| D8   | 8                   | 23              | 45            | $-90$       | 1                   | 1.46                |
| D25  | 25                  | 7               |               |             |                     |                     |

Table 2 AJVG geometrical and flow properties
alternately, with the laser pulse firing during every camera pair’s acquisition window. This doubles the effective acquisition rate of the system to 6 Hz.

The WN-PIV measurements were carried out at two spanwise locations (WN1 and WN2, see Fig. 2b), located at $z = 0D$ and $z = 1.5 D$, respectively. WN1 was aligned along the centreline of a jet orifice and WN2 midway between two orifices. Ensembles of ~700 – 1000 image pairs were obtained for each test case. Due to the functioning principle of the wind tunnel, these sets were collected over a span of multiple days.

A second PIV campaign, focusing on wall-parallel planes, was conducted to get insight into the behaviour of the streamwise vortex structures downstream of each AJVG array. For this campaign, a Quantronix Darwin-Duo 100 Nd:YLF laser was operated at 1000 Hz with a maximum pulse energy of 30 mJ per oscillator. The beam was shaped into a laser sheet of ~1.5 mm thickness and illuminated a plane in the streamwise/spanwise direction as depicted by green lines in Fig. 2a. The laser was synchronised with a Photron SA.5 high-speed camera (C5) placed above the wind tunnel, using an ILA high-speed synchronizer. The camera is equipped with a 1024 px × 1024 px CMOS sensor and covered a field of view of $8.86 \times 8.86$ (ranging ~3.6D in the spanwise direction for the largest D25 AJVG) with small constraints imposed by the top-wall optical access. A black-level correction was applied to the CMOS sensor prior to each recording to mitigate fixed-pattern noise. It has to be mentioned that, despite the ‘high-speed’ acquisition, most characteristic time scales of the flow are orders of magnitude smaller, and hence the acquired data sets should not be considered as time-resolved.

Measurements were carried out at two wall-parallel planes, WP1 and WP2 at $y = 0.24\delta$ and $y = 0.69\delta$, respectively. WP1 corresponds to the wall-normal location of maximum streamwise vorticity of a single spanwise-oriented jet in similar flow conditions, as obtained from Sebastian et al. (2020). WP2 is located in the outer region of the boundary-layer and is therefore comparable to the wall-parallel PIV measurements carried out by Blinde et al. (2009) on a micro-ramp array configuration (measured at $y = 0.6\delta$). Ensembles of ~1500 image pairs were obtained for all test cases at both wall-parallel planes.

The images obtained by both the WN-PIV and WP-PIV campaigns were processed with the software Dantec DynamicStudio 6.4 using an adaptive PIV algorithm. Final interrogation window sizes of $32px \times 32px$ at 75% overlap and $16px \times 16px$ at 50% overlap were
used for the WN-PIV and WP-PIV datasets, respectively. A universal outlier detector (Westerweel and Scarano 2005) with $\sigma = 2.5$ in a $5 \times 5$ neighbourhood and a constrain on the correlation peak ratio (1.15) were set to identify and replace spurious vectors. For all test cases, over 90% of the vectors were deemed valid. Fluctuations in wall position and total temperature, and thereby the free-stream velocity, were corrected prior to any vector processing/post-processing [see Ramaswamy and Schreyer (2021) for details]. Additionally, vectors in a transient series that were more than three scaled median absolute deviations, were discarded when calculating the mean and turbulent statistics. The PIV set-up and processing parameters are summarised in Table 3.

3 Measurement Uncertainties

Measurements of the freestream and stagnation quantities, as well as the velocities obtained from PIV, can be subjected to statistical or systematic uncertainties, which must be quantified to enable the accurate interpretation of results. In this section, we discuss the sources of uncertainties relevant for our study. All reported uncertainties are based on a 95% confidence interval.

Due to the intermittent working principle of the wind-tunnel facility and the necessity to collect data in multiple runs over several days, the freestream properties (see Table 1) are subjected to minor variations. The flow Mach number was relatively stable with not more than 0.6% variation. The stagnation temperature and stagnation pressure, however, fluctuate with the ambient conditions and come with uncertainties of 1.15% and 1.42%, respectively. This translates to a unit-Reynolds-number uncertainty of 2.8%.

The AJVG-plenum pressure was maintained equal to the wind-tunnel stagnation pressure, but small fluctuations exist due to non-uniformities in the institute pressure supply. Assuming statistical independence of uncertainties, this resulted in uncertainties of 2.96% and 2.1% for APR and J, respectively.

| Table 3 | PIV parameters |
|---------|----------------|
| Parameter | WN - PIV | WP - PIV |
| Test case | WN1 | WN2 | WP1 | WP2 |
| Measurement plane | $xy$ plane | $xz$ plane | $y = 0.24\delta$ | $y = 0.69\delta$ |
| Measurement locations | $z = 0\,D$ | $z = 1.5\,D$ | | |
| Laser | Litron NANO-L | Quantronix Darwin-Duo 100 | | |
| Camera | 4 $\times$ FlowSense EO 11M | Photron FASTCAM SA.5 | | |
| Lens | Tamron 180mm $f/3.5$ objective | | | |
| Pulse separation | $1\mu s$ | $4\mu s$ | | |
| Digital resolution | 43 px/mm | 36.5 px/mm | 11.1 px/mm | |
| Effective field-of-view | $12\delta \times 6\delta$ | $8.8\delta \times 8.8\delta$ | | |
| Effective acquisition rate | $6Hz$ | $1000Hz$ | | |
| Final interrogation window | $32px \times 32px$ | $16px \times 16px$ | | |
| Overlap factor | 75% | 50% | | |
| Ensemble size | $\sim 700 - 1000$ | $\sim 1500$ | | |
Statistical uncertainties in the estimation of mean and root-mean-squared (rms) quantities due to the finite number of samples, was evaluated using the variance estimate of Benedict and Gould (1996). The statistical uncertainties of all velocity components are summarized in Table 4. For the WN-PIV, the uncertainty values are reported as a percentage of their respective statistical component at the ramp corner at a distance from the wall of approximately half the bubble height; for the WP-PIV, the reported values are given at the centreline, upstream of the separation shock. These statistical uncertainties are based on the assumption that the particles accurately follow the flow. In reality, the particles have a small, finite response time, as measured by an oblique shock test (see Sect. 2.3). Such oblique shock tests overestimate the particle response to weak disturbances; the response time to boundary-layer turbulence thus is expected to be higher for the current measurements and Mach number (Williams et al. 2015). These larger uncertainties are mostly associated with the wall-normal and spanwise fluctuation measurements in the incoming undisturbed boundary-layer. Downstream of the shock wave, the response time improves due to an increase in flow density and viscosity, as well as the expected decrease in energy-containing frequency-content of the flow (Schreyer et al. 2018).

The WP-PIV measurements were carried out with a high-speed laser, featuring a long pulse width ($\sim 200\text{ns}$) compared with the low-speed laser used in the WN-PIV measurements ($\sim 7\text{ns}$). Variations in the laser-intensity profile over time between the two cavities of the high-speed laser thus introduced a noticeable discrepancy between the pulse-separation time set by the synchroniser and the effective pulse-separation time, which resulted in a systematic error of $\sim 3\%$ in the mean velocities. To account for this error, the procedure adopted by Marquardt et al. (2019) was followed to correct the $\sim 40\text{ns}$ shift in pulse-separation time, thereby reducing the final uncertainty to less than $\sim 1\%$.

