

Modal decomposition of actuated wingtip vortices by a pulsating active control in a 2D3C-PIV system

M. Garrido-Martin^{1,*}, P. Gutierrez-Castillo¹, F. J. Blanco-Rodríguez², A. J. Hijano¹, C. del Pino¹

1: Institute for Mechatronics Engineering and Cyber-Physical Systems (IMECH.UMA), Universidad de Málaga, Spain

2: Área de Mecánica de Fluidos, Departamento de Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla, Spain

*Corresponding author: manolouma@uma.es

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ABSTRACT

The reduction of wingtip vortex strength generated by aircraft is a key objective in modern aeronautics, as the persistence of these rotating flow structures represents a potential risk to flight safety and drives operational restrictions in air traffic management. An experimental active control based on a pulsating synthetic jet is proposed to reduce the strength of wingtip vortices. The pulsating injection supports the interaction with the intrinsic modes of the vortex, for which a correct determination of its governing parameters, such as frequency and location, is critical. The proposed experiments are performed using a 10-meter water towing tank at the Laboratory of Aero-Hydrodynamics at the University of Málaga. A synchronized 2D3C-PIV system is used to obtain the full velocity field of the actuated wingtip vortices. Several pulsating actuations are tested, measuring the effectiveness of the proposed active control in the evolution of maximum streamwise (axial) vorticity and the dissipation rate of the wingtip vortices. Modal-based decomposition techniques are applied as complementary tools to extract the dominant structures (energetic and unstable) and the associated temporal dynamics from the experimental data.

1. Introduction

Wingtip vortices dictate both aerodynamic efficiency and operational safety in modern commercial aviation. As the primary source of induced drag, they account for approximately one-third of a civil aircraft's total drag during cruise. Mitigating these vortical structures therefore yields highly significant reductions in both fuel consumption and environmental emissions. Furthermore, the persistent trailing wake shed by heavy aircraft creates severe rolling-moment hazards for following aircraft. To avoid this, strict minimum separation distances are prescribed by the International Civil Aviation Organization (ICAO), which inherently limit runway throughput and global airport capacity.

Before effective mitigation strategies can be designed or deployed, a rigorous characterization of the baseline vortex flow field is paramount. Accurately quantifying parameters such as the core radius and peak tangential velocity is essential to understanding the vortex's formation and evolution (see del Pino, Parras, et al. (2011); del Pino, López-Alonso, et al. (2011)). Driven by this baseline data, the fundamental analysis of vortex stability with respect to infinitesimal disturbances becomes possible. Understanding these underlying hydrodynamic mechanisms is the key to deliberately triggering early vortex breakdown, accelerating wake decay, and accurately predicting secondary phenomena such as contrail formation. Once the natural instabilities of the characterized vortex are identified, they can be intentionally exploited to reduce the wake's lifetime.

To exploit these destabilizing mechanisms, active control strategies provide a highly effective, dynamically adaptable framework. Unlike fixed passive devices optimized for a single cruise condition, like winglets, active systems can be engaged or modulated in real-time. Within fluidic control, synthetic jets (zero-net-mass-flux jets) are particularly advantageous. By generating high-momentum fluid pulses alternating with suction phases, they successfully inject energy directly into the vortex core or its surrounding shear layer to trigger instability. Because they accomplish this without requiring complex plumbing or an external fluid supply, synthetic jets represent an ideal, lightweight candidate for next-generation active vortex mitigation.

Building upon this framework, the present paper introduces an active control device based on synthetic jet actuators for targeted vortex mitigation in the axial direction. Whereas previous attempts have been presented by García-Ortiz et al. (2020); Zaccara et al. (2022, 2023); Scala et al. (2026), the present conceptual design and operational parameters of this system are fundamentally grounded in the numerical results obtained for a parallel Lamb-Oseen vortex, as previously detailed in Blanco-Rodríguez et al. (2016); Garrido-Martin et al. (2025).

