

CLUSTER-BASED TRACKING METHOD FOR THE IDENTIFICATION AND CHARACTERISATION OF VORTICES

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ABSTRACT

An unsupervised, flow-agnostic and automatic cluster-based tracking algorithm for the segmentation of vortex-dominated flows has been successfully developed. It combines the Rortex method and density-based clustering algorithms. The Rortex method differs shear from rotation and overcomes the sensitivity to user-defined thresholds that characterises current practice of vortex identification methods. The algorithm is demonstrated with experimental Stereoscopic Particle Image Velocimetry data from two cases; a high-Reynolds ($\approx 10^6$) vortex generated by a half-delta wing, and distorted flow in a scaled-model of a civil aero-engine intake under cross-wind conditions. The approach is a successful method for the segmentation of complex vortical flows under a wide range of conditions.

NOMENCLATURE

$\varnothing$	Diameter, mm
h	Resolution of the experimental data, mm
L	Length, mm
M	Mach number
x, y, z	Cartesian frame of reference
X, Y, Z	Cartesian frame of reference upon rotation
u, v, w	Cartesian instantaneous velocities, m/s
U, V, W	Cartesian instantaneous velocities upon rotation transformation, m/s

Acronyms

AIP	Aerodynamic Interface Plane
AoA	Angle of Attack, degrees
CFD	Computational Fluid Dynamics
DBSCAN	Density-Based Clustering of Applications with Noise
GV	Ground vortex
VG	Vortex generator

Subscripts

<i>in</i>	Inlet value
<i>out</i>	Outlet value
<i>ref</i>	Reference value

Operators

$\langle \rangle$	Time average
$-$	Area average

Greek Symbols

δ	Distance from the trailing edge, mm
Γ	Circulation, ($\frac{m^2}{s}$)
θ	Angle of rotation transformation, degrees
ξ	Immersion of the vortex generator, mm

1. INTRODUCTION

Turbulent flows are critical for various industrial applications because of their effective mixing of mass, momentum, and energy. However, they also induce adverse effects such as cavitation and fluctuations, leading to inefficiencies and structural integrity risks [1]. A fundamental element of turbulence is the vortex. Despite its ubiquity, the lack of a rigorous mathematical definition has led to a trail of methods attempting their characterisation.

The vorticity, defined as the curl of the velocity vector, is a potential identification metric. Nevertheless, it does not provide physical insight into the mechanisms generating vorticity owing to its coupling with shear. An example of high values of vorticity due to shear, but not to rotating structures is the two-dimensional laminar boundary layer [2].

Other well-established approaches rely on the invariants of the velocity-gradient tensor (∇V), widely used in industry and academia. However, these methods also suffer from inherent shear noise due to their derivation from the velocity gradient tensor. Their reliance on abstract

eigenvalues or absolute differences of tensor components impedes a clear physical interpretation. In addition, they depend on user-defined thresholds without clear guidelines, leading to significant variability in vortex detection and boundary identification.

The first criterion based on physical significance is the Omega (Ω) method [3]. It defines Ω as the ratio of vortical vorticity to total vorticity. However, the mathematical modeling of the fluid element rigid-body rotation (vortical vorticity) was not developed at the time, and instead an approximation based on the conventional velocity tensor decomposition (Equation 1) was adopted.

$$\Omega = \frac{b}{a+b} \quad (1)$$

where a and b are the traces of the matrices A and B in Equation 2

$$\nabla V = \frac{1}{2}(\nabla V + \nabla V^T) + \frac{1}{2}(\nabla V - \nabla V^T) = A + B \quad (2)$$

Therefore, Ω is the ratio of total vorticity over the sum of deformation and total vorticity. These two magnitudes are not independent in Newtonian fluids, as fluid flow rotation always implies a degree of deformation. The method establishes that a vortex is present when the vorticity surpasses the deformation, providing physical meaning and the capability to isolate shear. Moreover, the method has an objective threshold, which has shown optimal performance at $\Omega \geq 0.52$ on numerical grounds[4].