Additionally, the finite thickness of the light sheet at the WP1 measurement plane, coupled with the large velocity gradients in the wall-normal direction that are expected at this location, lead to about $5\%$ overestimation of the mean velocity. At WP2, however, the lack of high wall-normal gradients subdues the averaging effects, and mean-velocity matches that of the WN-PIV at this location.

| Test case | U  | V  | W  | u' | v' | w' | u'v' |
|-----------|----|----|----|----|----|----|------|
| Baseline  |     |    |    |    |    |    |      |
| WN        | 1.19 | 0.45 |    | 4.69 | 5.21 |    | 27.95 |
| WP1       | 0.52 | –    | 0.14| 10.3 | 3.68 |   | –    |
| WP2       | 0.15 | –    | 0.11| 3.85 | 3.93 |   | –    |
| D4        |     |    |    |    |    |    |      |
| WN1       | 1.23 | 0.57 |    | 5.10 | 5.54 |    | 30.79 |
| WN2       | 1.35 | 0.62 |    | 5.41 | 5.64 |    | 38.70 |
| WP1       | 0.65 | –    | 0.40| 3.69 | 3.83 |   | –    |
| WP2       | 0.23 | –    | 0.14| 3.78 | 4.06 |   | –    |
| D8        |     |    |    |    |    |    |      |
| WN1       | 1.09 | 0.43 |    | 3.93 | 4.29 |    | 28.11 |
| WN2       | 1.13 | 0.48 |    | 4.34 | 5.13 |    | 36.19 |
| WP1       | 0.33 | –    | 0.25| 3.88 | 3.92 |   | –    |
| WP2       | 0.90 | –    | 0.47| 3.80 | 3.99 |   | –    |
| D25       |     |    |    |    |    |    |      |
| WN1       | 0.98 | 0.44 |    | 4.58 | 5.00 |    | 35.24 |
| WN2       | 1.34 | 0.51 |    | 4.41 | 5.08 |    | 37.01 |
| WP1       | 0.52 | –    | 0.33| 5.29 | 5.84 |   | –    |
| WP2       | 1.08 | –    | 0.50| 3.26 | 3.71 |   | –    |
4 Results and Discussions

We will first present the incoming undisturbed boundary-layer (Sect. 4.1) and the uncontrolled baseline compression-ramp interaction (Sect. 4.2). We will then discuss the effects of jet spacing in AJVG flow control on the control effectiveness (Sect. 4.3) and flow organisation downstream of injection (Sect. 4.4). Finally, the modifications of the mean flow and turbulence will be discussed in Sects. 4.5 and 4.6, respectively.

4.1 Undisturbed Incoming Turbulent-Boundary-Layer

For the undisturbed, adiabatic, and fully-developed turbulent boundary-layer, we show the mean velocity measured at \( x = -4.5\delta \) upstream of the ramp corner in inner variables (Fig 3a) and the fluctuating components in Morkovin scaling (Morkovin 1962) (Fig 3b), and compare them with literature. The van-Driest transformation (Driest 1951) was used for the mean velocity to account for compressibility effects. The main boundary-layer parameters are summarised in the text box in Fig. 3a. The mean streamwise velocity agrees well with the log-law until \( y^+ = 72 \), with log-law constants of \( \kappa = 0.40 \) and \( B = 5.0 \). The Clauser chart method [see White (2006)] was used to estimate the friction velocity and skin-friction coefficient to \( u_\tau = 25 \text{ m/s} \) and \( C_f = 0.0017 \), respectively. The compressible displacement and momentum thicknesses are \( \delta^* = 2.66 \text{ mm} \) and \( \theta^* = 0.85 \text{ mm} \), respectively, thus giving a momentum-thickness-based Reynolds number of \( Re_{\theta^*} = 8225 \). The mean velocity profile from a large eddy simulation (Sebastian et al. 2020) at similar conditions (\( M = 2.5 \) & \( Re_{\theta^*} = 7000 \)) is shown in Fig 3a for comparison, and the profiles agree well. The wake component for \( y^+ > 300 \) corresponds to a wake parameter of \( \Pi = 0.55 \) and follows the characteristics of the law of the wake (Coles 1956), which is in good agreement with the reports of Fernholz and Finley (1980).

The rms streamwise (\( \sqrt{u'^2} \), solid symbols) and wall-normal (\( \sqrt{v'^2} \), open symbols) velocity fluctuations obtained from WN-PIV and the rms streamwise (blue symbols) and spanwise (\( \sqrt{w'^2} \), red symbols) velocity fluctuations from WP-PIV at \( x = -4.5\delta \) are plotted in Fig. 3b. The fluctuations are normalised with the friction velocity obtained from Fig. 3a and scaled with \( \sqrt{\rho/\rho_w} \) (Morkovin 1962) to allow for comparisons with incompressible data. Turbulent-boundary-layer measurements of Klebanoff (1955) (\( Re_{\theta^*} = 7447 \)), DeGraaff and Eaton (2000) (\( Re_{\theta^*} = 5200 \)), Elena and Lacharme (1988) (\( M_e = 2.32 \) &

Fig. 3 Undisturbed boundary-layer assessment of (a) mean and (b) turbulence quantities
Re_{\theta} = 4700), and Marquardt et al. (2019) (M_e = 2.45 & Re_{\theta} = 7011), as well as the LES of Sebastian et al. (2020) (M = 2.5 & Re_{\theta} = 7000) are included for comparison. The density-ratio used to scale the velocity fluctuations was obtained using the mean velocity profile and the adiabatic Crocco-Busemann relation (see White (2006)), corresponding to a recovery factor of r = 0.89. The measured velocity fluctuations show satisfactory agreement with literature and with earlier measurements in the same facility (Marquardt et al. 2019). The wall-normal velocity fluctuations, however, are slightly under-predicted, especially close to the wall, due to challenges with particle frequency response as discussed in Sect. 3. No reference data have been included for the spanwise fluctuating components; their magnitude is compatible with that of the wall-normal velocity fluctuations, though, as expected for canonical supersonic turbulent boundary-layers (Guarini et al. 2000). The WP-PIV measurements agree satisfactorily with the WN-PIV results. The velocity fluctuations are slightly underpredicted close to the wall (WP1) due to difficulties associated with accurate measurement of fluctuating components owing to large pixel size of the high-speed cameras and an elongated temporal profile of the high-speed laser. We will therefore only discuss the mean velocities from WP-PIV in the remainder of the manuscript.

4.2 Baseline Shock-Wave/Turbulent-Boundary-Layer Interaction

To be able to distinguish the effects of AJVG control, we first discuss the topology of the fully-separated shock-wave/turbulent-boundary-layer interaction induced by a 24° compression-ramp without the influence of the AJVGs. Fig. 4 shows the normalised mean streamwise (Fig. 4a, c), wall-normal (Fig. 4b), and spanwise (Fig. 4d) velocity distributions at the WN and WP measurement planes. Additionally, the normalised wall-normal component of vorticity ($\omega_\gamma$) is also shown in Fig. 4e. As the turbulent boundary-layer approaches the ramp corner, it experiences a large adverse pressure gradient and separates from the

![Fig. 4](image-url) Normalised streamwise (a,c), wall-normal (b), spanwise (d) velocities and wall-normal vorticity (e) of the baseline interaction. Streamlines are superimposed in a, streamwise velocity profiles in the separation zone are superimposed in b. Red dashed line (a and b): dividing streamline. Black dashed line (c–e): position of the surrogate separation shock.
surface (see Fig. 4a), which leads to a large region of reverse flow (see streamlines in Fig. 4a and velocity vectors in Fig. 4b). The average separation area in the streamwise/wall-normal plane is $A_{sep} = 0.59\delta^2$. The contour of zero velocity, which marks the boundary of the reverse flow, is highlighted in red dashed lines in Fig. 4a, b. The boundary-layer separates from the flat plate at approx. $2.5\delta$ upstream of the ramp surface (i.e. approx. $1.5\delta$ downstream of the extrapolated location of the mean separation-shock foot ($x = -4\delta$)). The separated shear layer reattaches on the inclined ramp surface at approximately $1.1\delta$ downstream of the ramp corner, measured along the inclined ramp-surface. The reattached flow further develops on the ramp surface, but does not reach equilibrium conditions until it reaches the expansion corner at $x = 3.5\delta$.