In order to characterize the proposed actuator efficacy, Stereo-PIV is performed on the actuated wingtip vortices, comparing the results with baseline experiments without active actuation. Additionally, to accurately isolate the underlying instabilities and optimize the proposed active control strategy, advanced modal decomposition techniques, in particular Proper Orthogonal Decomposition (POD) and Higher Order Dynamic Mode Decomposition (HODMD), are applied to process the obtained high-dimensional flow data and extract dominant coherent structures, pinpointing the precise modes responsible for natural vortex decay, see Gutierrez-Castillo et al. (2022).

The remainder of the paper is organized as follows: Section 2 details the experimental setup, including the proposed actuator and 2D3C-PIV equipment. Section 3 presents the wingtip velocity results obtained from Stereo-PIV for different actuations. Section 4 discusses the modal decompo-

sition findings, identifying the dominant modes within the base and actuated flow field. Finally, Section 5 summarizes the key findings and outlines the main conclusions.

2. Experimental setup

In the present work, a novel active control device based on the application of synthetic jets to wingtip vortices is introduced. The device, whose design has been recently submitted for evaluation as a Spanish National Patent (del Pino et al., 2026), features an internal conduit within the wing model whose exit is oriented in the streamwise direction. This configuration enables a pulsating synthetic jet to be precisely applied at a specific radial location of the wingtip vortex. Characterized by an exit section that approximates localized momentum injection, this proposed actuator is hereafter referred to as the Single Point Injection (SPI) device. The driving mechanism of the device consists of a hydraulic cylinder (15 mm diameter, 53 cm stroke) driven by a servomotor coupled with a screw transmission and a 10:1 reduction gearbox. This cylinder pushes water through a polyamide tube connected directly to the submerged wing model on the towing guide. The test subject is a 3D-printed NACA0012 wing model with a chord length $c = 10$ cm and a semi-aspect ratio of $sAR = 2$. This wing model has been manufactured via 3D printing using VeroBlue RGD840 photopolymer resin, and includes the SPI device with an outlet located at a spanwise spacing of 15mm to the wingtip (see Figure 1).

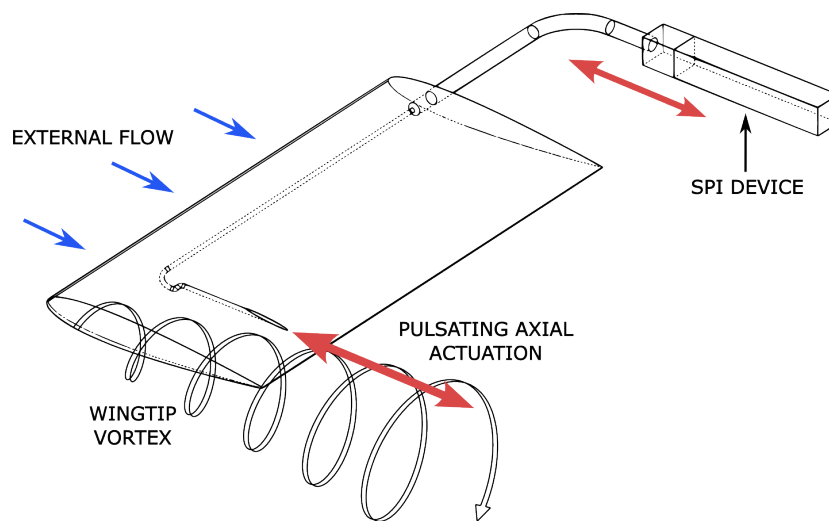


Figure 1. 3D diagram of the NACA0012 wing model and the proposed synthetic actuation device.

