Transonic shock wave boundary layer interaction control using a combination of swirling flow and vortex generators

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This research presents the results of numerical analysis of a co-rotating array of mini swirling air jet vortex generators installed on the supercritical P-18-415 airfoil profile wing model at an angle of attack $\alpha = 4°$. The active flow control system is aimed to be operated when the flight is in cruise mode. Simulations were conducted under conditions representative of steady state cruise mode flight, with a freestream Mach number of $\mathrm{M}_\infty = 0.75$ at which point shock wave separation occurs in the boundary layer. Ansys Fluent software is utilized to solve 3D compressible Reynolds Averaged Navier.Stokes equations, employing the two-equations $k-\varepsilon$ realizable turbulence model. The study identifies the optimal design configuration based on pressure coefficient (C_p) and the lift-to-drag ratio $(K = C_l/C_d)$.

Keywords: mini swirling air jet vortex generators, transonic flow controls, buffeting, shock wave boundary layer interaction.

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In the domain of high-speed aerodynamics, shock wave boundary layer interactions (SWBLIs) are prevalent across a wide range of aerospace applications, including transonic wings, supersonic inlets, rocket nozzles, and hypersonic re-entry vehicles. The interaction between shock waves and boundary layers induces a significant adverse pressure gradient, which in turn leads to various complex phenomena such as unsteady shock oscillations, thermal stresses on surface structures, and pressure wave fluctuations. These effects may ultimately result in flow separation and other critical aerodynamic consequences [1]. The onset of transonic buffet, when occurring at frequencies that coincide with structural resonance, can induce structural fatigue, thereby increasing the risk of flight accidents. To mitigate the detrimental effects of SWBLIs, a variety of flow control techniques have been developed to suppress flow separation and delay or prevent the onset of transonic buffet.

Classical approach to flow control involves physically altering the boundary layer through suction and blowing [2], which have proven effective in separation control. Additionally, various active flow control methods such as tangential jet blowing [3], employment of trailing-edge flaps [4], and implementation of fluidic vortex generators [5] have demonstrated buffet control capabilities across a wide spectrum of flow conditions. These techniques offer the advantage of selectable switching modes during cruise flight, enhancing their adaptability.

Passive methods for controlling shock-induced buffet, including shock control bumps [6], micro-waved surfaces [7], and vortex generators [8], have also been explored for their simplicity compared to active approaches. Although these techniques are effective in controlling shock-induced separation, their physical presence on aerodynamic surfaces can introduce additional parasitic drag. Moreover, they are typically optimized for specific flight regimes and flow conditions, limiting their versatility. In contrast, air jet vortex generators provide an advantage by minimizing drag penalties, as they can be deactivated when not needed, offering a more adaptable and efficient solution for varying operational conditions. The recent research on the numerical analysis of a co-rotating array of mini air jet vortex generators (Mi-AJVGs) deployed on the supercritical P-18-415 airfoil profile wing model at an angle of attack $\alpha = 4°$ has demonstrated its efficacy in modulating shockwave boundary layer interaction (SWBLI) in transonic regimes [9].

Recent advancements in transonic flow control systems have incorporated swirling flow mechanisms into the design of Mi-AJVGs. In this study, we propose a novel concept involving the installation of mini swirling air jet vortex generators (Mi-SAJVGs) to further enhance flow control performance. In this research, we propose a novel idea of installing mini swirling air jet vortex generators. In contrast to Mi-AJVGs, the Mi-SAJVGs consist of jets with rotational velocity, generating their own vorticity that contributes additional momentum to the separated boundary layer.