Until the flow encounters the separation-shock—which deflects the flow in the wall-normal direction—no significant wall-normal velocity component is observed (see Fig. 4b). A nearly 2D arrangement of the interaction is confirmed by the streamwise-velocity contours in Fig. 4c, measured along the wall-parallel planes WP1 and WP2. To illustrate the spanwise behaviour of the separation line, we show a surrogate shock position along the spanwise length, defined by Ganapathisubramani et al. (2009) as the position where the local velocity reaches a value of $U_{u} - 4\sigma_u$, where $U_u$ and $\sigma_u$ are the line-averaged mean and standard deviation of streamwise velocity in the upstream boundary-layer (see black dashed lines in Fig. 4c–e). The results show a nearly 2D shock position for the baseline case along the spanwise direction. In this baseline interaction, variations in the spanwise velocity component are negligible (see Fig. 4d). Maximum spanwise velocities of $\sim 2\%$ of $U_\infty$ further highlight the 2D structure and absence of any significant corner effects along the entire spanwise width of the measurement domain. For further details on the structure and organisation of the baseline SWBLI, refer to Ramaswamy and Schreyer (2021).

We found evidence of weak streamwise-elongated structures in the upstream boundary-layer of the baseline interaction, with a spanwise spacing of $\sim 0.5\delta$. The maximum vorticity magnitude is only $\sim 1/10$th of a typical jet-induced vorticity magnitude (see. Fig. 6). These structures differ from the superstructures [see e.g. Adrian et al. (2000)] that appear in the form of high- and low-momentum large-scale coherent structures in the log-layer. The standard deviation of mean streamwise velocity in the spanwise direction for the current measurement is $\sim 0.7\%$ and is comparable with the results of LES of a similar boundary-layer (Sebastian et al. 2020). We think that these observed structures are a remnant of the forced tripping of the boundary-layer by the zig-zag trip; such trips have been shown to weakly impact the development of compressible turbulent boundary-layers (Williams and Smits 2017; Bross et al. 2018). As the boundary-layer mean and turbulent statistics show good agreement with literature and numerical simulation under similar conditions (see Sect. 4.1), these weak structures are not expected to influence the interpretation of the results. A detailed analysis onto their origin and the effect of the tripping device is currently under-way.

4.3 Effect of Jet-Spacing on Control Effectiveness

The effects of three air-jet vortex-generator (AJVG) arrays with different jet spacings ($D=4d_{jet}$, $8d_{jet}$, and $25d_{jet}$) on the compression-ramp interaction are illustrated in the oil-flow visualisations shown in Fig. 5a. The baseline interaction (BC) is also included for comparison. The images represent a top view of the interaction region, with the flow direction from top to bottom. In the uncontrolled interaction, the oil accumulates close to the separation-shock foot due to large adverse pressure gradients on the surface, while
a series of saddle points are observed on the inclined ramp surface, marking the interface between streamlines travelling in either direction upon flow reattachment. These two features were used to identify the separation and reattachment lines (marked with dashed and dash-dot lines), respectively. The overall separation length for the baseline interaction is $L_{sep} = 5.10\delta$, measured along the local surface directions.

Fig. 5 Oil-Flow visualisation (left) and the corresponding normalised separation length (right)

Fig. 6 Normalised mean streamwise velocity (left), mean spanwise velocity (middle) and mean wall-normal vorticity (right) for the D4 (a - c) D8 (d - f) and D25 (g - i) inlets at WP1 ($y/\delta = 0.24$) and WP2 ($y/\delta = 0.69$) planes. Black dashed-line depict the surrogate baseline separation shock position and black solid lines trace the corresponding surrogate shock positions of the controlled cases.
Upon injection, the jets present obstructions to the incoming flow, whose strength is dependent on the injection pressure and the spacing between the jets: both influence the degree of interactions between adjacent jets (Ramaswamy et al. 2020). The flow locally separates upstream of each jet (Sebastian et al. 2020), which is highlighted by oil accumulations due to jet-induced shock waves in the oil-flow visualisations. Streamwise vortices are introduced downstream of jet injection, identified by the streaky oil-flow pattern in the control cases. The streaks are a result of the streamwise vortices redistributing the momentum within the boundary-layer; they cause spanwise periodic regions of high- and low-speed flow close to the wall. Along low-speed regions, the oil accumulates, whereas it is swept away along high-speed regions. Consequently, the nearly 2D separation line observed for the baseline cases is now corrugated, with the degree of corrugation depending on the spacing between the jets in the array.

When the jets are closely spaced, as for $D = 4d_{jet}$ (D4 case), a single (merged) bow shock forms along the spanwise extent of the jet array. This jet-induced separation upstream of the jet orifices is the largest among the three cases, measuring about $7d_{jet}$ at the AJVG symmetry plane ($z = 0$). The setup also seems to cause strong jet/jet interactions that disrupt the boundary-layer downstream and increase the SWBLI separation length, as evident by the upstream movement of the separation line compared to the baseline case. The separation line and jet-induced structures are severely skewed into the direction of jet injection ($-z$-direction), highlighting the detrimental effect of very small jet spacing in AJVG arrays on shock-induced separation.

A slight increase in jet spacing to $D = 8d_{jet}$ (D8 case) achieves a much more favourable behaviour. The jet-induced shocks upstream of the orifices interact but are not fully merged, resulting in a wrinkled shock pattern and a reduced mean upstream separation of $\sim 5.5d_{jet}$ along the AJVG symmetry plane. The jet-induced streamwise vortices develop stably downstream and corrugate the separation line symmetrically. The separation at the ramp corner is significantly reduced.

With a further increase in jet-spacing to $D = 25d_{jet}$ (D25), individual bow-shock waves with a mean stand-off distance of $\sim 4.6d_{jet}$ form around the jets. This topology indicates an absence of interactions between the jets in the array. Only a local corrugation of the compression-ramp-induced separation line is observed at spanwise locations directly downstream of the jet orifices.

The influence of jet spacing in the AJVG array on the separation-control effectiveness is visualised in Fig. 5 (right). The measurements of the separation length are taken along the symmetry plane of the AJVG array and the compression-ramp model ($z = 0$) to limit the influence of edge effects. Fig. 5b shows the separation length of the control cases normalized with the separation length of the baseline case ($L_{sep} = L_{sep, control}/L_{sep, baseline}$), where the limits of the error-bar signify statistical uncertainty with a 95% confidence interval. Additionally, the separation length varies in the spanwise direction due to the local corrugation of the separation line. A second figure, Fig. 5c, shows the same variation with the error-bars now representing the amplitude of separation-line corrugation as observed for a range between $-0.5D \leq z \leq 0 \leq 0.5D$, corresponding to one jet-pitch. A maximum of 25% reduction in separation length can be observed for the D8 spacing, while the cases with very strong (D4) and very weak (D25) jet/jet interactions exhibit decreased effectiveness. Note that the spanwise corrugation is relatively small for the D4 case along the inner $\sim 4.5\%$ of the AJVG insert where the separation length was measured; this does not reflect the severe skew of the separation line along the entire spanwise length of the D4 insert.

