Event-based imaging velocimetry for jet flow control

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Abstract

This study investigates the use of Event-Based Imaging Velocimetry (EBIV) as a viable sensing technology for optimising open-loop jet-flow control strategies. EBIV is deployed in a jet-control experiment in which the actuation system combines both acoustic and synthetic jet forcing; the resulting velocity fields are used to evaluate the performance of the control action. The goal is to develop and assess EBIV as a fast, reliable sensor in-the-loop to support advanced flow control optimization algorithms such as Bayesian Optimization and Deep Reinforcement Learning.

Introduction

Jet flows are fundamental in numerous industrial applications, ranging from the aerospace industry to the chemical sector. They impact key challenges in the aviation sector, such as reducing noise and pollutant emissions. Their control might enhance propulsion efficiency, mixing, combustion processes, heat transfer or noise emissions. Adaptive control strategies are crucial for enhancing efficiency and unlocking new capabilities, which can be hardly obtained by exploring the parametric space. Jet flow control has traditionally relied on high-frequency single-point sensing methods. These methods provide high-bandwidth flow data, often exceeding O(kHz) frequencies, making them suitable for real-time feedback control [1, 2]. However, they are typically intrusive and limited to point-wise measurements, requiring flow-state estimation from sparse data if full-field information is sought. This can be a limitation for jets, where coherent spatiotemporal structures play a dominant role in determining mixing, noise, and overall dynamics.

Particle Image Velocimetry (PIV) provides non-intrusive, full-field measurements, capturing key topological features of the flow that are essential for flow control. This enhances observability, improving state estimation and enabling more effective control strategies [3]. However, its high demands in data bandwidth and computational resources for processing have limited its use as an efficient flow sensor for control purposes. Event-Based Vision (EBV) sensors offer an efficient alternative for flow measurement by detecting contrast changes asynchronously at the pixel level, achieving high temporal resolution with reduced data bandwidth [4]. This enables effective frame rates of several kHz while maintaining a high dynamic range, making them particularly useful for challenging imaging conditions. A key advancement in this field is pulsed Event-Based Imaging Velocimetry (EBIV, [5]), which synchronizes the event detection with a pulsed laser, thereby mitigating the sensor latency and the limitations in the event rate. More recently, through synchronized PIV and EBIV experiments, including tests in air comparing EBIV to high-speed cameras, demonstrated that EBIV can reliably capture flow properties and dynamics and allow accurate estimation of low-order coordinates, validating its potential as a powerful and cost-effective tool for flow control applications [6].

The present study investigates the application of EBIV as an efficient and effective tool for jet flow control experiments. The objective is to optimize open-loop control policies with different objectives (e.g. mixing control, suppression of instabilities, etc.) using EBIV as a fast "highly-informed" estimator of the cost function.

Experimental Set-up

The experiments are conducted in the air jet facility located inside the anechoic chamber at *Universidad Carlos III de Madrid*. The setup consists of a round jet issuing from a nozzle with an exit diameter of $D = 20\,\mathrm{mm}$. To ensure turbulent boundary layer conditions in the nozzle, a tripping device is installed at the beginning of the nozzle contraction section.

The flow is seeded with $1\,\mu\mathrm{m}$ diameter droplets of Di-Ethyl-Hexyl-Sebacate (DEHS). A low-cost laser module (Lasertree LT-4LDS-V2), originally developed for engraving applications and delivering an optical power of 20 W, is used for flow illumination. The laser beam is pulsed and shaped into a thin light sheet of approximately 1 mm thickness through a set of lenses. The resulting laser plane is aligned with the longitudinal midplane of the jet.

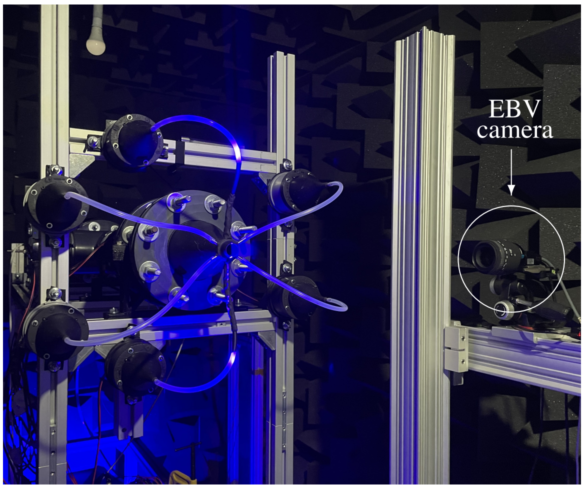

Figure 1: Experimental set-up showing nozzle, loudspeaker arrangement, and event-based camera.