The approaching flow investigated had a freestream Mach number of $\mathrm{M}_\infty = 0.75$ at which a strong SWBLIs occurs on the supercritical airfoil P-18-415 [9]. The Reynolds number based on the chord length is $\mathrm{Re} = 3.0 \cdot 10^6$ and is assumed to be fully turbulent; 3D compressible Reynolds averaged Navier.Stokes (RANS) equations are solved based on finite-volume method in ANSYS Fluent solver. The two-equation $k-\varepsilon$ realizable turbulence model with enhanced wall treatment was applied to compute turbulent viscosity. Second-order implicit upwind Roe-Flux differencing split-

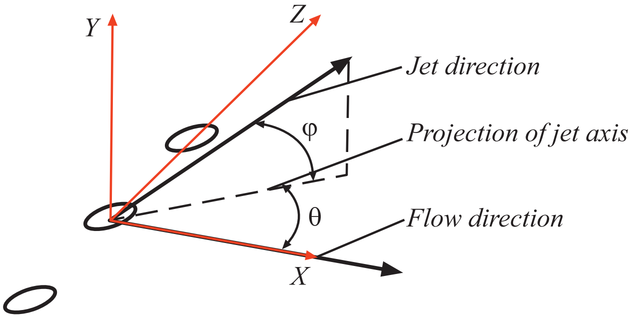

Figure 1. Schematic diagram of Mi-SAJVGs angles [2].

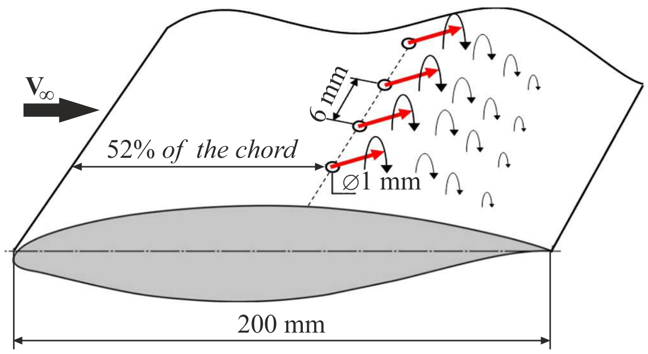

Figure 2. Overview of the Mi-SAJVGs location on the supercritical airfoil [2].

ting scheme is used for the spatial discretization. The results, notably the pressure coefficient (C_p) and lift-to-drag ratio (K), show promise in mitigating the transonic SWBLI.

The numerical simulations were performed with reference to a supercritical wing having an airfoil profile of P-18-415 at an angle of attack $\alpha = 4^\circ$ (cruise condition). Mi-SAJVGs are pitched and skewed at $\varphi = 45^\circ$ and $\varphi = -45^\circ$ respectively. The pitch and skew angles were shown in the Fig. 1. They are organized in a co-rotating array, with all swirling jets pointed in the same direction and vortices shed in the same rotational direction, and are located at 52% of the chord length as shown in Fig 2.

For the numerical investigation, a structural mesh comprising approximately 10 million cells was developed. This mesh primarily encompasses the forward movement region, with additional specialized meshes positioned over each gap to account for rotational regions. To simulate the boundary layer, a dedicated O-grid consisting of 20 cells in height was constructed normal to the surface. The height of the first grid cell near the wing surface was determined to ensure an adequate number of cells for accurate wall function: $y^+ = \rho u_\tau y_p/\mu$, where u_τ is the characteristic velocity, y_p is the distance from a point in space to the profile wall, ρ is the ambient density, and μ is the air viscosity. Computational grids were tailored to meet the requirements of the calculation program, specifically targeting a y^+ parameter of ≤ 5 as recommended for the $k-\varepsilon$ realizable turbulence model; in this study, y^+ was maintained at ≤ 0.52. Each rotational flow region was characterized by a radius (r) of 0.002 m and a rotation velocity (N) of 10 471 rad/s, aligned with the coordinates of the rotational axis for each gap and directed at angles $\varphi = 45^\circ$ and $\varphi = -45^\circ$.