The mathematical modeling of the rigid-body rotation is the Liutex method ([5], [6]). The existence of a unique rotation axis ($\vec{r}$) is proven for any ∇v , such that, if a rotation transformation from the original velocity tensor(∇v) in the reference frame x, y, z to ∇V referenced in X, Y, Z , where the new Z -axis coincides with the unitary vector $\vec{r}$ is performed, the rotation will be contained in the XY plane of the new frame. It uses the theorem that a tensor has no rotation around axis X_i if $\frac{\partial U_j}{\partial X_k} = 0$ [5]. The modulus of the vector is given by Equation 3.

$$R_Z = 2\omega_{rot} \quad (3)$$

where:

$$\omega_{rot} = \begin{cases} \beta - \alpha, & \text{if } \beta^2 - \alpha^2 > 0 \\ 0, & \text{if } \beta^2 - \alpha^2 \leq 0 \end{cases} \quad (4)$$

$$\alpha = \frac{1}{2} \sqrt{\left(\frac{\partial U}{\partial X} - \frac{\partial V}{\partial Y}\right)^2 + \left(\frac{\partial V}{\partial X} + \frac{\partial U}{\partial Y}\right)^2} \quad (5)$$

$$\beta = \frac{1}{2} \left(\frac{\partial V}{\partial X} - \frac{\partial U}{\partial Y}\right) \quad (6)$$

The Omega and Rortex methods, classified as the "third generation" vortex identification techniques by Liu et al. [2], address key limitations of vorticity- and eigenvalue-based methods, which are known as first

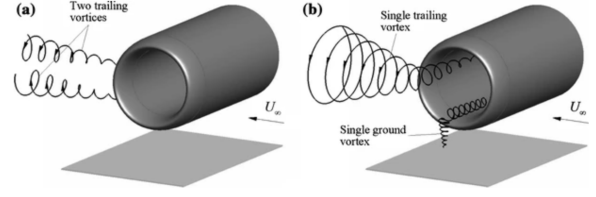


Figure 1: Potential ingested vortex of an aero-engine under crosswind conditions [16].

and second generation, respectively. As assessed in [7, 8, 9, 10], they mitigate issues such as shear contamination and sensitivity to user-defined thresholds.

While black-box, image-based AI methods have shown moderate success, they remain constrained by strong assumptions. For instance, the supervised machine-learning approach for vortex core detection proposed by Zhenguo et al. [11] relies on steady vortex assumptions and streamline-based methods. Such approaches require vortices to be well-formed and undistorted, which are not usually encountered in complex data. Additionally, the need for time-consuming manual labelling introduces subjectivity and reliance on expert judgement.

Aero-engine intakes have the purpose of conditioning the mass flow that enters the engine. Owing to their integration with the aircraft, the presence of the other relevant bodies, i.e. fuselage, wings or other control surfaces depending on their positioning, may imprint on the inflow of air certain disturbances. Given that the engine and aircraft manufacturers are different entities, industrial bodies have defined practices to ensure that the integrated systems perform as designed to. In the case of engine-aircraft integration, the Aerodynamic Interface Plane (AIP) is a plane located upstream the fan of the engine. In theory, designing the intake to match a defined pattern at the AIP guarantees that the engine ensure that the distortion pattern the fan will encounter. Next-generation aero-engines, featuring shorter or convoluted intakes, are expected to experience increased distortion levels [12]-[13]. The most common location for civil aero-engines is underwing, where extensive research of the intake performance has been conducted in the past [12], [14], to assess the distortion levels at the AIP. Distortion refers to the non-uniformity of a variable in the flow field. Therefore, all aero-engines perceive a certain level of distortion in their intakes, but are kept within admissible ranges to ensure fan-intake compatibility [15]. Elevated levels of distortion at the AIP may reduce the ingested mass flow and the fan operability margin or induce blade vibrations. A particular operating condition of interest is crosswind. Under this condition, several phenomena can take place as illustrated in Fig. 1.