In the course of our study, we identified the number of orifices in an AJVG array—or rather the total mass-flow rate through the array—as another relevant control parameter.
In our earlier parametric study (Ramaswamy et al. 2020), we utilised flow visualisations to analyse the effects of similar AJVG arrangements on the same baseline SWBLI as studied here. The number of orifices in the spanwise direction, however, was limited to \( n = 15 \). For the D4 case, the AJVGs were placed between \(-2.69\delta \leq z \leq 2.69\delta\) and amounted to a total mass-flow rate of \( \dot{m} = 0.0027\, \text{kg/s} \); for D8 the corresponding range was \(-5.36\delta \leq z \leq 5.36\delta\). In the current study, arrays with \( n = 23 \) orifices are tested, resulting in \( \dot{m} = 0.0041\, \text{kg/s} \) and an increased spanwise extent of the row of jets \((-4.23\delta \leq z \leq 4.23\delta\) for D4; \(-8.46\delta \leq z \leq 8.46\delta\) for D8). All other jet and boundary-layer parameters remain unchanged. While \( \dot{m} \) is nearly doubled, it still amounts to only 1.4\% of the boundary-layer mass-flow deficit. For reasons of comparability with the PIV results, to reinforce our earlier observations, and to identify and reduce possible edge effects of the AJVG insert with the crossflow, we repeated the oil-flow visualisations (as discussed above) for the current setup.

The observed trends are qualitatively the same in both studies. The separation length \( (L_{sep}) \) increases similarly (by \( \sim 8\% \)) for both D4 cases. For D8, however, a better control effectiveness was observed: the separation length was reduced by 25\% for \( n = 23 \) instead of the \( \sim 10\% \) reported for \( n = 15 \) for the same momentum-flux coefficients. The momentum-flux-coefficient \( (J) \)—which is commonly used to characterise single jet-in-crossflow setups—might thus not be adequate for array arrangements with multiple jets that allow jet/jet interactions as it does not take into account the influence of such interactions and the number of jet orifices \( (n) \). Since higher total mass-flow rates through the AJVG array result in better control effectiveness for such cases, the total mass-flow rate needs to be maintained similar when comparing AJVG arrays with spacings that allow for jet/jet interactions. For D4, the lack of well-defined streamwise structures (see Sect. 4.4) might have cancelled out any favourable effects brought about by the higher mass-flow-rate. For D25, we expect that the results are not influenced by the number of orifices in the array (and hence the total mass-flow rate) due to the lack of jet/jet interactions.

### 4.4 Flow Organisation Downstream of Jet-Injection

PIV measurements in two wall-parallel planes (WP1 at \( y/\delta = 0.24 \) and WP2 at \( y/\delta = 0.69 \)) were conducted to gain better insight into the overall development of vortical structures in all jet-spacing cases and to assess the coherence and interaction between the jet-induced vortices. The resulting velocity contours are shown in Fig. 6. The mean streamwise and spanwise velocities, as well as the normalised wall-normal vorticity, are plotted for D4 (Fig. 6a–c), D8 (Fig. 6d–f), and D25 (Fig. 6g–i) at both wall-parallel planes. For all cases, velocities and distances are normalised with the velocity at the edge of the undisturbed boundary-layer \( (U_\infty) \) and the corresponding boundary-layer thickness \( (\delta) \), respectively. The surrogate separation line, based on the definition introduced in Sect. 4.2, is also included, depicted by black dotted lines for the baseline case and black solid lines for the corresponding control cases.

The streamwise velocity contours for the D4 case (see Fig. 6a), show a sharp velocity deceleration due to jet injection (at \( x/\delta = -7.69 \)) at both WP1 and WP2 (further details in Fig. 8). Weak velocity streaks with a spanwise spacing in the order of \( O(4d_{jet}) \) occur in the spanwise velocity component at WP1 (Fig. 6b). Their coherence and constant spacing strongly decreases beyond \( x = -5\delta \), i.e., \( \sim 2.7\delta \) downstream of jet-injection. The vortices generated by the outermost orifice of the D4 AJVG array, at \( z/\delta = 4.23 \), have fewer occasions to interact with an adjacent jet and produce strong edge effects at WP1 and WP2.
Fig. 6b). These effects, however, only affect the flow beyond $z/\delta \geq 2$ ($z/D \geq 5.2$), which is outside of the measurement domain of the WN-PIV discussed in Secs. 4.5 and 4.6.

The absence of well-defined coherent vortical structures downstream of each jet orifice is further illustrated in the wall-normal vorticity contours ($\omega_z$) in Fig. 6c: while intermittent streaky structures are present, their spacing only weakly correlates with the D4 jet spacing ($D = 4d_{jet} = 0.34\delta$), and largely varies across the span. A possible explanation can be derived from Ali and Alvi (2015), who also reported an accelerated vortex dissipation downstream of an array of very narrowly-spaced jets (injected perpendicular to the surface). The counter-rotating vortex pairs are so close together that it hinders their coherence and potentially cancels their mutual influence, which leads to an erratic pattern of intermittent streaky structures within the boundary-layer. These modifications of the boundary-layer downstream of the D4 jet array lead to a strong asymmetric corrugation of the separated shear layer at both measurement planes and result in an undesired enlargement of the separation length compared with the baseline case.

With an increase in jet spacing to $D = 8d_{jet}$ (D8 case), coherent streamwise vortices form at WP1 and generate an alternately positive and negative wall-normal vorticity component of about constant magnitude (Fig. 6f). The vortices lead to a consistent spanwise modulation of both the streamwise (Fig. 6d) and spanwise (Fig. 6e) velocities, whose amplitudes remain largely similar along the model span. The surrogate separation line is uniformly corrugated at both WP1 and WP2 (see Fig. 6d). The absence of large-scale flow distortions in the WP2 measurement plane confirms that the streamwise vortices remain within the inner parts of the boundary-layer, leaving the outer region largely unaffected. In this aspect, the effects of AJVGs and micro-ramps differ: Blinde et al. (2009) ($h/\delta = 0.2$; $Re_{\theta_j} = 51240$; $M_\infty = 1.84$) observed appreciable modulation of the flow velocities also in the outer part of the boundary-layer downstream of a micro-ramp array.

For the largest spacing (D25), the contours of the streamwise (Fig. 6g) and spanwise (Fig. 6h) velocities and the wall-normal vorticity (Fig. 6i) corroborate the existence of isolated vortex pairs from the individual orifices. The surrogate separation line at WP1 (see Fig. 6g) is strongly differing from the baseline case only within a spanwise distance of about $0.8\delta$ on either side of the jet orifices, which corresponds to approximately 33% of the jet spacing; the setup can thus be considered as a row of individual AJVGs that do not interact to a significant degree.

In contrast to the D8 case, periodic regions of positive and negative spanwise velocities are observed in the outer part of the boundary-layer for D25 (WP2 in Fig. 6h) at $x/\delta \approx -6.5$. The bow shocks induced by each individual jet engulf the jet without any hindrance from adjacent jet-induced shocks (see oil-flow images in Fig. 5). As the streamlines pass through the shock wave, the flow deflection on either side of the jet registers as regions of positive and negative spanwise velocity. A second row of spanwise-periodic regions of alternate spanwise velocities occurs shortly downstream at both WP1 and WP2 as a result of a similar passage of streamlines through the jet-reattachment shock.

