BOUNDARY LAYER TRIPPING STRATEGIES FOR SUPERSONIC AIR INLET APPLICATIONS

Samuel Deleu*, Álvaro Sánchez Del Río, Romain Gojon, Jérémie Gressier and Stéphane Jamme ISAE-SUPAERO, University of Toulouse, France *email: samuel.deleu@isae-supaero.fr

ABSTRACT

This paper presents a numerical study for different boundary layer tripping solutions on a simplified geometry of a compression ramp found in supersonic air inlet configurations. The investigated tripping solutions will force the boundary layer to be turbulent at the tip of the external supersonic diffuser, where the first shock appears. The different proposed solutions consist of a geometrical trip, a bypass transition with an isotropic homogeneous turbulence injection in the domain and a combination of both. We perform a characterization of the boundary layer developing on the simplified ramp configuration and compare the different tripping strategies.

INTRODUCTION

Several air inlet shapes and sizes exist depending on aircraft operability. When experiencing supersonic flow conditions, the air intake's major role consists of decelerating the incoming flow before entering the combustion chamber. As opposed to rounded subsonic inlet shapes, supersonic inlets display a sharp lip to minimize performance losses. The supersonic flight regime involves compressible phenomena: shock waves and expansion fans from the ramp compression devices or the inlet cowl lips. The design of the air intake then plays a key role in the performance of the propulsion system as it will ensure a consecutive shock series up to the terminal shock, forcing the flow to be subsonic before entering the core of the engine, therefore satisfying the maximum admissible mass flow rate without choking. However, the so-created shocks can impact the boundary layers (BL) developing on the opposite walls. These shock wave/boundary layer interactions (SBLI), have direct consequences on the performance and operation of the supersonic air inlet (Chen et al. (2018)). The strong adverse pressure gradient induced by a shock wave on a boundary layer may indeed cause a separation of this lowspeed region and lead to the development of a separation bubble. The mass flow rate is then reduced, which is detrimental to the propulsion system.

While the basic geometry of the inlet is optimized for stationary flight conditions, problems arise during the transient phases of engine and inlet operation. Abrupt changes in engine throttle, inflow disturbances (such as high angles of attack), or other factors can disrupt the balance between the air mass flow demanded by the engine and the air mass flow entering the inlet. The disruption in airflow balance due to sudden downstream flow blockage can lead to a severe airflow mismatch. This, in turn, affects the upstream shock wave pattern and can cause the inlet to operate in an undesirable "subcritical" mode. This unsteady process is known as the supersonic inlet buzz phenomenon which can lead to a terminal shock standing upstream of the inlet entrance. When the supersonic inlet buzz occurs, it results in self-excited streamwise normal-shock oscillations and periodic duct pressure fluctuations. This provokes a sharp drop in captured air mass flow, which can have several undesirable consequences, including engine thrust penalties, engine surge, or structural damage to the aircraft.

In a previous numerical study on this specific air intake configuration (Hammachi et al. (2022)), different backpressures have been imposed by setting a moving plug at different axial positions at the exit of the internal intake, resulting in different "throttling ratios" for the inlet duct. This work showed that the primary physical behaviours - including the triggering of the buzz phenomenon observed in Chen et al. (2018) experiment - were retrieved. However, their occurrence was not established at the same frequencies nor the same throttling ratios as the one observed in Chen's experiments. It has been estimated that, in the simulations from Hammachi et al. (2022), the emerging shock from the cowl lip finds the opposite ramp BL to be laminar, which is certainly not the case in the experiments. Computational cost led the previous numerical work to halve the experimental actual Reynolds number. This is assumed to be the main cause for the BL state to be laminar together with the numerical inherent ideal fluid state or ramp smoothness, acting against the apparition of small perturbations. This discrepancy with the experimental situation spreads an error in the loop process initiating the buzz. It is assumed to be the cause of the differences observed between the performed Large Eddy Simulations (LES) and the experimental observations.