The flow topology under crosswind conditions is com-

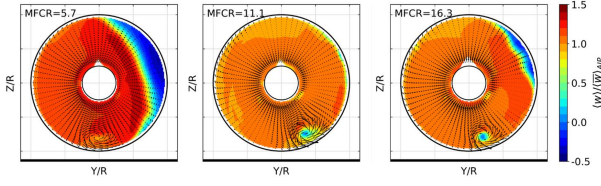


Figure 2: Flow topologies for a civil intake at crosswind across a range of Mass Flow Capture Ratios (MFCR). Left: Diffusion-driven separation (left), attached (middle) and shock driven separation (right). Ground vortex appears in all cases. View from upstream. Crosswind direction is right to left. [17].

plex owing to the number of elements that may be encountered depending on the operating point. Fig. 2 illustrates three characteristic patterns in civil intakes under crosswind conditions, in which there are different flow physics. It includes diffusion-driven separation, attached flow, shock-driven separation and a ground vortex due to the proximity with the ground plane.

There is a strong industrial interest to understand the distortion impact on the engine performance to support early-design optimisation and future certification programmes. For that purpose, developing the capability to replicate complex intake patterns in test rigs is crucial to advance the understanding of the generation, characterisation, and interaction with downstream turbomachinery [18] of distortion patterns at the AIP.

Advanced experimental techniques, such as Stereoscopic Particle Image Velocimetry (S-PIV) [19], offer the high spatial resolution which enables the understanding of the complex flow topologies across an representative AIP plane. Previous research where unsteady measurements were conducting using S-PIV aiming to to characterise the flow at the AIP are ([13], [20], [17]). Pivovesan et al. [17] studied the segmentation of the topology at a plane upstream a turbofan of a civil aero-engine scaled model under crosswind conditions is carried out. In the cases where two or more phenomenon coexisted in the plane, multiple methodologies were combined. There was not a unique method able to segment the full flow field without prior knowledge.

This paper presents an unsupervised algorithm for high Reynolds number ($\approx 10^6$) applications integrating third-generation vortex identification methods [2] using density-based clustering to segment flow. No spatial constraints are needed to mitigate noise sensitivity and is not constrained by fully circular vortex disks which is the case with previous methods [17]. The method was verified in two different flow fields. Firstly, a representative conical vortical flow generated by a half-delta wing vortex generator (VG) for a range of conditions. The second case is a representative flow upstream of a rotating fan on civil aero-engine short-intake under crosswind condi-

tions.

The application of this method enables robust identification and characterisation of complex distorted flows that are present in closely coupled aircraft-engine configurations ahead of the engine face, and are known to penalise the performance and stability of the entire propulsion system. The potential impact of the knowledge gained through the use of this tool is the education on early-stage design which impact the fan performance and stability. Subsequently, it can be used to establish guidelines for testing and certification programs of novel architectures.

2. EXPERIMENTAL SET UP AND DATA PROCESSING

2.1 Half Delta Wing Test Rig Set-up

The measurements were carried out in the facility for complex intakes at Cranfield University. The straight-centreline test rig is shown in Fig. 3. It houses a half delta wing in the vortex generator box. The diffuser is characterised by the inlet diameter ($\varnothing_{in} = 121.6mm$) and the area ratio ($\frac{A_{out}}{A_{in}} = 1.52$). The rig is sucked-driven with a centrifugal compressor downstream.

The half delta wing has sharp leading and trailing edges. Its support system consists of a sharp-edged rectangular splitter plate where several bolt positions are manufactured to enable the variation of the Angle of Attack (AoA) to -6° or -12° (Fig. 5). It is attached to a handling bar, which enables the accommodation of the VG in the vortex generator box and the regulation of the immersion (ξ) into the free-stream flow.

2.1.1 Instrumentation

The wake was characterised at two downstream location; one $1.6D_{in}$ upstream the diffuser inlet and the second one $0.5D_{in}$ downstream the diffuser outlet (Fig. 6). They also correspond to a downstream distance from the trailing edge (δ) of $3.3c$ and $8.3c$ respectively.