The temporal velocity profile of the injected jet is strictly controlled via a PC, which generates a sequence of GCODE commands defining the piston's displacement and velocity. This digital control architecture allows for the precise creation of highly customizable injection waveforms, including

sinusoidal, square, or sawtooth functions. To verify the fidelity of the prescribed waveforms, thorough calibration tests were conducted for piston velocity amplitudes ranging between 0.000853 m/s and 0.08 m/s, and frequencies between 0.1 and 2 Hz. Piston displacements were initially recorded using a 30 fps camera and compared against the GCODE reference positions. As shown in Figure 2 (left), the piston accurately follows the commands up to the manufacturer's mechanical limit of 2400 mm/min (0.04 m/s). For smaller amplitudes, where short piston displacements reduce optical tracking precision, the pulsating flow was validated by connecting a 1 mL syringe to the terminal end of the polyamide tube (Figure 2, right).

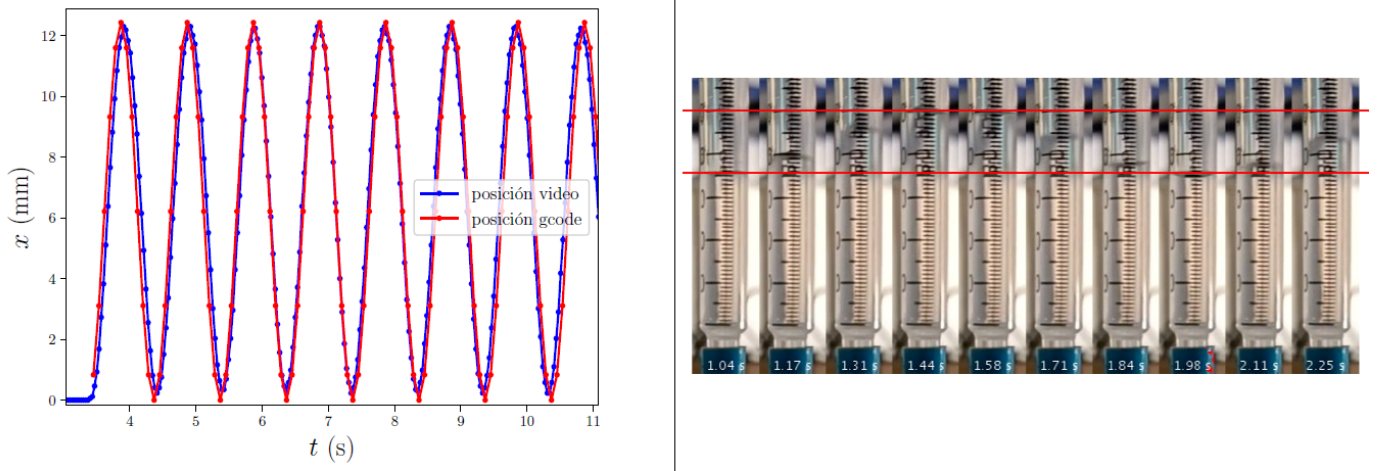


Figure 2. Calibration of the SPI device: (left) position x (mm) of the piston of the syringe obtained at 30 fps (blue curve) compared with the reference position specified in the GCODE command file (red curve), for a frequency of 1 Hz and a piston velocity amplitude of 0.04 m/s, and (right) pulsation of the injected water in a 1 mL syringe connected at the end of the guide, for a piston velocity amplitude of 0.0025 m/s and a frequency of 1 Hz. The red lines indicate the oscillation limits of the syringe volume, with the smallest scale divisions corresponding to 0.1 mL.

