On the effect of low blowing ratio continuous jets on wingtip vortex characteristics

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Vortices are an unavoidable effect of flight, which appear behind the wing with a bounded length. The strength of these vortices, which are extremely stable, is due to the lift force [1]. That is the reason why this phenomenon is especially relevant during take-off and landing operations. In these situations, when aircraft are departing from or arriving to the airport runways, the following aircraft might feel two counter-rotating vortices which remain long time under normal environmental conditions. Unfortunately, this huge rotation of airflow patterns always destabilizes the following aircraft. Consequently, trailing vortices have a mighty influence on the air traffic control of airport runways, and they have justified the research interest in this topic since the 1960s [2]. However, aeronautical engineers are still searching for different technological strategies to breakdown these wingtip vortices.

![Fig. 1 3D Schematic of experimental setup: wing model NACA0012 in a support moving from right to left (1), perspex channel (2), laser sheet (3), guide rail (4), velocity control of guide rail (5), high speed camera (6), and blue iron structure (7). The inset on the right represents a 3D front view with both the syringe and the connection to the NACA0012 wing model. The inset on the top left shows the wing model dimensions (l, c) and the direction of the injection, whereas the inset on the top right shows the detail of the wing model fastening to the guide rail.](image)

There are research works related to the above problem aiming to the characterization of these vortices to reduce the associated hazard [e.g., 3, 4]. Multiple solutions based on the perturbation of the flow with oscillating elements which are located on the wings, such as vortex generators or devices in flags [5–7] have been suggested. These techniques, which use spanload modifications, are denominated Passive Control.

The techniques that affect the vortex through forcing by an actuator are defined as Active Control. These methods take into account wingtip blowing, synthetic jets and morphed wings. Blowing was the first technique and the most studied by researchers, probably due to its easier implementation. The treatment of active control strategies with

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low-intensity continuous blowing jets, and its performance using theoretical models have not been reported widely in the State of Art. This is the main motivation of the current work which deals with the experimental investigation of the effect of continuous jets actuation in the spanwise direction, and blowing from the tip of a wing model NACA0012 airfoil (see Fig. 1).

Different chord-based Reynolds numbers \( Re = c W_\infty / \nu \), where \( W_\infty \) is the velocity of the airfoil inside the water tank and \( \nu \) is the kinematic viscosity of the fluid and jet-to-crossflow blowing ratios \( R_{jet} = \frac{W_{jet}}{W_\infty} \) where \( W_{jet} \) corresponds to the injection velocity have been analyzed. The cases studied here were \( R_{jet} = 0, 0.75, 1, \) and 2 plus three Reynolds numbers: \( Re = 7 \times 10^3, 15 \times 10^3, \) and \( 20 \times 10^3 \).

We show in Figure 2(a)-(b) how these jets are good candidates to reduce the strength of the wingtip vortices at the lowest Reynolds numbers considered, e.g. \( Re = 7 \times 10^3 \).

However, as it is shown in Figure 2(c)-(d) the forcing has a weak influence on the vortex strength in the near-field once the rolling-up process has already finished, and especially at axial distances greater than 7 chords behind the wing, at \( Re = 15-20 \times 10^3 \).

The reason for the presence of two different strength decays depending on the Reynolds number is explained by the ability of the continuous jet to break the vorticity sheet creating a counter-rotating vortex and a co-rotating vortex at low and high values of \( Re \), respectively.

This mechanism makes the wingtip to decrease or remain its vortex strength as we apply different blowing ratios \( R_{jet} \). This effect is evident at the lowest Reynolds number studied at which we observe a strong vortex decay. Conversely, the continuous jet changes the characteristics of the vortex flow in the formation and the near-field evolution of the wingtip at high Reynolds numbers, but there is not an appreciable effect on both the vortex strength and its downstream

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Fig. 2  Results obtained for the maximum azimuthal velocity \( V_{\theta, max} \) and circulation \( \Gamma \) for \( Re = 7 \times 10^3 \) (a)-(b) and \( Re = 15 \times 10^3 \) (c)-(d)
We make use of theoretical models reported by Batchelor [8] and Moore and Saffman [9] to provide five theoretical parameters which offer a general, and quantitative characterization of the influence of continuous jets on the wingtip vortex. To sum up, Batchelor’s models includes two parameters: \( S \), which represents the vortex strength, and \( z_0B \) which represents one free parameter to settle a virtual vortex origin in the streamwise direction.

\[
\nabla = \frac{S}{\rho} \left( 1 - e^{\eta} \right),
\]

where

\[
S = \frac{\Gamma}{2 \pi c W_\infty},
\]

\[
\eta(\bar{r}, \bar{z}) = -\frac{\bar{r}^2}{4 \left( \bar{z} - \bar{z}_0B \right)}.
\]

In terms of the non-dimensional variables, Moore & Saffman’s solution for the azimuthal velocity follows the expression

\[
\nabla = \frac{b}{(\bar{z} - \bar{z}_{0MS})^{n/2}} V_n(\eta),
\]

where \( b \) is a non-dimensional constant related to the vortex circulation, \( n \) represents the vortex decay exponent (\( r^n \) is the external behavior of the azimuthal velocity outside the vortex core), \( \bar{z}_{0MS} \) is the virtual origin of Moore & Saffman’s model, and \( V_n(\eta) \) depends on the gamma function and the hyper-geometric function of the first kind.

Fig. 3  \( S \) and \( b \) against \( z/c \) for several \( R_{jet} \) at two Reynolds number: \( 7 \times 10^3 \) (a)-(b) and \( 15 \times 10^3 \) (c)-(d).
In Fig. 3 we represent the mean value obtained from the experiments for $S$ and $b$ at Reynolds numbers $7 \times 10^3$ (a)-(b) and $15 \times 10^3$ (c)-(d), for different values of $R_{jet}$. Again, it is depicted in these figures how the continuous blowing jet has a strong influence on the vortex strength for the lowest $Re$ considered, being the best candidates to diminish the vortex circulation $R_{jet}$ between 0.75 and 2. On the other hand, the blowing jet is weakly affected at higher $Re$ for which both parameters $b$ and $S$ present a similar behavior.

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