Influence of flow controls on aerodynamic characteristics

Flow controls	C_l	C_d	K
–	0.459	0.0395	11.6
Mi-AJVG	0.481	0.0392	12.3
Mi-SAJVG	0.486	0.0393	12.4

The Mi-SAJVGs, incorporating both translational and rotational velocity components of 10 m/s and 10 471 rad/s, respectively, augment jet momentum within the boundary layer region. This added momentum helps mitigate the adverse pressure gradients caused by the unsteady motion of shock waves. Typically, shock waves induce an abrupt pressure rise downstream, leading to a depletion of boundary layer momentum and the onset of flow separation. However, the application of Mi-SAJVGs on the supercritical wing results in a more gradual pressure shift, in contrast to the reference case, which experiences a rapid pressure jump through the shock as shown in Fig. 3.

Longitudinal vortices were formed when jets were activated, and they quickly decayed along the chord. Application of a higher velocity ratio results in more persistent vortices as seen in the case of Mi-AJVGs. Introducing an additional velocity component to the air-jet vortex generator enhances the vortices which can be traced over a larger distance from their origin to the trailing edge of the wing.

In the context of Mi-AJVG, a limitation arises as the vortices appear to be elevated across a chord length, constraining their efficacy. Conversely, in the Mi-SAJVG, swirling jets are initiated in a counter-clockwise direction, analogous to uniform flow with a doublet and vortex, generating circulation and a lifting force [10]. These counter-clockwise jets induce negative lift, aiding in the proximity of vortices to the boundary layer and preventing elevation from the surface. Fig. 3 illustrates the comparison of pressure coefficient distributions between the reference wing and two flow control methods. In the case of Mi-SAJVG, the presence of vortices instantaneously influences the C_p vs $\bar{X}$ plot following the injection of swirling jet location. The plot shows that the active flow control methods initiated just in front of a foot of a shock and its effects on the shock position.

In summary, the use of mini swirling air jet vortex generators (Mi-SAJVGs), which incorporate both translational and rotational velocity components, enhances jet momentum within the boundary layer, effectively counteracting adverse pressure gradients induced by unsteady shock waves. When compared to the reference case, Mi-SAJVGs exhibit a more gradual pressure shift across the shock. Aerodynamic improvements are evident, as

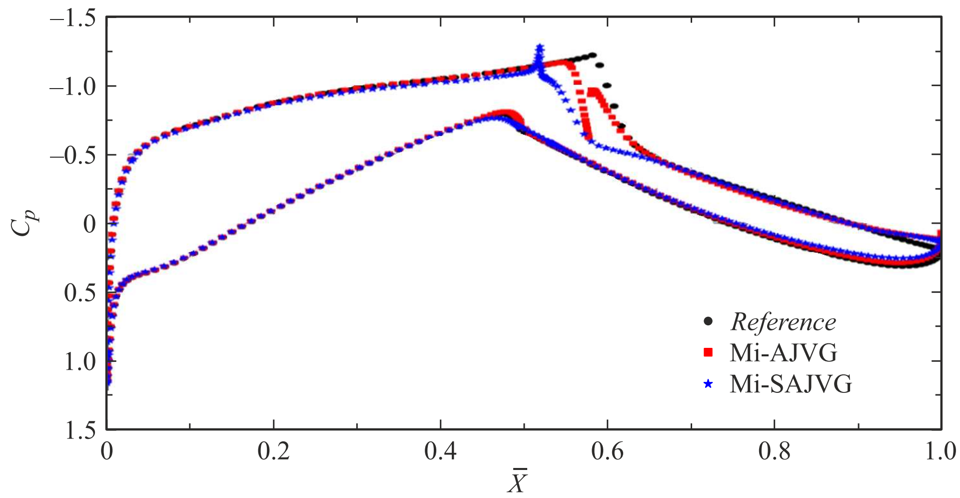

Figure 3. Comparison of pressure coefficient distribution at $M_\infty = 0.75$ and $\mathrm{Re} = 3.0 \cdot 10^6$ with and without flow control.

demonstrated in table. Furthermore, the introduction of an additional velocity component generates more persistent longitudinal vortices, which extend further along the wing chord at higher velocity ratios. These findings highlight the effectiveness of Mi-SAJVGs in improving aerodynamic performance and controlling shock-induced flow separation.

Conflict of interest

The authors declare that they have no conflict of interest.

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