For all cases, the wall-normal vorticity component is strong within the separation region also in WP2 (see locations $x/\delta \geq -2$). The separated shear layer exhibits characteristics associated with canonical mixing layers: the spreading rate and the turbulent shear stress are inter-dependent and exhibit approximate similarity (Dupont et al. 2019). The strong streaks of vorticity along the separated shear layer at WP1 and WP2 are most likely generated by the most probably occurring Kelvin-Helmholtz instability and mixing-layer-like vortical rollers. These are amplified by the strongly disturbed boundary-layer for D4. A similar vorticity streak was also observed in the separated shear layer of the baseline case (see Fig. 4e), albeit at a lower magnitude due to the absence of any large-scale disturbance.
of the upstream boundary-layer. For the D8 and D25 cases, the spacings between the vortices in the shear layer and separation region agree with their spacing upstream of the flow separation and thus the jet spacing, which indicates that the streamwise vortices lift off along with the separated shear layer. Additional regions of wall-normal vorticity of almost equal strength and at a spacing that agrees with the Kelvin-Helmholtz vortices observed for the D4 and baseline cases, are observed for D25, but not for D8. This behaviour might indicate that a) the jet-induced structures are superimposed onto the structure and mechanisms of the uncontrolled interaction and may modify, but not cancel them—which agrees with the observations of Schreyer et al. (2016) on microramp control—and b) that the strength of the jet/jet interactions is an influence here. The superimposition appears stronger in the D8 case (only the jet-induced vortices are visible), where the strongest interactions between the jet-induced structures occur.

For a more quantitative discussion of the effect of jet spacing in AJVG control on the boundary layer, we compare spanwise profiles of the streamwise ($U$) and spanwise ($W$) velocity components at two streamwise locations downstream of jet injection. $U$ and $W$ at $x = -6.5\delta$ and $x = -4\delta$ ($1.2\delta$ and $3.7\delta$ downstream of jet injection) are shown in Figs. 7a–d, respectively. The respective locations were chosen to represent the near-field and far-field modifications of the boundary layer downstream of jet injection. The spanwise dimension is normalised with the respective jet spacings of the D4, D8, and D25 cases, with the orifices symmetrically arranged with respect to $z = 0$. Velocities are normalized with $U_∞$. The baseline case is also shown for comparison.

The spanwise distribution of streamwise velocity at $x = -6.5\delta$ in the near-field of jet injection (see Fig. 7a) clearly shows the modulated boundary-layer of the control cases. At WP1, the D8 and D25 velocity distributions show a wave pattern, while the D4 case does not show any large amplitude modulation. For D8, the local minima coincide with the spanwise locations of the jet orifices, taking into account a small shift in the spanwise jet-injection direction. For D25, a spanwise wave length of the undulation of about half the jet-spacing is observed at WP1; these local intensity peaks are induced by the counter-rotating streamwise vortex on either side of jet-orifice. At WP2, the D25 case maintains a relatively weak modulation, where the maxima correlate with the spanwise locations of the jet orifices. Also in D8, the wave pattern is still recognizable, albeit at a very low amplitude.

In the spanwise velocity distribution in Fig. 7b, periodic wavy velocity patterns are observed at WP1 for the D8 and D25 cases, but not for D4. For both D8 and D25, local maxima occur downstream of each jet orifice. At WP2, farther away from the wall, the D25 AJVG array still induces a considerably strong wavy pattern due to the influence of the bow shock wave discussed above. Both D4 and D8 only show very minor spanwise velocity variations, which indicates the absence of any vortex-induced or shock-induced velocity modulations.

Farther downstream, at $x = -4\delta$ ($x - x_j = 3.7\delta$), the spanwise distribution of streamwise velocity at WP1 (Fig. 7c) is modulated more strongly than at $x = -6.5\delta$ for the D8 and D25 cases; the amplitude is increased by a factor of $\sim 2.5$. This behaviour is related to the slow rise of the jet-induced streamwise vortices into the measurement plane of WP1. For D25, the velocity strongly decreases in the wakes of the jets (i.e. at the spanwise locations of jet injection ($z/\delta = -1, 0, 1$)). The flow in-between the jet-orifice locations is largely unaffected due to the lack of interactions between neighbouring jets.

The spanwise velocity component for D25 at WP1 (see Fig. 7d) shows isolated peaks downstream of each jet-injection location, which are induced by the clockwise-rotating vortex generated on the side opposite to the jet-injection direction. A negative velocity peak, as had been observed at WP1 in the near field ($\sim 0.1D$ left of the jet-injection
location in Fig. 7b), does not occur any more. This lack indicates the absence (or a strong weakening) of the anti-clockwise rotating vortex, which agrees with the findings of Sebastian et al. (2020). Also at WP2, the spanwise velocity for D25 is modulated noticeably (Fig. 7d). Similar undulations are absent for D4 and D8: the jet/jet interactions appear to reduce the jet penetration into the boundary-layer.

For the D8 case, the wavelength of the streamwise (see Fig. 7c) and spanwise (Fig. 7d) velocity modulations at WP1 increases to \( \sim 1D \). However, the modulated mean streamwise velocity profile of D8 still exhibits a deficit with respect to the baseline case despite the observed favourable control effectiveness. As momentum is transferred from the upper parts of the boundary layer to the near wall region, the mean streamwise velocity along the spanwise direction will transition from a velocity-deficit distribution (with respect to the baseline case) to a velocity-surplus distribution, when moving closer to the wall (see Figs. 10a,b). At the measured wall-normal position of WP1, the D8 velocity distribution

![Fig. 7 Spanwise mean velocity distributions at (a) \( x = -6.5\delta \) (a,b); at \( x = -4\delta \) (c,d); at \( x = -3\delta \) (e,f)](image)
still exhibits a deficit, which agrees with the measurements of Souverein and Debiève (2010) and Szwaba (2011) at a comparable wall-normal location; The transition to the favourable velocity-surplus distribution thus must occur closer to the surface. The location of WP1 was chosen on the basis of an LES of a single spanwise-inclined jet-in-cross-flow (Sebastian et al. 2020) and corresponds to the wall-normal location of the maximum streamwise vorticity, where jet-induced coherent structures are expected.

To further emphasise the favourable modification of the boundary layer for D8, we present the spanwise variation of the streamwise and spanwise velocity distributions at WP1 at \(x = -3\delta\) (4.7\(\delta\) downstream of jet injection) in Fig. 7e and f, respectively. The coherent streamwise vortices generated by the D8 array achieve a downstream movement of the separation shock. The streamwise velocity profile of D8 at WP1 (see Fig. 7e) hence displays a velocity-surplus in comparison to the shock-induced decelerated boundary layer for all the other cases. The spanwise velocity distribution (Fig. 7f) shows only a minor evolution and is qualitatively similar to the profiles at \(x = -4\delta\).

With a further decrease in jet-spacing (D4), a consistent spanwise velocity component along the jet-injection direction (\(-z\)-direction) forms at WP1, both in the near- (Fig. 7b) and far-fields (Fig. 7d). This secondary flow denotes a spanwise sway of the flow downstream of the D4 array and explains the skew of the separation line observed in the mean velocity contours (see Fig. 6a,b) and the oil-flow images (see Fig. 5). The absence of well-defined and coherent streamwise structures for D4 results in an upstream movement of the separation shock and hence, the boundary-layer profiles at \(x = -4\delta\) suffer from the separation-shock-induced deceleration at this location (see Sect. 4.5 for details).