The velocity measurements were taken using a S-PIV two-camera set-up. The optical equipment is mounted in a bench structure to enable optical access for the cameras and the laser. Cameras were CMOS Phantom v2512 with a sensor resolution of $1280 \times 800 px^2$, mounted with 105mm focal length lenses. Cameras rough locations are displayed in Fig. 6. The time lapse between frames, exposure time, stand-off position, stereoscopic angle and tilt angle were optimised for both configurations. The light pulses were supplied by a dual-pulsed Nd:Yag laser with $532nm$ wavelength accommodated underneath the optical section. The beam was deployed into a laser sheet through a 20mm cylindrical lens. Seeding consisted of Di-Ethyl-Hexyl-Sebacate particles. The velocity field acquisition frequency was set to $8 kHz$ for both planes. For

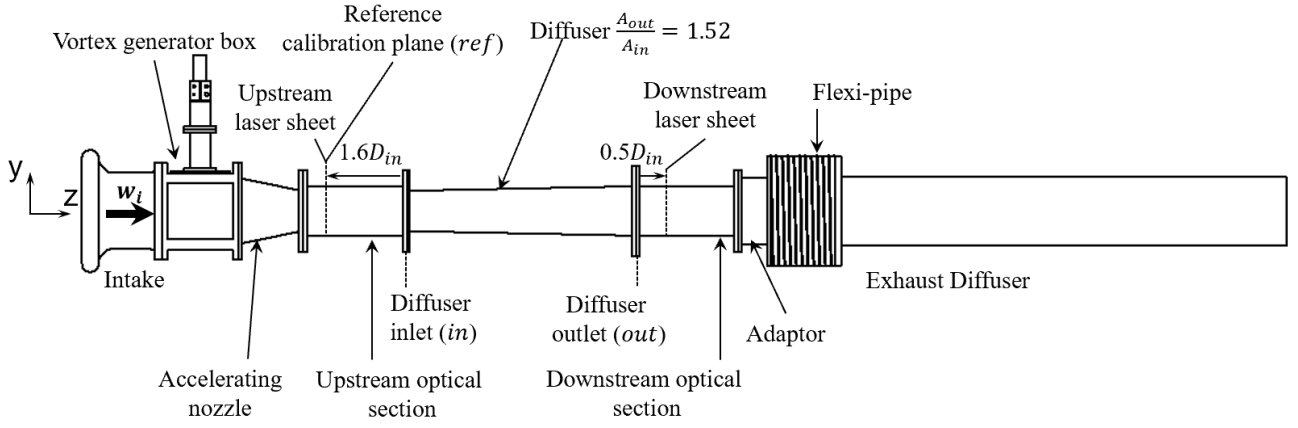


Figure 3: Side view schematic of the straight-centreline test rig.

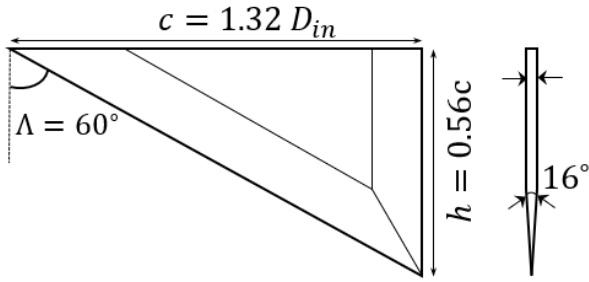


Figure 4: Vortex generator schematic.

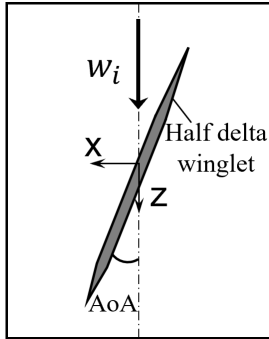


Figure 5: Vortex generator orientation. Definition of the AoA.

each study case, a population of 20,000 instantaneous flow images were acquired.

2.1.2 Operating Conditions

The VG is geometrically characterised by its chord and sweep angle (Λ). The operating conditions are given by AoA, ξ and the free-stream Mach number (M_∞). The Reynolds numbers per unit length ($\frac{Re}{L}$) are $6.8 \cdot 10^6$ and $1.5 \cdot 10^7$, respectively. The test matrix is listed in Table 1.