This paper investigates different known possibilities to trip the BL to obtain an appropriate turbulent BL to enhance the simulation results and come closer to the experimental setup. Amongst the various options, two ways are studied through a wall-resolved LES approach. The first solution reproduces a given turbulence level as an input in the domain to trigger the transition. This method is also known as bypass transition. The second solution consists of a geometrical tripping directly shaped in the boundary condition of the compression ramp. Finally, a skilfully weighted combination of both is proposed as an optimal way to trip the BL. In this paper, only simplified inlet results are provided. The next step will be to apply the depicted tripping solution on the real air inlet configuration as presented in previous works, to assess the influence of the turbulent state of the ramp boundary layer on the buzz cycle characteristics.

NUMERICAL SETUP

The present wall-resolved compressible LES were performed using the in-house IC3 solver, which solves the spatially filtered compressible Navier-Stokes equations for conserved quantities using a finite volume formulation on unstructured meshes. Time integration is performed using an explicit third-order Runge-Kutta (RK3) scheme. The solver relies on Vreman (2004) subgrid-scale model to represent the dissipative effect induced by the unresolved small-scale fluid motions. It also features a solution-adaptive methodology which combines a low-dissipative centred numerical scheme and a firstorder upwind scheme in regions of the flow where discontinuities are present. For this purpose, a DVPG shock sensor based on the values of dilatation β , vorticity ω and pressure gradient ΔP , is used to identify the presence of discontinuities in the flow: for cells with a ratio DVPG = $\frac{\beta}{\omega} \frac{\Delta P}{P}$ exceeding a threshold value to be defined, the first order scheme is applied whereas the low-dissipative scheme is kept for the remaining cells.

The simplified compression ramp used in the present work is set to respect the length L = 0.08m and the deflection angle $\theta_{inlet} = 8^{\circ}$ of the external ramp from the experiments of Chen *et al.* (2018). However, unlike the complex geometric profile characterized by an increasing deflection along the compression ramp observed in the real configuration, a rectilinear geometry has been selected for the simplified ramp configuration under investigation. An illustration is given in Fig. 1. All variables of the supersonic incoming flow are specified at the inlet boundary of the domain. The outlet is a relaxed pressure outlet. Adiabatic walls with no slip condition define the bottom walls and periodic boundary conditions are used in the spanwise direction.



Figure 1: (a) Geometrical representation of the numerical domain along with the different flow regions location for the simplified air inlet configuration: (I) upstream flow, (II) downstream shock flow, (III) boundary layer region ; (b) Roughness element shape (trip) located at x = 0 of the compression ramp.

To ensure uncorrelated turbulent fluctuations in the spanwise direction, the domain size is set to be $L_z = 2.4 \cdot 10^{-3} \text{m} \approx 3 \cdot \delta_{99}$, where $\delta_{99} = 7.77 \cdot 10^{-4} \text{m}$ is the laminar BL thickness close to the exit of the linear ramp (0.75L) at $Re = Re_{LES}$. The

computational grid is refined close to the wall enabling the wall-resolving feature with $y^+ < 1$, $z^+ = 14$ and $4 < x^+ < 84$ where the lower x^+ are found behind the trip. The mesh consists of a total of $15.5 \cdot 10^6$ cells for each case.

In the original experiments, the upstream flow had specific characteristics, including an upstream Mach number M =2.41 and Reynolds number $Re_{exp} = 494640$, based on the upstream quantities and the height of the final straight portion of the air inlet duct. In the present study, the Mach number is kept the same as in the experiments. We use a halved Reynolds number of $Re_{LES} = Re_{exp}/2$ by adjusting the viscosity as in the previous LES from Hammachi *et al.* (2022). The objective is to assess the potential of the investigated tripping strategies to induce a turbulent state in the boundary layer of the ramp at the lower Reynolds number being examined.

PRESENTATION OF THE DIFFERENT TRIPPING SOLUTIONS

We describe below the two methods implemented for the tripping of the boundary layer on the ramp. The choice of the different necessary parameters is explained for both cases and the way in which they affect the flow is specified.