The experiments were conducted at the Laboratorio de Aerohidrodinámica de Vehículos of the Universidad de Málaga (LAHV-UMA). The primary facility is a 10-meter-long water towing tank with a $500 \times 500 \text{ mm}^2$ cross-section, constructed with 25-mm thick perspex walls to easily provide optical access for flow visualizations (see Figure 3 (a)). A key advantage of this facility is that the fluid remains entirely quiescent prior to testing; the absence of mechanical pumps or moving parts within the water ensures exceptionally low background turbulence levels of $< 0.1\%$. Additionally, the extensive length of the tank allows for the continuous observation of the vortex evolution over a wide range of chords downstream. The traverse system consists of a linear guide mounted on a steel frame and supported by four nylon wheels. The carriage is driven by a servomotor coupled with a pulley and toothed-belt system. During the experimental runs, the wing model is set to a specific angle of attack α and displaced at a constant axial velocity U_∞ in the Z -direction. To capture the full velocity field of the actuated wingtip vortices, a synchronized Stereoscopic Particle Image Velocimetry (2D3C-PIV) system from Microvec is utilized (see Figure

3 (b)). The measurement framework relies on a fixed laser sheet while the wing model travels through it. The fluid is seeded with neutrally buoyant, silver-coated glass spheres with a diameter of $10\ \mu\text{m}$. Their neutral buoyancy is critical, as it minimizes any relative motion between the tracer particles and the surrounding fluid caused by gravitational or severe centrifugal effects inherent to strong vortical flows. Illumination is provided by a dual-pulse laser (a solid-state, double-cavity, flashlamp-pumped Nd:YAG system). The laser emits a $532\ \text{nm}$ wavelength sheet with a repetition rate of $15\ \text{Hz}$, delivering an output energy of $2 \times 200\ \text{mJ}$ per pulse and a pulse duration of 8 to $12\ \text{ns}$. The flow field is recorded by two cameras positioned on one side of the towing tank and arranged at a mutual viewing angle of 90° . The angular stereoscopic PIV configuration is used to reduce the measurement uncertainty of the out of plane component of the velocity vector, which decreases by increasing the angle between the cameras. These cameras are equipped with Nikon PC-E Micro Nikkor $45\ \text{mm}\ f/2.8\text{D}$ lenses. They feature a 5-megapixel CCD sensor with a resolution of 2448×2050 pixels and a pixel size of $3.45\ \mu\text{m}$. The cameras operate at an overclock frame rate of $16\ \text{Hz}$, and a configurable shutter speed chosen appropriately for the maximum observed velocities as $4\ \text{ms}$. The synchronization between the stereo cameras, the double-pulse laser, and the pulsating active control device is strictly managed by an external synchronizer. Finally, and to perform the modal decomposition analysis with higher resolution along the axial direction, plain 2D2C-PIV is performed via a high-speed camera parallel to the Z-direction.