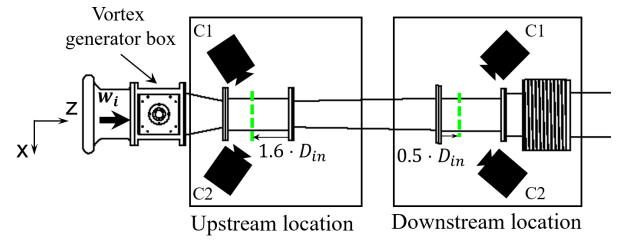


Figure 6: Top view of the test rig and cameras assembly for both measuring locations.

chord c [mm]	M_∞ [-]	Inmersion ξ [mm]	AoA $[\circ]$
160	0.27	0	-6°
			-12°
		-25	-6°
			-12°
	0.6	0	-6°
			-12°
		-25	-6°
			-12°

Table 1: Cases studied at both plane locations ($\delta = 3.3c$ and $\delta = 8.3c$).

2.2 Civil aero-engine under crosswind conditions data

To further verify the method, a more complex flow field was utilised from a previous experiment with a civil aero-engine at crosswind conditions. The experiments were conducted at the Large-Low-speed-Facility (LLF) of the German-Dutch Wind tunnels (LLF-DNW)[21]. The test rig accommodates a nacelle housing, rotating fan and conical centre body. The axisymmetric intake model is a $1/13^{th}$ scale of a representative large civil aero-engine. The air was drawn in by the fan driven by

a turbine power simulator. The model was perpendicular to the incoming flow to simulate the crosswind conditions. The intake model is a $1/13^{th}$ scale representative of a civil aero-engine. The intake model was tested at a fixed ground clearance of $\frac{h}{D_{hi}}$, where h is the vertical distance between the ground plane and the leading edge of the intake bottom lip and D_{hi} is the intake highlight diameter. The measurement plane, which is representative of the AIP, was located in front of the rotating fan (Fig. 7) [21]. The dataset presented here correspond to a fixed crosswind velocity ($v_{crosswind}$) for two mass flow capture ratios (MFCR); low MFCR case and a high MFCR case. These two cases were selected because of their different flow topologies ahead of the fan face. The low revolution case is representative of the engine starting, and the ground vortex is not sufficiently strong to maintain its position. Hence, the diffusion of the structure is discussed. The high revolution case presents a ground vortex at the bottom of the AIP and a diffusion-driven separation region.

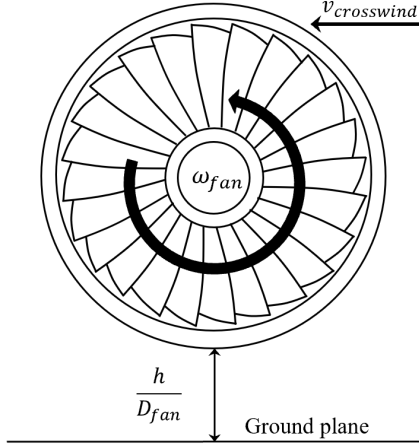


Figure 7: Crosswind test rig schematic with fan. View from upstream.

3. VORTICAL STRUCTURES CHARACTERISATION AND ANALYSIS ALGORITHM

The algorithm first locates and characterises the region in the plane where a high-density of peak Rortex values are located in time. The characterisation of the vortical structures was carried out by computing of their circulation in each snapshot. Finally, the region is excluded for further iterations.

