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We investigate in this study how the height \( h \) and distance to the interaction \( d \) of microramp vortex generators (mVGs) placed upstream of a shock wave/boundary layer interaction (SBLI) may influence the efficiency of such passive devices in controlling the unsteady mechanisms and shock-induced separation suffered by this kind of flow configuration. To this end, high-fidelity Large Eddy Simulations (LES) are carried out on four different micro-vortex generators geometries in order to assess the effectiveness of low-profile microramp vortex generators \((h < 0.4\delta)\) and medium size devices \((0.5\delta < h < 0.8\delta)\) to alleviate the detrimental unsteadiness of SBLI, see Panaras & Lu (2015). All computations are performed at the same flow conditions as in the experiment of Wang et al. (2012) with a free-stream Mach number of \( M = 2.7 \) and a Reynolds number of \( Re_B = 3600 \). The medium size micromaps are found to generate the shedding of large scale structures in their wake triggering a high-frequency unsteadiness in the flow, two orders of magnitude higher than the low-frequency unsteadiness related to the reflected shock foot motion and leaving it unaffected in terms of frequency content. This family of medium size micro-vortex generators is however shown to significantly reduce the area of the separated region induced by the SBLI, as well as the pressure loads intensity on the wall surface. These improved performances come with very limited drag penalty. On the contrary, low-profile devices do display any significant change in the SBLI features.

### ABSTRACT

Shock-boundary layer interaction is a common feature of high-speed aeronautical flows. With the aim of simplifying complex industrial configurations, the interaction of an oblique shock wave impinging on a turbulent boundary layer (TBL) developing over a flat plate has been the focus of many fundamental studies in the past decades (see Clemens & Narayanaswamy (2014) for a review). This flow configuration is known to give rise to a separation bubble that exhibit low-frequency streamwise oscillations around \( St_u = 0.03 \) (a Strouhal number based on the separated region length). Because these oscillations yield wall pressure or load fluctuations, efforts are made to reduce their amplitude using control devices such as passive microramp vortex generators.

In order to evaluate the potential of this kind of approach, we have performed large eddy simulations reproducing the experiments by Wang et al. (2012) where mVGs were inserted upstream the SBLI. This baseline case allowed us to validate our numerical strategy and deepen our knowledge of the underlying mechanisms driving the natural and controlled SBLI configurations (see Grébert et al. (2018)). The geometry of the mVGs selected in this preliminary work was based on the study by Anderson et al. (2006) who concluded that mVGs protruding by \( h = 0.47\delta \) in the upstream TBL and located at a distance \( d = 16\delta = 34h \) from the impingement point of the incident shock \((\delta \text{ being the TBL thickness immediately upstream the mVGs})\), were the most efficient settings to mitigate the effect of the incident shock wave on the TBL. However, this optimization study was based on RANS simulations that may not include all the main ingredients of the interaction, especially regarding the unsteady nature of this configuration. This last consideration has been the motivation for the present contribution that aims at running complementary LES with different mVGs heights and/or distances from the impingement point than in the reference case. This will allow to check, using high fidelity simulations, how the geometrical parameters of the control devices affect the efficiency of the control, regarding the size of the separated area, the pressure loads on the wall and the unsteady properties of the interaction.

### NUMERICAL SET-UP

The present LES were performed using the CharLES\textsuperscript{V} solver, see Bermejo-Moreno et al. (2014), which solves the spatially filtered compressible Navier-Stokes equations for conserved quantities using a finite volume formulation on unstructured meshes. An explicit third-order Runge-Kutta (RK3) scheme is used for time advancement. The solver relies on Vreman (2004) subgrid-scale model to represent effect of unresolved small-scale fluid motions. It also features a solution-adaptive methodology which combines a non-dissipative centered numerical scheme and an essentially non-oscillatory second-order shock-capturing scheme.