Bypass transition

The first investigated solution is the bypass transition achieved by injecting isotropic turbulence at the entrance to the computational domain. The bypass transition scenario involves three regions along the development of the boundary layer: the first one corresponds to a disorganized laminar boundary layer, then an intermittent region occurs, and finally a fully turbulent state is reached. In the first region, disturbances from the turbulence in the core flow penetrate the boundary layer. This is governed by the shear sheltering mechanism, where the boundary layer acts as a low-pass filter for disturbances from the external flow. These low-frequency disturbances give rise to longitudinal velocity fluctuations known as Klebanoff modes or streaks (Kendall (1985), Klebanoff (1971)). The formation of these streaks is attributed to the lift-up effect, which involves the displacement of momentum by fluctuations of velocity normal to the wall. This results in high-speed streaks when there is an excess of momentum near the wall, and low-speed streaks when there is a deficit of momentum at the boundary layer's edge.

The turbulence injection utilizes a numerical unsteady inlet boundary condition, inspired by the methodology introduced by Klein et al. (2003), relying on a digital filtering technique. This inlet boundary condition has been used and validated for the generation of a turbulent boundary layer on a flat plate within the IC3 solver framework in the work of Hermet et al. (2022) and Grébert et al. (2018). In the present work, we adapt this technique to specify a homogeneous isotropic turbulence (HIT) in the vertical inflow of the computational domain upstream of the ramp. To validate the characteristics of the perturbations acting on the ramp BL, the decay spectrum of the synthetic turbulence injected at the inlet of the domain is examined for various probe positions located in the first part of the domain. For the case involving a HIT featuring a turbulent length scale of $l_t = 5 \cdot 10^{-4}$ m, it is demonstrated that a distance of $4 \cdot 10^{-3}$ m - as illustrated in Fig. 2 - depicting the Power Spectral Density (PSD) of the longitudinal velocity component at various probe locations - is sufficient to achieve the characteristic -5/3 decay. This observation aligns well with the current objective of sufficiently perturbing the BL for the transition to occur.

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Figure 2: Turbulence spectrum calculated at the inlet and for different probe locations ahead and after the shock at y = 20% of the inlet length for the case with Tu = 5% and no trip.

The intensity of the injected perturbations is linked to the turbulence level Tu which can be defined as follows:

$$Tu = \frac{\sqrt{u'^2}}{U_{\infty}} = \frac{\sqrt{\frac{2}{3}k}}{U_{\infty}} \tag{1}$$

with $k = \frac{1}{2}Tr(R_{ij})$ the kinetic energy of the fluctuating motion and $R_{ij} = \overline{u'_i u'_j}$ the Reynolds stress tensor in the filtered Navier-Stokes equations. Isotropic turbulence imposes $\overline{u'^2} = \overline{v'^2} = \overline{w'^2}$. Turbulent fluctuations are applied at the inlet with a modification of the Reynolds tensor ensuring a turbulence level of Tu = 2.5%, 5% and 8%.

The turbulence length scale l_t is set to $5 \cdot 10^{-4}$ m $\approx 0.65 \cdot$ δ_{99} . This value is chosen as a compromise between the numerical resolution constraints of the targeted real air inlet configuration (which imposes a minimum value) and the height of the geometrical trip that will be defined in the next paragraph (which imposes a maximum value). Here, l_t corresponds approximately to 3 times the height of the geometrical trip. The obtained velocity field is shown in Fig. 3b. Perturbations appear to be inside the BL after a distance of approximately 25 - 30% of the compression ramp. A more precise investigation of the relevant parameters allowing us to assess the turbulent nature of the BL and the location of transition will be conducted in the next section. Accurately ensuring the transition location along the ramp is indeed important, aiming to position it as close to the leading edge as possible, which is crucial for the final application.

Geometrical trip

Unlike the classical configurations described in the literature about geometrical BL tripping - where the trip elements are sized according to the thickness of the undisturbed BL at the trip location - the trip is placed in our case at the beginning of the ramp, where the BL is not yet established. The choice is thus made to size the trip element using a laminar boundary layer thickness at 75% of the ramp at $Re = Re_{LES}$. The roughness element size in our study has been defined following De Tullio *et al.* (2013). The flow conditions studied in De Tullio's paper are the closest to those studied here, as they investigate the roughness element influence over the BL



Figure 3: Color map of the instantaneous velocity U (a) without and (b) with a trip with homogeneous turbulence injection (Tu = 5%).

for a compressible flow at Mach M = 2.5. Following De Tullio's tripping sizes, the estimation of the trip height is set to $h = 0.22 \cdot \delta_{99} = 1.71 \cdot 10^{-4}$ m. A schematic representation of the trip is given in Fig. 1b.