The inputs were the in-plane horizontal and vertical velocity fields (u, v) for the N snapshots to study (Fig. 8, step 1) in each case. The distribution of the Rortex values (Fig. 8, step 2) for each snapshot was calculated by applying equations 4, 5, and 6. To ensure

that the relevant structures were captured regardless of the orientation of the rotation, the data were divided into positive and negative Rortex values. From the distribution, the maximum Rortex value coordinates are stored, which enables plotting the locations of the peak values, the 'Peak Rortex Map' (Fig. 8, step 3). The rationale behind such vortex-location criterion is that, in the presence of a persistent rotatory vortical structure, the peak value over time should be primarily within its region. Subsequently, a density-based clustering is applied to the map. Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [22] is selected due to its widespread use, proven reliability, and the minimal number of hyperparameters to tune. It discards the scattered points as noise and groups the remaining points in clusters. It is imposed that the cluster with the highest number of instances is selected as the potential vortical structure (Fig. 8, step 4). The 'Cluster Area' is defined by its centroid, $C_{cluster}$ (Eq. 7) and a scaled characteristic ellipse, given by its two main semi-axis $r_x^{ellipse}$ and $r_y^{ellipse}$ (Eqs. 8 and 9).

$$C_{cluster} = \frac{1}{N} \sum_{i=1}^N i; \quad i = x, y \quad (7)$$

$$r_x^{ellipse} = SF \cdot \left| \frac{x_{max}^{peak} - x_{min}^{peak}}{2} \right| \quad (8)$$

$$r_y^{ellipse} = SF \cdot \left| \frac{y_{max}^{peak} - y_{min}^{peak}}{2} \right| \quad (9)$$

where x^{peak}, y^{peak} are the coordinates of the points in the cluster and SF is a scaling factor. The next step (Fig. 8, step 5) is the characterisation of the structure, which is carried out by sweeping over the N snapshots of the dataset, limiting the Rortex peak location to the 'Cluster Area'. The DBSCAN must be applied again to select the vortex core. Potential sources of several clusters or noise are experimental noise, vortex shedding, diffusion, displacement or interaction. The vortex is quantified through its circulation value. To ensure adaptability to any shape, the cluster may present, the circulation is calculated with its discretised form (Eq. 10).

$$\Gamma = \sum_i^{n_{cluster}} \omega_i \cdot A_i \quad (10)$$

The overall characterisation of the vortex is defined by the statistics of the circulation values, namely the time-average ($\langle \Gamma \rangle$) and standard deviation ($\sigma(\Gamma)$). For the second and consecutive iterations, this is the stop-criterion evaluation point. An order-of-magnitude drop has been found to be a suitable criterion for the data fed into the algorithm so far. Therefore, the iterations would stop if the circulation of the latest structure is lower than 10% of the circulation of the first identified.