We quantified the extent of jet influence on the boundary-layer by assessing the streamwise evolution of the mean streamwise velocity at multiple wall-normal locations (see Fig. 8). Three wall-normal positions are presented: \(y/\delta = 0.3\) (see Fig. 8a, d), \(y/\delta = 0.7\) (see Fig. 8b, e), and \(y/\delta = 1\) (see Fig. 8c, f) at the WN1 (top row) and WN2 (bottom row) measurement planes. The average flow deceleration is largest for the D4 case, with up to \(\sim 36\%\) of the undisturbed velocity at \(y/\delta = 0.3\). The deceleration is caused by the strong jet-induced shock and the associated wake downstream of jet injection. As the spacing between the jets increases, the shock strength drops, resulting in an average flow deceleration of only \(\sim 20\%\) for the D8 case. For D25, the disparity between WN1 and WN2 is largest: a large deceleration of up to 32\% occurs at WN1 (measured along jet-orifice centreline), whereas the flow development is largely unaffected at WN2 (in-between two adjacent jet orifices) due to the lack of jet/jet interactions.

At \(y/\delta = 0.7\) (see Fig. 8b, e), the profiles are qualitatively similar, but with a reduced amplitude due to the weaker influence of jet-injection higher up in the boundary-layer. This trend continues and the influence is even smaller at \(y/\delta = 1\) (see Fig. 8c, f), with only a

![Fig. 8](image-url) Streamwise evolution of mean streamwise velocity at: \(y/\delta = 0.3\) (a,d), \(y/\delta = 0.7\) (b,e) and \(y/\delta = 1\) (c,f). Figs (a,b,c) and (d,e,f) correspond to WN1 and WN2 measurement planes, respectively.
small dip of $\sim 10\%$ of the undisturbed velocity that recovers within a distance of $\sim 1.4\delta$ downstream for D4 and an even weaker deceleration for D8 and D25 that recovers within $1\delta$ downstream. These results highlight that any (favourable or adverse) impact on the SWBLI brought about by the air-jet vortex generators is only achieved by modifications of the boundary-layer and not due to any large scale alteration of the free stream.

### 4.5 Effects of Jet Spacing on the Mean-Flow Arrangement of the SWBLI

The effects of AJVG arrays with different jet spacings on the $24^\circ$-compression-ramp interaction will be discussed on the basis of mean streamwise-velocity contours and profiles along the interaction. While detailed mean-flow modifications will be discussed based on boundary-layer profiles, the 2D velocity contours help identifying the global impact of the modified boundary-layer on the separation zone. The contours for all three jet-spacing cases are shown in Fig. 9. Measurements were carried out at two streamwise/wall-normal planes, WN1 and WN2, positioned at $z = 0$ (aligned along the centreline of a jet orifice) and $z = 1.5D$ (aligned with the midplane in-between two jet orifices), respectively. The zero-velocity contour of the baseline case (red dashed lines) and the corresponding control cases (white dashed lines) are also included in the figure; the contour line serves as an interface between the outer separated shear layer and the inner region of reverse flow.

For D4, the separation shock at the ramp moves upstream in both measurement planes. The extrapolated location of the separation-shock foot is, however, considerably farther upstream at WN1 ($x_s; D_{4WN1} = -4.9\delta$) than at WN2 ($x_s; D_{4WN2} = -4.2\delta$). The separation-bubble area increases by $\sim 4.5\%$ compared with the baseline case and has a standard deviation of $\sim 0.037\delta^2$ between the two WN measurement planes. This spanwise variation is not a measure of periodic modulation, however, unlike for the other cases to be discussed below: for D4, the separation bubble shows a strong spanwise skew.

At the slightly larger jet spacing of $D = 8d_{jet}$, coherent streamwise vortices form within the boundary-layer (see Fig. 6f) and induce the entrainment of high-momentum fluid to the near-wall region. As a result, the separation-shock foot moves downstream compared with the baseline case at both WN1 ($x_s; D_{8WN1} = -3.4\delta$) and WN2 ($x_s; D_{8WN2} = -3.2\delta$). The mean separation bubble area decreases by $\sim 52\%$. The mean separation bubble also shows a periodic spanwise variation (with a standard deviation of the separation area of $0.04\delta^2$), in addition to the corrugation of the separation line (see Fig. 5) and the separated shear-layer (see Fig. 6d).

![Fig. 9 Normalised mean streamwise velocity contours (WN-planes) of the control cases. White dashed lines and red dashed lines depict the zero-velocity contour of the baseline and control cases, respectively](image-url)
A further increase in jet-spacing to \( D = 25d_{jet} \) (D25 case) brings about isolated jet-induced vortices that reflect the characteristics of a row of single jets-in-crossflow. A very strong mean-flow modification is observed directly downstream of each injection location (see Fig. 9c), while only very minor boundary-layer modifications occur at the mid-plane between the jets (WN2 measurement plane, Fig. 9f). The extrapolated location of the separation-shock foot is quite similar at WN1 \((x_{s,D25,WN1} = 3.8\delta)\) and WN2 \((x_{s,D8,WN2} = 3.9\delta)\), which agrees with the results of the oil-flow visualisations. The mean separation bubble reduction is \( \sim 14\% \); the separation bubble size, however, shows a strong spanwise variation with a standard deviation of \( \sim 0.53\delta^2 \).

To better understand the observed behaviour, we extracted mean streamwise velocity profiles for all cases at various streamwise locations for both the WN1 and WN2 measurement planes (see Fig. 10). All velocities and wall-normal distances are normalised with the freestream velocity \((U_{\infty})\) and the boundary-layer thickness \((\delta)\) of the uncontrolled interaction, respectively. The extraction locations were selected to aid the interpretation of the flow behaviour development: downstream of jet injection \((x/\delta = -6)\), just upstream of the baseline separation shock \((x/\delta = -4.5)\), close to the separation-shock foot of the most control-effective D8 case \((x/\delta = -3)\), within the separation bubble \((x/\delta = 0)\) and along the ramp surface \((x/\delta = 1; x/\delta = 3)\). Note that the profiles along the inclined ramp surface are resolved and presented along the local wall-parallel and wall-normal directions, and they are given in a rotated coordinate system \((x^*, y^*)\).

Downstream of jet injection, at \( x = -6\delta \) \((x - x_j = 1.69\delta); \) see Fig. 10a) the array with the largest jet spacing (D25) induces individual vortex systems directly downstream of each jet orifice. The vortices result in strong flow entrainment, as highlighted by an S-shaped velocity profile at WN1. Due to the large spacing between the jets, the induced vortices do not influence the flow along the center plane between orifices (WN2; Fig. 10g), where the velocity distribution is nearly identical to the baseline case. For D8, the characteristic S-shape appears both at WN1 and WN2, with a fuller profile below \( y/\delta = 0.15 \). This behaviour indicates a transport of high-momentum fluid by the jet-induced vortices, energizing the near-wall region and making the boundary-layer more resistant to separation. The smallest investigated jet spacing D4, on the other hand, induces a large velocity deficit at both WN1 and WN2. This destabilisation of the

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**Fig. 10** Normalised mean streamwise velocity at \( z = 0D \) (WN1) and \( z = 1.5D \) (WN2)
boundary-layer is due to the strong jet-induced shock wave and the associated velocity deceleration.

Just upstream of the separation shock, at \( x = -4.5\delta \) \( (x - x_j = 3.19\delta; \) see Fig. 10b, h), these shapes and trends are maintained for all velocity profiles. The distribution of the mean streamwise velocity at this location helps understand the impact of AJVGs on the SWBLI: at WN1, the flow entrainment of the jet-induced vortices is largest for D25, which explains the large local reduction in separation-bubble size observed in the mean-velocity contours in Fig. 9c. The corresponding boundary-layer profile at WN2 does not differ from the baseline case, which results in the lack of control effect at spanwise locations in-between jets visible in Fig. 9f. For D4, the very small jet spacing resulted in no discernible coherent vortex structures (see Fig. 6a) and a large velocity deficit, as evidenced by the lacking S-shape (which would indicate entrainment) in the mean velocity profiles at WN1 (10b) and WN2 (10h). This behaviour, coupled with the sustained spanwise velocity component observed earlier (see Sect. 4.4), results in the highly spanwise-skewed, upstream-shifted separation line (see Fig. 5) and thus an enlarged separation bubble (see Fig. 9a, d).