RESULTS

The numerical collection of investigated cases is available in Table 1. It is important to note that the cases where the BL did not achieved a transition to a turbulent state will not be presented in this section. The reported cases thus have a turbulence level of 5% and 8%. For these two turbulence levels, a transition to turbulence of the BL is observed with and without the geometrical trip. We focus in the following on assessing which of these four configurations gives the earliest and most established turbulent BL. To do so, we investigate the main parameters allowing to evaluate the BL properties.

As seen in Fig. 4, the value of Re_{θ} evolves with the BL along the ramp. Between 0 and 25%, the wake of the trip noticeably influences the BL establishment for both of the presented turbulence levels. The presence of the trip artificially thickens the momentum thickness of the BL, inducing a higher

Table 1: Performed run cases at $Re_{LES} = Re_{exp}/2$ with different combinations of investigated tripping solutions. The injected free stream turbulence level and the presence of the trip are indicated. (X): no transition occurred, (V): transition occurred.

Ти	0%	2.5%	5%	8%
No trip	X	×	~	~
Trip	×	×	~	~

 Re_{θ} value for a given position on the ramp. The freestream turbulence level seems to have the same, though lighter, effect than the trip as the higher the turbulence level, the higher the Re_{θ} . Fig. 5 displays the values obtained for Re_{θ} at the end of the ramp for the different configurations and compare them to the values calculated for a fully turbulent BL on the ramp using theoretical correlations, for the Reynolds number used in Chen's experiments and the one used in the present LES. The intermediate values obtained for $Re_{\theta}(L)$ in the four simulations show that all the presented tripping strategies partially compensates for the decrease of the global Reynolds number in the LES, without allowing a full recovery of the $Re_{\theta}(L)$ obtained in the experiments.



Figure 4: Evolution of Re_{θ} along the ramp for the triggered transition configurations.

The shape factor, defined as the ratio of displacement and momentum thicknesses, $H = \delta^* / \theta$, can also be used as a quantitative indicator of the BL state. In Fig. 6, its evolution along the ramp is provided for the different cases and is compared to the laminar and turbulent compressible correlations of H for a flat plate, given as:

$$H_{corr} = H_{inc} + \alpha M e^2 + \beta \frac{T_w - \mathcal{F}_f}{Te}, \qquad (2)$$

with turbulent and laminar correlation values being respectively $(H_{inc}, \alpha) = (1.4, 0.4)$ and $(H_{inc}, \alpha) = (2.591, 0.667)$. In the presented cases, the wall is adiabatic and its temperature $T_w = T_f$, with T_f the adiabatic temperature. For all cases, the shape factor on the second half of the ramp is close to the value expected for a turbulent compressible BL. In this region, no clear influence of the geometrical trip is observed on this



Figure 5: Comparison of the value obtained for Re_{θ} at the end of the ramp for the triggered transition configurations. $Re_{\theta}^{th}(L)$ corresponds to the value calculated for a fully turbulent BL on the ramp using theoretical correlations.

quantity, but a slight difference can be seen between the two different turbulence levels. In this regard, cases with Tu = 5% seem to come closer to the red limit of the turbulent BL.



Figure 6: Evolution of the shape factor H for the triggered configurations. - - - H_{lam} and - - - H_{turb} correspond to the laminar and turbulent compressible correlations for a flat plate respectively.

Considering this, the configuration including the trip and a turbulence level Tu = 5% appears to be the most promising candidate for achieving the earliest turbulent boundary layer. For further validation, the evolution of the incompressible skin friction coefficient Cf_i along the ramp, obtained using the van-Driest II transformation (Huang & Coleman (1994)), is performed. Results are presented in Fig. 7 and compared to Kármán-Schoenherr and turbulent Blasius correlations: $Cf_{KS} = 1/(17.08 \cdot \log (Re_{\theta_i})^2 + 25.11 \cdot \log (Re_{\theta_i}) + 6.012)$

and $Cf_{BL} = 0.026 \cdot Re_{\theta_i}^{-1/4}$, with $Re_{\theta_i} = (\mu_e/\mu_w)Re_{\theta_i}$. A higher turbulence level seems to provide an overall bet-

ter matching friction coefficient. However, in both cases, the presence of the trip delays the achievement of an expected turbulent value for the skin friction coefficient. Moreover, the cases corresponding to a turbulence level of Tu = 8% seem to

reach a turbulent Cf_i level far more upstream than the Tu = 5% cases.