The baseline configuration selected in the present work strictly follows Wang et al. (2012) experiments, as sketched in Figure 1. It is characterized by a freestream Mach number of \( M = 2.7 \) and a Reynolds number \( Re_B = 3600 \) based on the TBL momentum thickness at the position of impact of the incident shock. As in the experiments, a shock gen-
erator is included on the opposite wall yielding a flow deflection of $\phi = 10.5^\circ$. The spanwise extent of the computational domain has been carefully chosen in order to prevent spurious effects on the size of the separation bubble $L_{sep}$. It has been set to $6\delta_0$, where $\delta_0$ is the TBL thickness just upstream of the SBLI (i.e. $1.5L_{sep}$ upstream of $x_{imp}$, see Figure 1), leading to a domain 1.2 times larger than the interaction length scale $L_{int}$. As a consequence, the spanwise extent of the domain includes two spanwise periods of the mVGs rake in order to replicate the geometry of Wang et al. (2012) experiments. The baseline microramp geometry is the same as in the experiments, Figure 1 (top), with a height of $h = 0.47\delta_0$, a chord length $c = 7.2h$ and a wedge half-angle $\alpha_p = 24^\circ$.

![Figure 1](image)

Figure 1. (top) Reference parameters and length scales and (bottom) microramps configurations of the present study.

The grid parameters used for the present LES are given in Table 1 where the lowest values in the range of $\Delta x^+$ and $\Delta z^+$ correspond to the mesh refinement on the edges of the mVGs. The turbulent boundary layer is established using the digital filter inlet conditions proposed by Xie & Castro (2008) and modified by Touber & Sandham (2009). The parameters of the digital filter are chosen according to Touber & Sandham (2009) prescription. The flat plate and mVGs are modelled as adiabatic no-slip walls, whereas symmetry conditions are used for the shock generator and the downstream top part of the computational domain. Periodicity is enforced for the lateral boundaries of the domain, and the outflow boundary condition uses linear extrapolation of all flow variables.

In order to investigate the influence of the mVGs height and position on the mitigation of the SBLI, several high-fidelity LES (see Figure 1 (top)) have been carried out, varying $h$ and $d$ (see Table 2), but keeping the same grid resolution constraints and other physical parameters constant. It should be noted that configuration $B$ is identical to the experiment of Wang et al. (2012) and features the optimal microramp geometry identified by Anderson et al. (2006). For comparison purpose, the authors will be referring to $A$ as the reference clean configuration, i.e. SBLI without mVGs.

![Table 1](image)

<table>
<thead>
<tr>
<th>$\Delta x^+$</th>
<th>$\Delta y_{min}^+$</th>
<th>$\Delta z^+$</th>
<th>$L_x/\delta_0$</th>
<th>$L_y/\delta_0$</th>
<th>$L_z/\delta_0$</th>
</tr>
</thead>
</table>

Table 1. Grid parameters for the LES with $\delta_0$ the TBL thickness just upstream of the SBLI.

In order to address the SBLI’s unsteadiness, wall-pressure fluctuations have been recorded in the interaction region and its vicinity, $x_B^+ = [-2.8.2.6]$ with $x_B^+ = (x-x_{imp})/L_{sep}$, where $L_{sep}$ denotes the separated region length in case $B$, and $x_{imp}$ is the wall inviscid-impingement location of the incident shock wave. In addition to these measurements at the wall, velocity probes have been placed in the wake of the microramps in the center location $z_0$ of each mVG and along the median plane between them $\pm z_{inter}$, see Figure 2. It should be noted that the total integration time for case $A$ equals 6458$\delta_0/U_{\infty}$, which corresponds to 55 low-frequency (LF) period of the reflected shock foot. The total integration time of the reference controlled configuration (case $B$) is 34 LF (4054$\delta_0/U_{\infty}$) and cases $C_{1,2,3}$ cover nearly 30 LF (3370$\delta_0/U_{\infty}$).

![Table 2](image)

<table>
<thead>
<tr>
<th>Case</th>
<th>$B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h/\delta_0$</td>
<td>0.476</td>
<td>0.3</td>
<td>0.3</td>
<td>0.75</td>
</tr>
<tr>
<td>$d/\delta_0$</td>
<td>16</td>
<td>16</td>
<td>10</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 2. Height ($h$) and distance to SBLI ($d$) of the 4 controlled configurations investigated.

RESULTS

One of the main features of the mVGs is to reduce the separated region by adding near wall momentum to the incoming TBL. Figure 2 shows the time-averaged skin friction lines for the clean SBLI configuration and all controlled cases. In order to characterise the performance of the microramps we computed the separated area located between the separation and reattachment lines (black thick solid lines in Figure 2). These values are summarized in Table 3.

