Far field behavior of wingtip vortices under synthetic jet actuation

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Wingtip vortices are an undesired byproduct of finite-span lifting wings because of their adverse effects on flight efficiency and safety, i.e. induced drag and wake hazard. As such, active flow control technologies have been applied over the years trying to reduce the long-lasting nature of the wingtip vortices by prematurely triggering the inherent long-wave or Crow (1970) and short-wave or Widnall (1975) instabilities. In particular, the use of synthetic jets (SJs) allows to enhance the growth rate of the vortices by adding turbulence, momentum, and vorticity to the flow with a variable frequency and zero-net-mass-flux. Magaris and Gursul (2006) and Dghim et al. (2020) demonstrated the benefits of this device in alleviating the vortex strength with a significant reduction of the maximum induced velocity and vorticity peak up to 60% in the near wake. In the present work, a far-wake investigation up to 40 span lengths downstream of a finite-span wing has been conducted to analyze the effectiveness of the synthetic jet control tuned to the inherent instability frequencies of the vortices in different blowing configurations.

The experiments have been performed in the Laboratoire de Mécanique des Fluides de Lille (LMFL) boundary layer wind tunnel which has a test section 2 m wide, 1 m high and 20.6 m long. The wing model is a NACA 0015 rectangular finite-span wing, with a chord $c = 0.05$ m and a wingspan $b = 0.1$ m, resulting in an aspect ratio 2. The synthetic jet is generated by a 50 W loudspeaker (Ciare HW100) placed at the basis of the wing support. The air runs throughout the support and the wingspan ending at the tips in two rectangular slots, which are 0.5 mm high and 30 mm wide, positioned at 3.2 mm from the leading edge. Stereoscopic particle image velocimetry (SPIV) is used to measure the instantaneous three-component velocity field in a plan orthogonal to the flow at several stations downstream of the wing. Illumination is provided by a double pulsed Nd:YAG Innolas laser (150 mJ per pulse). Images are acquired by two LaVision’s Imager sCMOS cameras (2160 × 2560 pixels, pixel pitch of 6.5 $\mu$m) in forward scattering on one side of the wind tunnel, producing a field with a spatial resolution of about 14 pixel/mm. The images were processed with a homemade algorithm of LMFL which is a multi-grid multi-pass with image deformation at the final pass. The 3D reconstruction uses the Soloff method. A total of 4500 image pairs have been acquired and phase-locked measurements have been conducted dividing the periodic phenomenon in 15 phases, yielding 300 fields per phase. All the experiments have been conducted at $Re_c = 2.86 \cdot 10^4$. The free-stream velocity $U_\infty$ is 8.6 m/s.

The synthetic jet is operated at a momentum coefficient $C_p = 0.2\%$ and dimensionless frequencies $F^+ = 0.0698$ and $F^+ = 0.558$ tuned to the Crow or Widnall instability, respectively. The contour maps of the normalized time-averaged vorticity for the investigated cases are reported in Figure 1. Here, the dashed black line represents the projection of the wing trailing edge onto the measurement plane.

As it can be noted from the baseline cases, the wingtip vortices increase their size and naturally reduce their strength propagating downstream due to their mutual interaction. Under the control configuration tuned to the Crow and Widnall instabilities, the vortices appear to diffuse over a wider area, characterized by a smaller vorticity gradient too. The SJ actuation leads to a vorticity peak reduction of 35% and 58% for the downstream location $z/b = 13$, while slightly lower effects are registered for the remaining locations (-30%, -40% for $z/b = 26; -19\%$, -24% for $z/b = 40$). The Widnall instability-based control leads to an elliptic deformation of the wingtip vortices’ cores differently form what observed for the Crow instability-controlled configuration. This can be clearly deduced from the phase-averaged oscillations present in the two cases and reported in Figure 2 for the $z/b = 13$ plane. At greater distances, it is difficult to detect the wingtip vortices’ cores during the complete synthetic jet actuation period. Indeed, the synthetic jet, during its blowing phase, forces the wingtip vortex causing a complete break up of its coherence at these locations.
Figure 1: Contour maps of the time-averaged normalized streamwise vorticity at (a, d, g) $z/b = 13$, (b, e, h) $z/b = 26$ and (c, f, i) $z/b = 40$, for (a-c) baseline case, (d-f) Crow controlled case, (g-i) Widnall controlled case.

Figure 2: Phase-averaged evolution of the vortices’ positions at $z/b = 13$ for (left) Crow and (right) Widnall controlled cases. The time-averaged baseline positions are marked with a red cross, while the gray lines represent the $\pm 45^\circ$ directions.

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References