The D8 AJVG array generates coherent streamwise vortices downstream of jet injection (see Fig. 6d-f); the associated momentum transfer is also recognisable in the S-shape of the mean velocity profiles at \( x = -4.5\delta \). The similarity of the profiles at WN1 and WN2 is evidence for a redistribution of momentum along the entire spanwise extent of the AJVG array— which explains the good control effectiveness of the D8 array.

At \( x = -3\delta \), the flow decelerates strongly for D4 (see Fig. 10c, i) and separates early along the entire span. Compared with the baseline case, D25 shows slightly favourable flow behaviour at WN1, while remaining largely unchanged at WN2. For D8, the profiles are fuller than in the baseline case due to the downstream movement of the separation point.

Within the separation bubble \( (x = 0\delta) \), the high degree of spanwise corrugation of the separation bubble for D25—and to a smaller extent also for D4—is clearly visible from the strongly varying wall-normal boundaries of reverse flow at WN1 and WN2. Interestingly, while the velocity profiles at locations upstream of the ramp corner collapse for the baseline case and D25 at WN2 (due to the lack of jet/jet interactions for D25), the streamwise vortices lifting off with the separated shear layer affect the separation-bubble characteristics. The D25 profile at \( x = 0\delta \) (WN2) is visibly shifted away from the wall, in comparison to the baseline case. Earlier studies (Piponniau et al. 2009 and Priebe and Martín 2012) have highlighted the link between convective structures within the separated shear layer and the breathing motion of the separation bubble. With the introduction of jet-induced streamwise vortices into the shear layer, the complex dynamics of this interaction could have been altered. Due to the strong flow-modulation in the spanwise direction, the separation-bubble structure and dynamics may also be influenced at WN2, even though there is no observable alteration of the boundary-layer upstream. Further research is necessary to better understand any such interactions.

Along the ramp surface, at \( x = 1\delta \) and \( x = 3\delta \), the velocity distributions of the control cases approach that of the recovering baseline case and the flow slowly starts to transition towards an equilibrium state. The length of the ramp is not sufficient for a complete recovery of the boundary-layer, though. At \( x = 3\delta \) and WN1, all control cases still have visible alterations, probably due to the direct impact of the vortex structures. At WN2, the profile is less full between \( 0.3 \leq y/\delta \leq 1 \) only for the D4 array; for all other cases, the velocity profiles collapse with the uncontrolled case.
4.6 Turbulence Statistics

In the following section, we will discuss the streamwise and wall-normal velocity fluctuations and the Reynolds shear-stress distributions across the boundary-layer, which were extracted at the same streamwise locations along the flat-plate and ramp sections as the mean profiles presented earlier. The fluctuations are given in the respective local wall-parallel and wall-normal directions, and are normalised with the free-stream velocity and boundary-layer thickness of the baseline case.

Fig. 11 shows the rms of streamwise-velocity fluctuations in the WN1 (top row) and WN2 planes (bottom row) for all jet-spacing cases. The baseline case is also included for reference. At $x = -6\delta$, directly downstream of the jet orifices at WN1, the D25 case shows a peak in the streamwise velocity fluctuations at $y/\delta = 0.35$. This peak is related to the induced streamwise vortices and the associated large-scale coherent turbulent structures on the leeward side of the jet (Santiago and Dutton 1997). It is largest for D25 (the intensity is increased by a factor of 1.9 compared with the baseline case); for D4, the peak is weaker and located closer to the wall ($y/\delta = 0.25$).

At WN2, in-between jets, D25 does not deviate significantly from the baseline case due to the absence of jet-induced features. For the D4 case on the other hand, the small inter-jet spacing increases jet/jet interactions and enhances the turbulence near the wall at both spanwise locations. The streamwise turbulence intensities are increased by factors of 1.5 and 1.3 compared with the baseline case at WN1 and WN2, respectively. With moderate jet/jet interactions, the D8 case only induces a mild turbulence amplification with a peak of 1.25 times the baseline case at $y/\delta = 0.3$ at WN2. This peak increases in intensity and shifts away from the wall in the downstream evolution of the flow ($u'/U_{\infty} = 0.095$ at $y/\delta = 0.45$ for $x/\delta = -4.5$).

At $x = -4.5\delta$, the streamwise fluctuation intensity at WN1 is highest for D25 (followed by D4 and then D8), while at WN2, the intensity is highest for D8 and the profile for D25 does not deviate from the baseline case. For the D4 case, the intensity peaks are almost equally large at $y/\delta \approx 0.3$ at both WN1 and WN2.

At $x = -3\delta$, the boundary-layer is already separated for the baseline, D4, and D25 cases, which results in the fluctuation intensity peak induced by the separated shear

![Fig. 11](image-url)
layer at $y/\delta \approx 0.15$ at WN2. At WN1, the corresponding intensity maximum occurs at varying distance from the wall for the different cases, depending on the separation-bubble height and location of the shear layer. Due to the delayed flow separation, the shear-layer-induced intensity peak for the D8 case is located at a much lower wall-normal position ($y/\delta \approx 0.05$).

Within the separation bubble, at $x = 0\delta$, the streamwise velocity distribution for D4 is very similar at WN1 and WN2, with broad maxima in turbulence intensity of $\sim 0.20U_\infty$ at around $y/\delta = 1$ (WN1) and $y/\delta = 1.1$ (WN2), and thus considerably farther away from the surface than for most other cases. Only D25 also shows an intensity maximum of even larger wall-normal extend at a similar distance from the wall at WN1, albeit at a lower turbulence-intensity level. The large wall-normal extend is possibly due to a widening of the mixing layer by the jet-induced streamwise vortices that lift off along with the separated shear layer. For all other cases, a maximum is reached at around $y/\delta = 0.8$ at $x/\delta = 0$ (and moves towards the wall in the downstream evolution).

The largest velocity-fluctuation intensity at WN2 is observed for D25 ($\sim 12.3\%$ larger than the peak value of the baseline case), followed by D4, the baseline case, and D8 with the lowest intensity. At WN1, the intensity is largest for D4, then the baseline case, D8, and D25, in the order of descending energy content. The deviation of D25 from the baseline case at WN2 is despite the absence of any large variations from the baseline profiles at other upstream positions; this behaviour highlights the spanwise influence of shear-layer vortical structures within the bubble.

Downstream of the ramp corner, along the ramp surface at $x = 1\delta$ and $x = 3\delta$, the velocity profiles show similar trends. The intensity peaks move back towards the wall and the turbulent intensity levels of all cases decrease with downstream evolution of flow. The absolute turbulence intensity levels for D8 are lower than in the baseline case (by $\sim 7.6\%$ and $\sim 17\%$ at WN1 and WN2, respectively at $x = 1\delta$) but larger for D4 (by $5.9\%$) and D25 at WN2 (by $13.5\%$). From $x/\delta = 3$ onwards, a narrow secondary near-wall peak develops for all cases and spanwise locations.