![Table 3](image)

<table>
<thead>
<tr>
<th>$A$</th>
<th>$B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.65</td>
<td>3.99</td>
<td>4.64</td>
<td>4.5</td>
<td>3.65</td>
</tr>
<tr>
<td>$-14.2%$</td>
<td>$-0.35%$</td>
<td>$-3.2%$</td>
<td>$-21.5%$</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Separated area measurements ($\times 10^{-5}$ m$^2$) and difference w.r.t. case $A$ for all cases.

We clearly observe that the most efficient mVGs configuration in reducing the separated area is case $C_3$. This
Figure 2. Time-averaged skin friction lines for all cases: $x_B^* = (x - x_{imp})/L_{sep}$ and $z_B^* = z/L_{sep}$, with $L_{sep}$ the mean separation length of case B. Black thick solid lines indicate the separation and reattachment lines. Red dotted lines show the iso-contour of mean streamwise shear-stress $<\tau_{w,x}> = 0$. On the right side, black triangle denotes the symmetry plane of the mVG ($z_0$), white triangles indicate the 25% span of the mVG and grey triangles show the location of the plane in-between the mVGs ($\pm z_{inter}$). The configuration corresponds to the highest mVGs height, and displays a separated area reduced by 21.5% compared to the clean configuration A, while this reduction is only of 14.2% in the reference controlled case B. We retrieve in case C3 the same spatial organization as in case B, with two tornado-like vortices developing inside the recirculation bubble (their wall signature, see Délery (2001), can be seen in Figure 2) but with increased strength and size. In case B, we only observe pockets of positive streamwise shear-stress inside the separated area, whereas case C3 exhibits an emphasized phenomenon with a reverse flow region displaying three negative shear-stress zones separated by two positive streamwise shear-stress ridges. This is due to the two powerful counter-rotating vortices arising from the sides of the mVGs, as reported by Babinsky et al. (2009); Sun et al. (2014); Ye et al. (2016), tearing the reverse flow region. The tornado vortices are thus created because of these intense shear zones at the wall. For the two smaller mVGs height, i.e. cases C1 and C2, we found no evidence of such vortices inside the recirculation bubble and teared reverse flow region. In addition, these low-profiles microramps appear to be the less effective controlled devices with a separated area reduced by only 0.35% to 3.2% respectively compared to case A.

Another detrimental effect of the SBLI is the reflected shock foot low-frequency motion. In order to characterize this unsteadiness we rely on pressure probes located at the wall, equally spaced in the streamwise direction, covering the entire span and surrounding the SBLI region. Wall-pressure probes were sampled at a very high frequency of approximately $St_{L_A} = 60$, where $St_{L_A}$ is the reduced frequency based on the mean separation length of the uncontrolled case A, $L_{sepA}$, and the free-stream velocity $U_\infty$. This normalization, based on the reference case A, is used in order to quantify the influence of the microramps on the frequency content of the baseline SBLI. The total integration time for these wall-pressure probes allow to capture more than 30 low-frequency periods of the reflected shock foot. Wall-pressure spectra are obtained using Welch’s algorithm with Hann window for a total number of 7 segments and a 50% overlap. Therefore, these spectra have a minimum resolvable Strouhal number of $St_{L_A} = 3 \cdot 10^{-3}$. Note that we applied a Konno-Omachi smoothing filter (Konno & Ohmachi, 1998) to all power spectral densities (PSD). Furthermore, due to the symmetry properties of our SBLI configuration with mVGs, all the reported PSD are spatially av-
A clear damping for cases related to the reflected shock foot motion, is altered with capability of cases $B$ and $C_3$, at $z_0$, and in-between the mVGs $±z_{inter}$, whereas in the clean SBLI configuration, i.e., without mVGs, the low-frequency unsteadiness is homogeneous in the spanwise direction, the wakes of the microramps are inducing a modulation of this unsteadiness in this direction. In the wake of the microramps, the wakes of the microramps are inducing a modulation of the low-frequency activity for cases $B$ and $C_3$ compared to the low-profile mVGs ($C_1$ and $C_2$). However, this damping of the low-frequency broadband activity is limited to the zone of influence of the microramps’ wake since in-between the mVGs, at $z_{inter}$ location, we observe that the damping capability of cases $B$ and $C_3$ is canceled and even reverted with an amplification of the low-frequency. The other two microramps configurations ($C_1$ and $C_2$) exhibit nearly the same spectra as in the wake of the microramps, with similar activity levels in the low-frequency range. Interestingly, the characteristic frequencies of the low-frequency motion of the reflected shock foot do not appear to be affected by the mVGs and their effect seems to be limited to the modulation of its intensity.