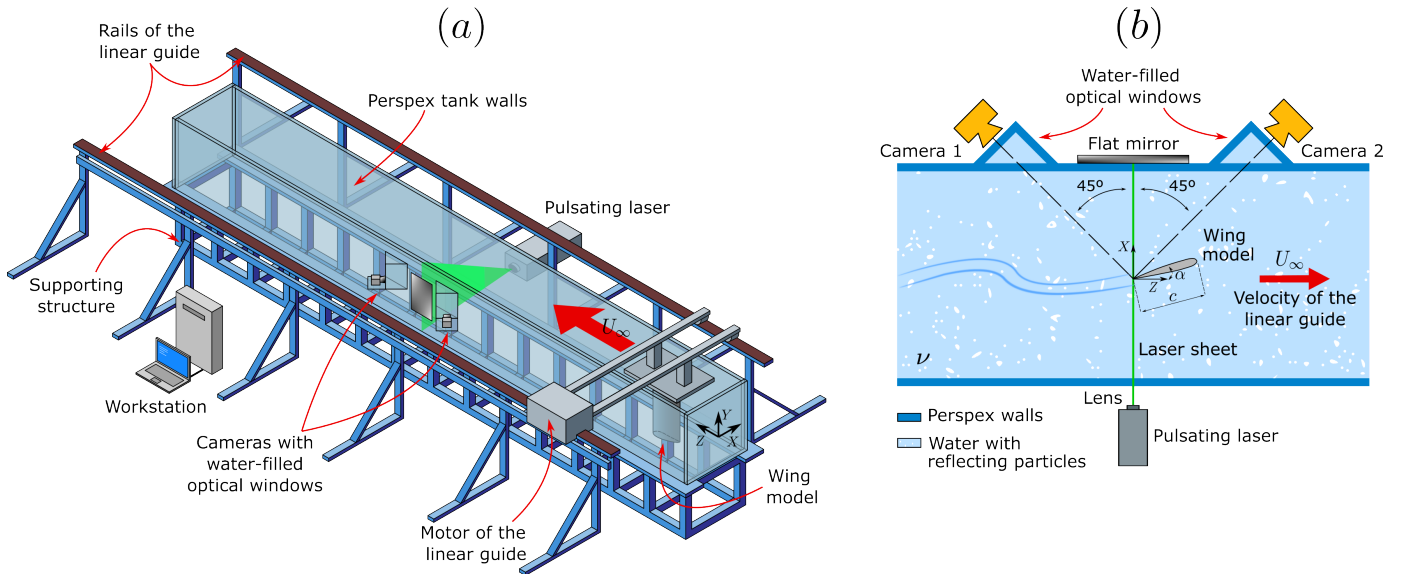


Figure 3. Schematics of the experimental setup at University of Málaga: 3D diagram of the water towing tank (a) and 2D3C-PIV configuration (b).

The velocity fields were extracted from the acquired particle image sequences utilizing the GPU-accelerated DPIVSoft software Aguilar-Cabello et al. (2022). The cross-correlation evaluation employs an interrogation window-shifting technique coupled with a multi-iterative, double-pass

window deformation scheme. The stereo reconstruction algorithm chosen is that commonly referred to as warping, described in Soloff et al. (1997), that uses a gradient based formulation to avoid the image de-warping step and applies directly the PIV algorithm on the recorded images. To calibrate the 2D3C-PIV system, images were acquired of a dual-plane calibration target aligned parallel to the laser sheet. The target features a grid of dot markers with a 10 mm spacing, facilitating robust detection via standard image-processing techniques. Distributing these markers across two distinct out-of-plane Z-positions enables a highly precise determination of the stereoscopic transformation functions.

3. PIV results

Prior to analyzing the experimental outcomes, the fundamental parameters governing the flow and actuation must be established. The baseline wingtip vortex strength is primarily dictated by the chord-based Reynolds number, $Re_c = \frac{cU_\infty}{\nu}$, which is set to $Re_c = 40,000$ throughout this study. The operational frequency f of the SPI device is non-dimensionalized as the reduced frequency, $f^* = \frac{fc}{U_\infty}$. Meanwhile, the actuation amplitude is characterized by the peak jet velocity, u_{jet} , generated over a full oscillation cycle. To guarantee that the SPI device introduces strictly small-amplitude perturbations, thereby preserving the energetic efficiency and practical engineering feasibility of the active control strategy, the jet velocity ratio u_{jet}/U_∞ is usually maintained below unity.

Representative 2D3C-PIV velocity fields for both the baseline (without SPI actuation) and SPI-actuated cases are compared in Figure 4. The momentum injection does not visibly alter the macroscopic axisymmetric topology of the vortex; notably, the axial velocity distribution preserves its centered Gaussian profile. Cross markers denote the computed vortex centers within each sub-plot.

Experiments were conducted across a range of reduced frequencies and for two distinct output jet velocities. The primary metric evaluated for effective wingtip vortex mitigation is the maximum axial vorticity. Figure 5 (left) illustrates the relative reduction in peak axial vorticity compared to the unactuated baseline over the downstream spatial domain $z/c = [2, 20]$. All tested actuation scenarios successfully achieve a net decrease in peak vorticity, with the $f^* = 0.56$ configuration yielding particularly promising results with an approximate reduction of 9%. Notably, a substantial increase in the output jet velocity does not significantly alter this favorable trend within the observed parametric range. Furthermore, for the mentioned actuation case, the axial evolution of the azimuthal velocity radial profile is shown in Figure 5 (right). Here, it can be observed the substantial decrease of the peak tangential velocity along the axial direction of the actuated case (blue curve) with respect to the base case (red curve).