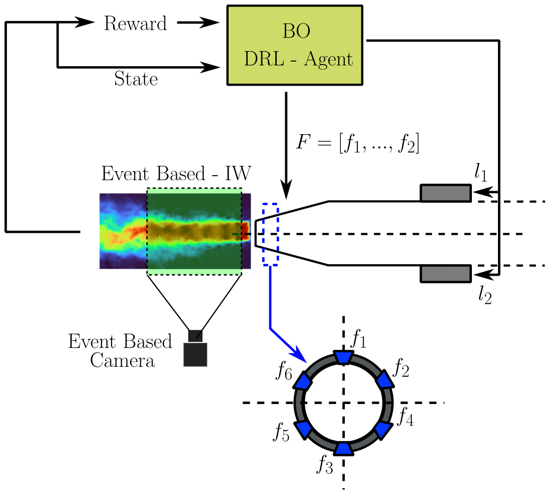

Figure 2: Implementation of EBIV in the control loop for jet flow control experiments.

The actuation system combines two types of forcing mechanisms. First, two counter-facing loudspeakers are flush-mounted inside the stagnation chamber to provide purely acoustic excitation. Second, six synthetic jets are azimuthally distributed around the nozzle, positioned one nozzle diameter upstream of the exit. Each synthetic jet actuator consists of a loudspeaker connected to a 3D-printed waveguide. These actuators are connected to the nozzle boundary layer via flexible silicone tubes and can be operated independently to allow phase- and frequency-specific control.

The experimental rig is illustrated in Figure 1, highlighting the arrangement of the loudspeakers, tubing, nozzle assembly, and the EBV camera. Control signals are generated using a National Instruments Compact-RIO (cRIO) system equipped with an NI-9263 module. The signals are then amplified by an 8-channel amplifier (Sirus I-Amp 8.150). All loudspeakers used in the setup, both for the stagnation chamber and the synthetic jets, are Dayton Audio ND65-4 compact models.

Flow measurements are acquired using a Prophesee EVK-4 event-based vision (EBV) camera featuring the IMX636 sensor, with a full resolution of 1280×720 pixels^2. A 50 mm objective lens was employed, resulting in a spatial resolution of approximately 20 pixels/mm. The laser module is controlled by an Analog Discovery device, which provides the pulsation frequency and the pulse width. This signal is also sent to the EBV camera, enabling synchronization of the laser pulse with the event stream. Both the Analog Discovery and the cRIO system are connected to a common PC. Figure 2 presents a schematic of the EBV camera integration within the control loop. The event data associated with each laser pulse are accumulated over a defined time window, termed the *accumulation time*, starting from the laser trigger. These events are processed into pseudo-images using conventional PIV algorithms to extract instantaneous velocity fields. Short sequences of events are recorded, processed, and analyzed to evaluate the control cost function and determine the next control episode.

The objective of this study is to integrate EBIV-based sensing with advanced control strategies, such as Deep Reinforcement Learning (DRL, [7]) and Bayesian Optimization (BO, [8]), which have already proven effective in complex flow control problems. This integration aims to establish a fast and efficient framework for real-time jet flow optimization.

Preliminary Results

A detailed characterization of the synthetic jet actuators has been performed using hot-wire anemometry, measuring the exit velocity of the jets. A mapping of the peak exit velocity U_p as a function of actuation frequency f and signal amplitude to the amplifier V_{0p} was obtained. An example of the characterization result is shown in Figure 3, showing the isolines for different desired U_p. For the current experiment, a constant U_p is imposed for all actuators. The actuation frequency f and phase ϕ of each actuator are individually optimized. From a practical standpoint, the signal amplitude required for each loudspeaker is selected from the isoline corresponding to the target U_p, based on the chosen actuation frequency.