Efficient microramps devices for the control of SBLI configurations should reduce the overall pressure loads intensity sustained by the wall. We introduce the following metric in order to characterize this quantity:

$$\mathcal{I}_{F_3}(x) = \sqrt{\left\langle \frac{F_3(x)}{F_3^0} \right\rangle} \quad \text{with} \quad \left\langle F_3(x) \right\rangle = \int f p_w(x,z,t)ds$$

(1)

Using this metric $\mathcal{I}_{F_3}(x)$, we retrieve the partial pressure loads on the wall surface. Pressure loads are only partial due to the incomplete discretization of the pressure probes in the spanwise and streamwise directions. Figure 4 displays the streamwise evolution of the pressure loads intensity for the clean SBLI configuration and all controlled cases, and overall integrated values of $\mathcal{I}_{F_3}(x)$ are reported in Table 4. Again, case $C_3$ proved to be the most efficient mVG configuration with a 23% decrease of the pressure loads intensity compared to the uncontrolled case $A$. The baseline mVG (case $B$) showed a 9% decrease and the least effective mVG configurations are cases $C_1$ ($-3.2\%$) and $C_2$ ($-1.6\%$).

It should be noted that case $C_3$ is the only one showing a clear decrease of the pressure loads in the recirculation bubble, all other cases presenting a peak at $x_B' = -0.4$ with levels similar to the uncontrolled case $A$.

![Figure 3](image1.png)

Figure 3. Weighted power spectral densities of wall-pressure $p_w$ fluctuations at the reflected shock foot location of all controlled cases in the symmetry plane of the microramps $z_0$ (top) and in-between the mVGs $±z_{inter}$ (bottom). Spectra are normalised by the integrated spectrum of case $B$.

![Figure 4](image2.png)

Figure 4. Streamwise evolution of pressure loads intensity $\mathcal{I}_{F_3}(x)$ for all cases considered, with $F_3(x,t) = \int_s p_w(x,z,t)ds$.

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{F_3(x)\text{-}}{F_3^0}$</td>
<td>6.24</td>
<td>5.68</td>
<td>6.04</td>
<td>6.14</td>
<td>4.81</td>
</tr>
<tr>
<td>Difference w.r.t. case $A$</td>
<td>$-9.0%$</td>
<td>$-3.2%$</td>
<td>$-1.6%$</td>
<td>$-23%$</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Pressure loads intensity measurements ($\times 10^{-4}$) and difference w.r.t. case $A$ for all cases.

Therefore, even though we observed an increase of the low-frequency activity for cases $B$ and $C_3$ in-between the microramps, the overall pressure loads have been reduced. Increasing the mVGs’ height, and consequently the strength and size of their wake, appears to be the key feature to reduce the detrimental effect of the low-frequency motion of the reflected shock foot. The microramps do not seem to
alter the frequencies involved in this motion, although it has been shown that mVGs’ wakes feature highly coherent structures, see Wang et al. (2012); Sun et al. (2014); Grébert (2018) for more details. To characterise the unsteady forcing induced by these structures we focus on the wall-normal velocity spectra, following the same procedure as for the wall-pressure probes. Figure 5 displays the weighted PSD of wall-normal velocity at the edge of the TBL just upstream of the SBLI \( (x^*_B = -1.5) \) in the wake of the microramps \( z_0 \) and in-between the mVGs \( z_{inter} \). It can clearly be seen that the spectra in the wake are altered by the presence of these highly coherent structures for all the configurations but case \( C_2 \). For this particular configuration, the limited height of the mVGs \( (h = 0.3\delta) \) and their location closer to the SBLI where the TBL is thicker (leading to an lower effective height of the mVGs in that case compared to case \( C_1 \)) did not enable the formation of these structures. We thus retrieve the same spectrum as in-between the mVGs, similar to the one obtained for an unaltered turbulent boundary layer. Regarding the medium size configurations, cases \( B \) and \( C_3 \), the highly coherent structures are shed at a very specific frequency of \( St_{LA} = 2.4 \) and \( St_{LA} = 2.15 \) respectively, see Table 5. The low-profile configuration \( C_1 \) exhibits a slightly different spectrum, with a clear shift towards higher frequencies, compared to the TBL in-between the microramps, but with unchanged energy levels. This indicates that the mVG’s height of \( h = 0.36 \) doesn’t seem to be sufficient to induce strong enough coherent structures that may induce a clear high-frequency forcing in the wake of the microramps.