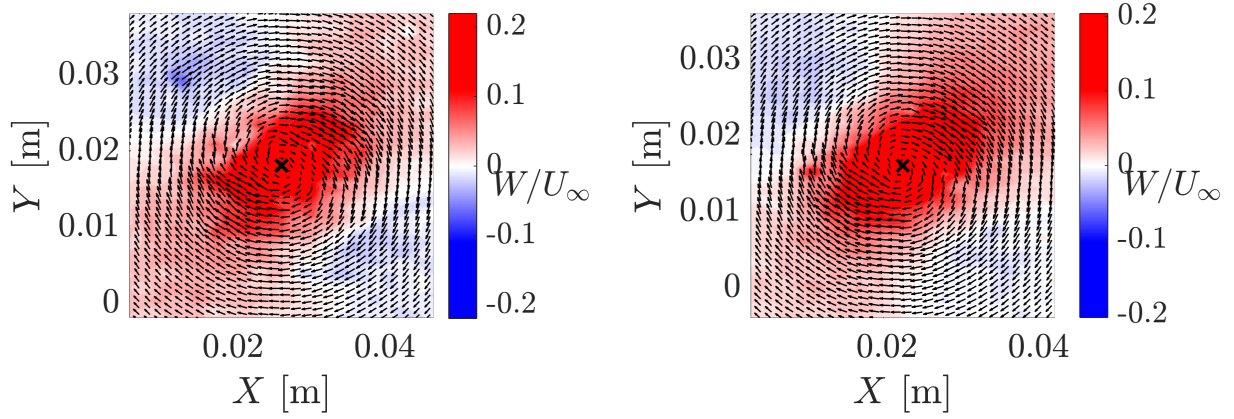


Figure 4. Comparison of 2D3C-PIV fields for a non actuated vortex (left) and actuated vortex with $f^* = 0.56$ and $u_{jet}/U_\infty = 0.66$ (right), both at an axial position of $z/c = 46$.

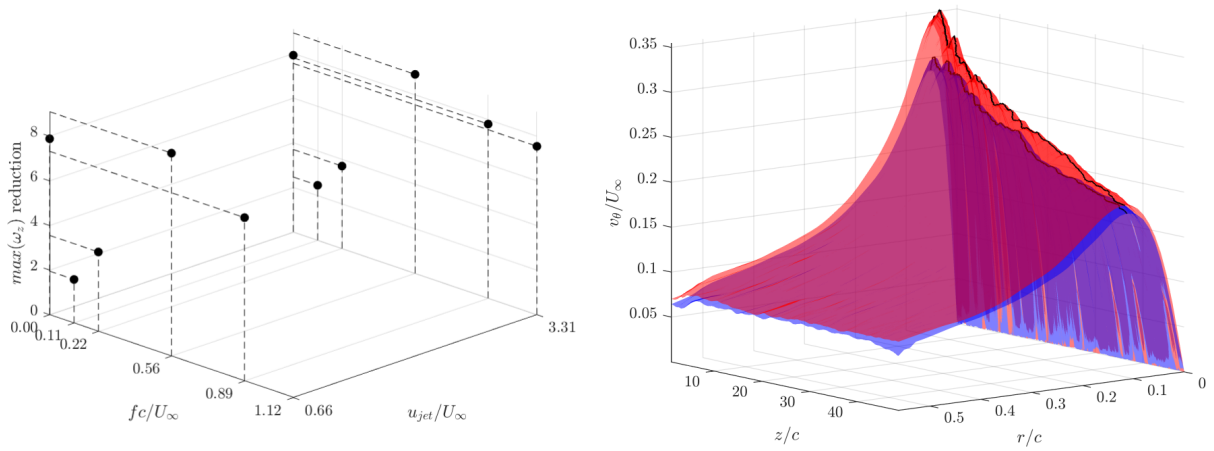


Figure 5. On the left, average percentage reduction of the maximum axial vorticity, computed over the non-actuated case, for different actuation frequencies and injection velocities, in the axial range $z/c = [2 - 20]$; on the right, comparison of the axial evolution of the azimuthal velocity radial profile for both the base case (red curve) and the actuated case (blue curve) with $f^* = 0.56$ and $u_{jet}/U_\infty = 0.66$.