Andreopoulos et al. (2000) have pointed out that any changes in the turbulence characteristics of the upstream boundary-layer (which are inflicted by the jets in the current scenario), can influence their amplification across a SWBLI. Ramaswamy and Schreyer (2021) already showed a relieving effect of jet injection for one AJVG configuration, the D8 array, on the turbulence amplification factor across a compression-ramp interaction. The current findings indicate that the spacing between the jets affects this amplification factor. The amplification factor, in this context, is defined as the ratio of the turbulence intensity upon flow reattachment ($x = 1\delta$) to the turbulence intensity just upstream of the separation shock ($x = -4.5\delta$).

The smallest jet spacing (D4) yields amplification factors of $\sim 2.2$ and $\sim 2.6$ at WN1 and WN2, respectively, compared with the incoming BL of the same case (which was already amplified by the jet-induced structures). This value constitutes an average reduction of $\sim 30\%$ from the baseline case (amplification factor of 3.5), in spite of the adverse impact of the D4 array on the separation. However, the peak fluctuation amplitude is sustained for a considerably larger wall-normal extent, as visible in Fig. 11e, k.

For D8, the streamwise turbulence intensities are amplified by factors of $\sim 2.5$ and $\sim 1.7$ (an average reduction of $\sim 40\%$ compared with the baseline SWBLI), and the D25 case experiences factors of $\sim 1.6$ and $\sim 4$ at positions WN1 and WN2, respectively (i.e. a local amplification by $14\%$ at WN2, but an average reduction of $\sim 20\%$). The high turbulence amplification for D25 at the WN2 plane may not be related to the streamwise
dynamics of the SWBLI, though, but to spanwise mechanisms in the separation region, as discussed earlier.

The wall-normal velocity fluctuations (Fig. 12) and the normalised Reynolds-shear-stress distributions (Fig. 13) across the compression-ramp interaction follow similar trends as the streamwise velocity fluctuations. The wall-normal-turbulence and Reynolds-shear-stress intensities directly downstream of jet injection ($x = -6\delta$) are highest for the D4 case at both WN1 and WN2. This behaviour indicates an extended spanwise region of amplified turbulence due to both jet-induced structures and jet/jet interactions; the strong secondary spanwise flow probably contributes to this distribution. As for the streamwise turbulence component, the largest disparity between the WN1 and WN2 planes is observed for the D25 case, which exhibits high turbulent intensities in the plane of the jet orifices (WN1), but a largely unaffected boundary-layer in-between two jet orifices. Within the separated shear-layer ($x = 0\delta$) and close to the point of flow reattachment ($x = 1\delta$), however, also the wall-normal velocity fluctuations and Reynolds
shear stresses for D25 are amplified compared with the baseline case at WN2, indicating 3D effects within the separation zone.

For the D8 case, the peak values of the wall-normal turbulent intensities and the Reynolds shear stresses are reduced at both measurement planes (∼14.7% and ∼27.3% reduction at WN1 and WN2, respectively). This observation confirms the favourable attenuating impact of the D8 array, i.e. with a jet spacing of $O(10d)$, on the turbulent amplification across the SWBLI, in addition to the achieved massive reduction of the separated area. An overview of the turbulent amplification across the SWBLI is given in Table 5 for all cases.

## 5 Conclusion

An experimental investigation was carried out to investigate the effect of jet-orifice spacing in air-jet vortex generator (AJVG) arrays on the separation-control effectiveness. The baseline flow was a compression-ramp-induced shock-wave / boundary-layer interaction at a Mach number of $M_\infty = 2.52$ and a momentum-thickness-based Reynolds number of $Re_{\theta} = 8225$. AJVGs of three different jet-spacings were investigated with oil-flow visualisations and planar particle image velocimetry at two streamwise/wall-normal (WN) and two streamwise/wall-parallel (WP) planes. For all cases, the jets were injected from circular orifices of diameter $d_{jet} = 0.16\delta$ at an inclination of $45^\circ$, i.e. an injection purely in the spanwise direction.

The jets induce a series of streamwise vortices that strongly alter the 3D structure of the boundary-layer and the shock-induced separated region at the compression corner downstream. The extent of these alterations depends on the spacing between the jets in the array. For a very large jet spacing of $D = 25d_{jet}$ (D25), individual jet-induced shock-waves engulf the jet. Isolated pairs of counter-rotating vortices are generated by each jet and show characteristics similar to a series of single jets in supersonic crossflow. This setup affects the compression-corner interaction as follows: the separation line is locally corrugated and the separation-bubble area is reduced directly downstream of the jet orifice, whereas the streamwise/wall-normal locations in-between the orifices are much less affected.

For very small jet spacings of $D = 4d_{jet}$ (D4 case), on the other hand, the vortices dissipate more quickly and display only weakly coherent streamwise-elongated regions of vorticity. The closely-spaced jets induce a single strong bow shock engulfing the entire array instead of individual bow shocks. The boundary-layer profile downstream of the injection location shows a lack of entrainment and is dominated by a large velocity deficit. Also, a consistent spanwise velocity component in the jet-injection direction forms close to the wall; in combination with the strongly disturbed boundary-layer, this spanwise flow leads to the formation of a highly spanwise-skewed, upstream-shifted separation line and an undesired enlargement of the separation bubble.

| Table 5 Turbulence amplification factor across the SWBLI |
|-------------------------------------------|
| Reynolds stress | Baseline | $D = 4d_{jet}$ | $D = 8d_{jet}$ | $D = 25d_{jet}$ |
|                | WN1 | WN2 | WN1 | WN2 | WN1 | WN2 |
| $u'$           | 3.50 | 2.2 | 2.6 | 2.5 | 1.7 | 1.6 | 4.0 |
| $v'$           | 3.65 | 2.1 | 2.4 | 2.6 | 1.7 | 1.5 | 4.1 |
| $u'v'$         | 14.1 | 5.1 | 8.8 | 11.4 | 3.8 | 3.0 | 19.2 |
The most favourable control effect is brought about by air jets at an intermediate jet spacing of \( D = 8d_{jet} \) (D8 case). A coherent system of streamwise vortices forms downstream of jet injection and undergoes favourable jet/jet interactions. The resulting entrainment and transport of high-momentum fluid from the outer region to the near-wall region of the boundary-layer manifests itself in an S-shaped boundary-layer profile, both at spanwise locations downstream of jet orifices and in-between two orifices. As a result, the flow is more stable and the mean separation length and separation-bubble area reduce by 25% and 52%, respectively, compared with the baseline case.

The injection of jets also alters the turbulence behaviour across the modified boundary-layer and the separation region at the compression-corner interaction. The jets amplify the boundary-layer turbulence. Since the closer inter-jet spacing in the D4 case enables strong jet/jet interactions, the jet-induced turbulence amplification occurs for an extended spanwise length. The large jet-spacing of the D25 case results in amplified turbulent intensities at locations downstream of the jet orifice only and largely unaffected boundary-layer turbulence at locations in-between two jet orifices. Due to moderate jet/jet interactions, the jet-induced turbulent amplifications is only mild for the D8 case.

The boundary-layer turbulence undergoes further massive amplification across the shock-wave boundary-layer interaction. AJVG control reduces the degree of this amplification. This relieving effect is, on average, largest for the D8 case, by virtue of lower turbulent-intensity magnitudes downstream of the reattachment point than in the baseline case. For D4, a wall-normal elongated region of high turbulent intensities forms close to the flow reattachment point, although the average turbulence amplification factor is lower than in the baseline case. And for spacings that are too large to allow for jet/jet interaction (D25), the turbulence amplification is substantially reduced directly downstream of each jet orifice, whereas at spanwise locations in-between two jet orifices, these favourable effects are superimposed by adverse modifications of the separated shear layer and the separation bubble. These effects are observed in spite of an absence of boundary-layer modifications at corresponding spanwise locations upstream.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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