Finally, it appears that this shedding frequency is not linked to the mVG height itself, at least not directly, but rather to the alteration of the TBL thickness due to their presence. To corroborate this assumption, Figure 6 shows the same weighted PSD as aforementioned but with a different frequency scaling based on the local TBL thickness \( \delta_e \), \( St = f \delta_e / U_\infty \). It clearly appears that cases \( B \) and \( C_1 \) perfectly scale with this new TBL thickness based scaling. The larger the mVG, the thicker the TBL in their wake and therefore the lower the shedding frequency. In any case, the high-frequency forcing associated to the shedding of these large scale structures in the wake of the mVGs is two orders of magnitude above the low-frequency unsteadiness of the reflected shock foot, and therefore does not trigger any modulation of the SBLI unsteadiness.

In order to quantify the impact of the tested control devices on the global performances of the flow configuration, we have finally estimated the drag penalty induced by the presence of the different mVGs, see Table 6. It is interesting to see that the increase in the thickness of the mVGs introduces only a very limited additional cost in terms of drag, that doesn’t exceed 3.9% compared to the uncontrolled case \( A \) in the four tested configurations. The highest mVG configuration case \( C \) thus appears as a good candidate compared to other mVGs configurations, with respect to its improved performances in reducing the separated area and pressure loads intensity sustained by the wall surface, that comes with a very limited drag penalty.
Table 6. Summary of microramps effectiveness w.r.t. case A and their drag penalty.

<table>
<thead>
<tr>
<th>Case</th>
<th>$B$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep. area</td>
<td>-14.2%</td>
<td>-0.35%</td>
<td>-3.2%</td>
<td>-21.5%</td>
</tr>
<tr>
<td>$p_w$ loads</td>
<td>-9%</td>
<td>-3.2%</td>
<td>-1.6%</td>
<td>-22.9%</td>
</tr>
<tr>
<td>Induced drag</td>
<td>+2.1%</td>
<td>+0.7%</td>
<td>+0.5%</td>
<td>+3.9%</td>
</tr>
</tbody>
</table>

CONCLUSION

To the authors’ knowledge, this work provides the first high-fidelity, very long-time integrated (covering more than 30 LF periods) LES database describing a parametric study on the control of SBLI using passive devices. Four microramps configurations, with varying height and distance to SBLI, have been investigated under the same flow conditions corresponding to the experiment of Wang et al. (2012), with a free-stream Mach number of $M = 2.7$ and a Reynolds number of $Re_D = 3600$. We established that the addition of the microramps induces a high-frequency unsteadiness related to the shedding of highly coherent large scale structures. The shedding frequency is inversely proportional to the altered TBL thickness: the larger the mVG, the thicker the TBL in their wake and therefore the lower the frequency. We also found that only medium size mVGs ($0.58 < h < 0.86$) can trigger such unsteadiness that is two order of magnitude above the low-frequency unsteadiness related to the reflected shock foot motion. This detrimental feature of the SBLI remains unaffected in terms of frequency content, regardless of the microramps height, even if its energy is damped by the wake of the mVGs. A clear reduction of the SBLI separated region as well as a net damping of the pressure loads intensity on the wall have been highlighted when medium size mVGs are placed in the upstream TBL. Moreover, these improved performances appeared to come with a very limited drag penalty. We have thus shown in the present study that medium size microvortex generators, rather than low-profile ones, appear to be best suited to the control of SBLI. We also demonstrated that the originally optimised mVG design by Anderson et al. (2006) may not be the most efficient to control SBLI. Our results advocate for a reconsideration of the optimisation framework that should not be limited to RANS modelling only but should also include LES instead.

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