4. Modal decomposition results

Having identified $f^* = 0.56$ as the optimal actuation frequency, modal decomposition is applied to both this actuation configuration and the unactuated baseline. The present analysis focuses specifically on decomposing the spatial distribution of axial vorticity. While alternative flow variables, such as axial velocity, could similarly be analyzed, their comparative study is deferred to future research. To characterize the dynamical behavior and isolate the dominant decaying mechanisms of the wingtip vortices, the spatio-temporal evolution of the axial vorticity field $\omega_z(\mathbf{x}, t)$ is analyzed using two complementary data-driven techniques: Proper Orthogonal Decomposition (POD) and Higher Order Dynamic Mode Decomposition (HODMD).

POD is applied to extract the most energetic coherent structures within the vortex wake. By computing an optimal orthogonal basis that maximizes the captured kinetic energy (or variance) of the snapshot sequence, the method effectively separates the spatial structures from their temporal evolution. The truncated POD reconstruction of the axial vorticity field is expressed as:

$$\omega_z(\mathbf{x}, t) \approx \sum_{i=1}^{N_{POD}} a_i(t) \Phi_i(\mathbf{x}) \quad (1)$$

where N_{POD} is the number of retained energetic modes, $\Phi_i(\mathbf{x})$ represents the i -th spatial POD mode, and $a_i(t)$ is its associated time-varying amplitude. While POD provides a rigorous energetic hierarchy of the vortex structures, it does not directly yield the spectral properties of the flow. To complement the energy-based approach, HODMD is utilized to extract spectrally pure structures and directly quantify the temporal attenuation of the vortex core. HODMD extends standard DMD by incorporating time-delayed snapshots (based on Takens' embedding theorem), making it highly robust against noise and exceptionally capable of identifying transient or decaying dynamics in complex flows. The reconstructed vorticity field is approximated as a linear superposition of spatio-temporal modes:

$$\omega_z(\mathbf{x}, t) \approx \sum_{k=1}^{N_{HODMD}} c_k(t) \Psi_k(\mathbf{x}) e^{(\delta_k + i\omega_k)t} \quad (2)$$

where N_{HODMD} is the number of retained dynamic modes, $\Psi_k(\mathbf{x})$ is the complex spatial mode, and c_k is its modal amplitude. Crucially, the temporal dynamics are governed by the oscillation frequency ω_k and the growth/decay rate δ_k . By isolating the fundamental modes where $\delta_k < 0$, the dominant spatial structures responsible for the viscous decay and diffusion of the wingtip vortex can be explicitly extracted and analyzed. Figure 6 shows some results obtained after applying both techniques.