Figure 7: Mean friction coefficient versus Re_{θ} for the triggered configurations compared to Kármán-Schoenherr and turbulent Blasius correlations.

The choice for the best configuration is thus not straightforward and assumes an educated choice. Since the goal is to achieve the earliest transition towards a fully turbulent BL, a study of the internal BL mean velocity profiles (see Fig. 8) and Reynolds stresses (see Fig. 9 and Fig. 10) performed at various locations along the ramp will help to make things clearer.

The van-Driest-transformed mean velocity profile is plotted at different x-positions along the compression ramp in Fig. 8. A systematic comparison is made with the DNS data provided by Schlatter & Örlü (2010), chosen at a Reynolds number Re_{θ} corresponding as closely as possible to the considered location on the ramp. The obtained velocity profiles for each configuration at any given x-position are in good agreement with the linear law of the DNS data viscous sub-layer. However, the logarithmic law of the inertial sub-layer seems to be matched only by the cases without trip at x/L = 50% and beyond. For the cases featuring a trip, the agreement with the DNS data only comes later and is fully effective at the end of the ramp. A velocity jump is observed at high y^+ values and corresponds to the presence of the shock induced by the compression ramp.

The Root Mean Square (RMS) of the Reynolds stresses are given in Fig. 9 for Tu = 5% and in Fig. 10 for Tu = 8%. Each component of the tensor is compared to the corresponding DNS data at a fixed $Re_{\theta} = 1000$. The Reynolds stresses are expressed employing the van-Driest multiplier and semi-local scaling, represented as $\xi = \sqrt{\langle \rho \rangle / \rho_w}$, where $\langle \cdot \rangle$ indicates time averaging, and the subscript w denotes quantities at the wall. The evolution along the ramp is denoted using the color shade. The closer to the end of the ramp, the more accurate the profiles. It is important to note the non-zero value outside the BL due to the synthetic turbulence injection, which differs from the DNS cases. Also, the turbulence dissipation is acknowledged along the ramp as the turbulence level decreases with the growing x-position. There are no clear differences between both turbulent levels. However, the trip configurations appear to be slightly closer to the DNS data for both turbulence level values.

CONCLUSION

The turbulent transition over an inclined compression ramp induced by multiple tripping strategies at Mach number

2.41 has been thoroughly investigated. The proposed tripping strategies included by-pass transition through HIT injection, implementation of a roughness element at the ramp leading edge and a combination of both of them. The onset of the turbulent BL has been carefully evaluated using relevant BL parameters giving information on both the position and the establishment of the turbulent BL along the compression ramp. It has been found that the trip, as expected, makes the boundary layer thicken more quickly. This led to artificially increase the value of Re_{θ} and fall closer to turbulent BL-expected values. However, the geometrical trip seemed to delay the achievement of a correct friction level. On the other hand, HIT injection had a positive impact on this parameter. In the end, the case associating the roughness element and HIT injection with a turbulence level of 8% appeared as the most effective for combining encouraging effects on all the dimensioning parameters.

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Figure 8: Mean velocity profiles at different x-locations along the ramp for the triggered configurations: (a) 25%, (b) 50% and (c) 99% given at the closest Re_{θ} DNS available data.



Figure 9: Mean profile of the Reynolds stresses (a) with and (b) without trip at Tu = 5% compared to the DNS of Schlatter & Örlü (2010) at $Re_{\theta} = 1000$, evaluated at four locations along the ramp: 25%, 50%, 80% and 99%. The darker the shading, the further its corresponding position along the ramp.



Figure 10: Mean profile of the Reynolds stresses (a) with and (b) without trip at Tu = 8% compared to the DNS of Schlatter & Örlü (2010) at $Re_{\theta} = 1000$, evaluated at four locations along the ramp: 25%, 50%, 80% and 99%. The darker the shading, the further its corresponding position along the ramp.