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Numerical Investigation on the Effect of Active Injection Location on the Frequency Response of a Batchelor Vortex

Manuel Garrido–Martín[1], Francisco J. Blanco–Rodríguez[2], Paloma Gutierrez–Castillo[1], and Carlos del Pino[1]

manolouma@uma.es

[1]Departamento de Ingeniería Mecánica, Térmica y de Fluidos, Universidad de Málaga, Spain
[2]Departamento de Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla, Spain

This study investigates the effect of the variation of the active control application distance on the frequency response of a Batchelor vortex. The theoretical base flow pertains to the experimental configuration of a wing model with a NACA0012 airfoil at an angle of attack of α=9° and a chord-based Reynolds number of Re_c=40000. The injection was implemented using punctual and annular jet configurations. The findings of this research will serve as a basis for the optimization of the experimental parameters that characterize potential candidates for active control.

1 Introduction

Wingtip or trailing vortices are generated by aircraft due to the presence of lift forces in wings, remaining for a long time over airport runways. These persistent and highly rotating axial flows (Jacquin and Pantano, 2002) are, in fact, the main reason for the restrictive rules in air traffic management and close UAVs flight configuration (Z. Yu *et al.*, 2018). Therefore, the decay of trailing vortices is a fundamental problem in fluid mechanics and constitutes the basis of control applications that intend to alleviate the wake hazard.

A possible strategy to alleviate vortices would be an efficient vorticity reduction using an active control device based on pulsating spanwise blowing of a jet (J. H. García-Ortiz *et al.*, 2020). The importance of accurately tuning the experimental parameters that characterize the active control, namely the distance of application of the jet to the vortex core, has been previously noted (Tobias Bölle *et al.*, 2023), observing qualitative differences in the vortex response.

2 Numerical methodology and results

The numerical base flow used has been obtained by adjusting the theoretical parameters of Batchelor's model from 3D-2C PIV data. The experimental data has been divided into three areas: near (NF), intermediate (IF) and far-field (FF), since it provides a better understanding in terms of vorticity decay (Gutierrez-Castillo *et al.*, 2022).

We carried out the frequency response of the q-vortex, $[\boldsymbol{U}(r,\theta), P(r,\theta)]^T$, using 2-D simulations of the linear equations forced by a given out-of-plane (axial) wavenumber (Blanco-Rodríguez *et al.*, 2016). The equations are solved in a rectangular periodic domain of size L_x and L_y and periodic boundary conditions.

We used forcing jets that act only in the axial direction ($\mathbf{f} = F_z(x,y,t)\,\mathbf{e}_z$) varying harmonically in time with a frequency ω_f as

$$\mathbf{f}(x,y,t) = W_f(x,y)\left(\mathrm{e}^{i\omega_f t} + c.c.\right)\mathbf{e}_z. \quad (1)$$

The spatial structure of the axial forcing jet is given by

$$W_f(x,y) = \eta\,\mathrm{e}^{-\beta\, d^2(x,y)}, \quad (2)$$

where η is the maximum value of the forcing and β is a parameter that governs the jet spreading. Two different spatial configurations are proposed in this work: an annular jet (AJ) centered in the vortex axis which is applied at $r = a_f$,

$$d^2(x,y) = (r-a_f)^2, \quad a_f = 2, \quad (3)$$

and an off-axis (θ_f) single-point injection (SPI) which is located at a distance a_f of the vortex center

$$d^2(x,y) = (x-x_c)^2 + (y-y_c)^2, \quad \theta_f = \pi/3, a_f = 2, \quad (4)$$

where (x_c, y_c) is the vortex center.

The variation of the gain at large times, G_∞, is studied for a constant k and ω_f. We define $G(t)$ as

$$G(t;k,\omega) = \frac{\int_{\mathcal{D}} (u\,u^* + v\,v^* + w\,w^*)\;dx\,dy}{\int_{\mathcal{D}} W_f^2\,dx\,dy}. \quad (5)$$

A parameter analysis has been conducted on the axial wavenumber k and the forcing frequency ω_f, revealing that the highest gains correspond to low values of k and values around $\omega_f = 0.1$. Once we select a particular set of these parameters, we study the effect of the distance of the forcing jet to the vortex core. Not only does the steady gain value change significantly, but the flow structures also exhibit two distinct patterns, as it can be observed in the axial vorticity plots shown in Figure 1.

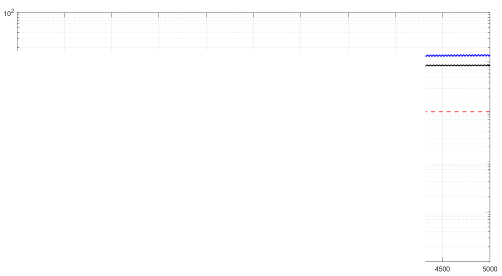

Figure 1: Time evolution of the energy gain of Batchelor's experimental vortex in two different SPI jet configurations, ($q = 4$, $Re = 300$, $a_f = 0$, in blue) and ($q = 4$, $Re = 300$, $a_f = 6$, in black) for the same axial wavenumber $k = 0.001$ and forcing frequency $\omega_f = 0.1$.

3 Conclusions

A parametric study of the active control of a trailing vortex has been achieved through the frequency response analysis of a Batchelor vortex varying the jet type and its distance to the vortex center. Different numerical base flows obtained from experimental data were also analyzed, ranging from the near to the far field of the vortex domain. The influence of the active control is clear not only in terms of the gain but also in the main vortex structure. Further investigation is necessary to complete the flow characterization to optimize the active control.

Acknowledgements

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