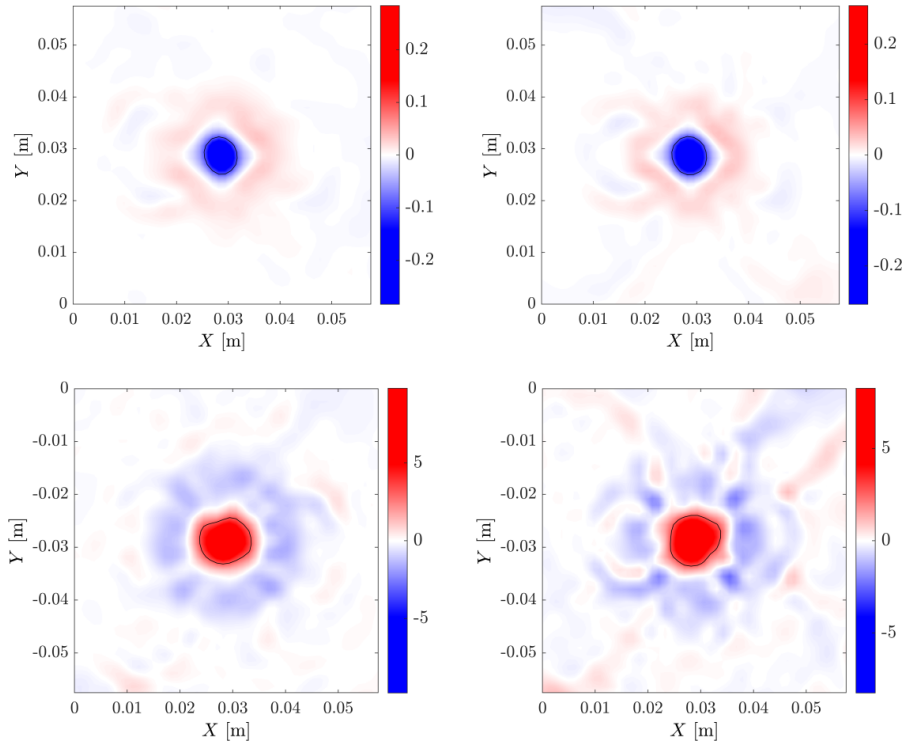


Figure 6. Selected spatial modes from POD (first row) and HODMD (second row), for both the base case (left column) and the selected actuated case (right row).

The selected spatial modes correspond to those exhibiting monotonic temporal decay for both the POD and HODMD techniques, with the latter demonstrating negligible oscillation ($\omega_k \approx 0$). Both methodologies successfully isolate a nearly axisymmetric structure that characterizes vortex mitigation along the axial direction. This modal extraction yields a critical reduced-order framework to inform the requisite forcing frequencies and amplitudes for the actuators, while simultaneously enabling the identification of unstable modes, as demonstrated by Gutierrez-Castillo et al. (2022). Although isolating these spatial coherent structures establishes a crucial baseline for comprehending wingtip vortex mitigation, it remains insufficient for drawing definitive conclusions regarding the underlying physical decay mechanisms. Consequently, future research must prioritize a rigorous investigation into the temporal dynamics associated with these modes, focusing specifically on the influence of modal attenuation rates, spectral characteristics, and frequencies.

5. Conclusions

Ultimately, this work successfully demonstrates the success of implementation of the proposed active control device and its capability to alter the axial evolution of wingtip vortices, promoting a significant reduction of their azimuthal velocity. By directly injecting momentum into the vortex core and surrounding shear layer, the system effectively accelerates the mechanisms lead-

ing to early vortex breakdown. However, comprehensively quantifying the overall efficiency of this actuation strategy remains a highly non-trivial challenge. A robust assessment cannot rely on aerodynamic improvements alone; rather, it demands a rigorous, multi-objective evaluation framework. Proving the ultimate viability of this technology will therefore require defining optimization criteria that guarantee a net-positive energy balance under operational flight conditions.

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Nomenclature

Re_c	Chord-based Reynolds number (-)
α	Angle of attack of the wing model (°)
U_∞	Axial velocity of the wing (m/s)
f	Actuation frequency of the SPI device (Hz)
u_{jet}	Actuation jet velocity of the SPI device (m/s)
ω_z	Axial vorticity (s^{-1})
PIV	Particle Image Velocimetry
2D2C	Two dimensional, 2 components (u,v) (referred to PIV)
2D3C	Two dimensional, 3 components (u,v,w) (referred to PIV)
POD	Proper Orthogonal Decomposition
HODMD	Higher Order Dynamic Mode Decomposition

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