A comparison between uncontrolled and controlled jet flow cases is presented in Figure 4 in terms of the time-averaged out-of-the-plane vorticity (ω_z). The results show the average vorticity field ω, computed from a 2-second acquisition period, corresponding to 3000 reconstructed velocity fields. The jet bulk velocity is set to

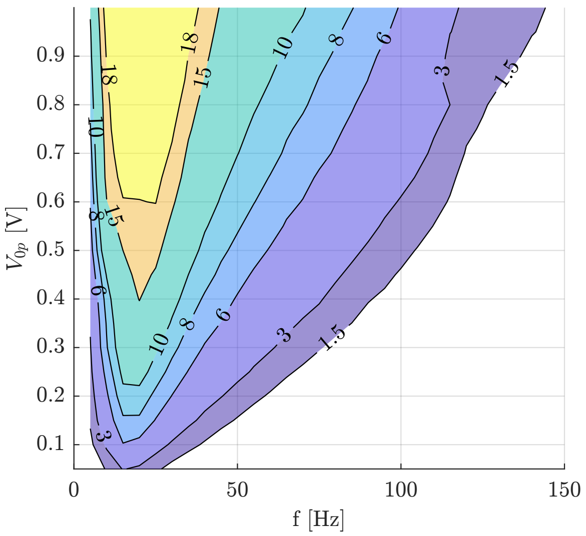

Figure 3: Characterization of the synthetic jet actuators. Isolines of the peak velocity U_p for values $U_p = \{1.5,\ 3,\ 6,\ 8,\ 10,\ 15,\ 18\}\,\mathrm{m/s}$, plotted as a function of actuation frequency f and input signal amplitude V_{0p}.

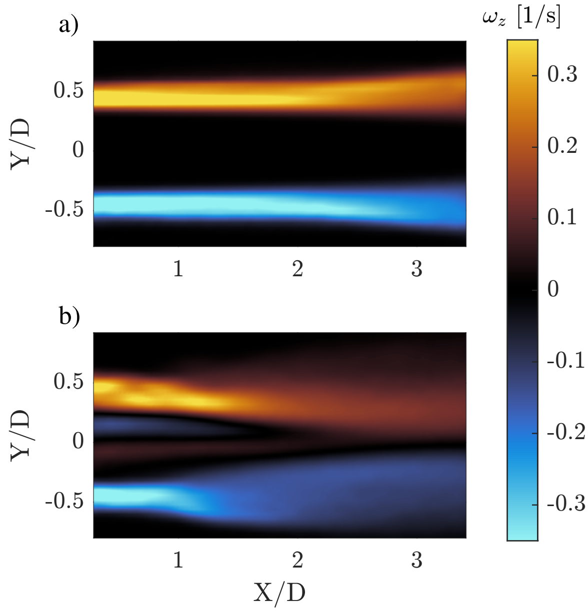

Figure 4: Comparison of out-of-plane vorticity fields ω_z for the uncontrolled (a, top) and controlled (b, bottom) jet flow. In the controlled case, the six synthetic jets are actuated at $f = 75\,\mathrm{Hz}$ with a phase shift of 60° between adjacent actuators.

$U_j = 1.5\,\mathrm{m/s}$, corresponding to a Reynolds number of Re $\simeq 2000$. The laser operates at a pulsing frequency of $f_{\mathrm{EBIV}} = 1500\,\mathrm{Hz}$. In the controlled case, the actuation is performed with a peak synthetic jet velocity of $U_p = 1.5\,\mathrm{m/s}$, resulting in a velocity ratio $U_p/U_j = 1$. The six synthetic jets are actuated at a frequency of 75 Hz, corresponding to a Strouhal number St $= 1$, where St $= fD/U_j$. A phase shift of 60° is applied between each adjacent actuator.

The upcoming conference presentation will showcase jet flow control results, highlighting how EBIV can serve as a fast reward and state estimator to optimize actuation strategies and actively modify the jet characteristics in real time.

Key Words: Flow control; Event-Based Imaging Velocimetry; Jet Flow; Synthetic Jets; Optimization.
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