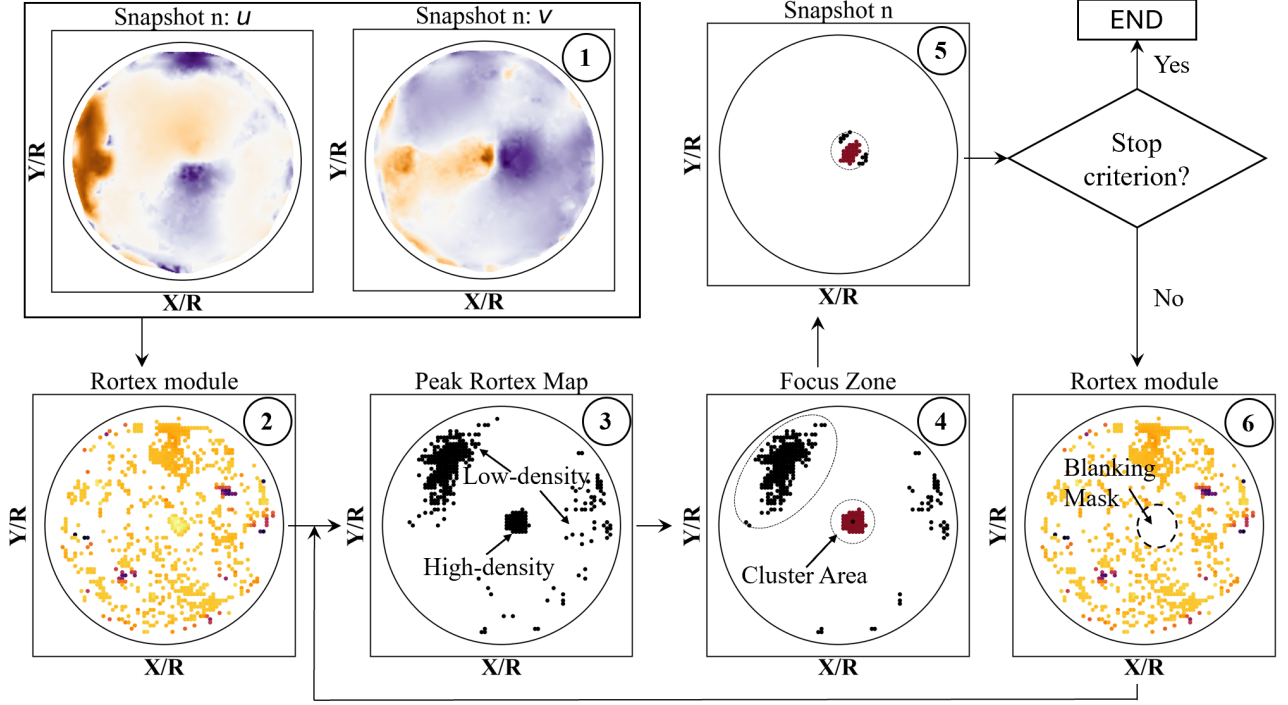


Figure 8: Workflow diagram.

$$\langle \Gamma_n \rangle \leq 0.1 \cdot \langle \Gamma_1 \rangle \quad (11)$$

The underlying hypothesis in the vortex pinpointing assumption is that the peak Rortex value will be within the area of the vortex, which does not pose the risk of overlooking other vortices of similar strength. This is a reasonable assumption for persistent vortical structures because the Rortex value is the module of the strength of the fluid element rotation.

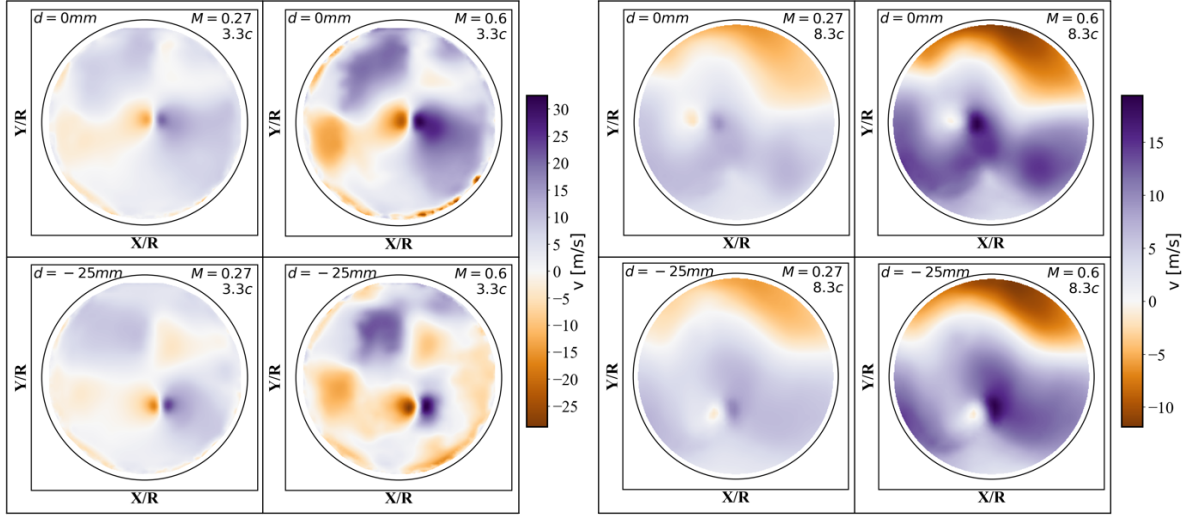
DBSCAN has two hyperparameters that require tuning: k , the minimum number of points required for an aggregation to be categorised as a cluster and ϵ , the maximum distance between two points to belong to the same cluster. Similar to any other machine learning algorithm, the performance accuracy must be verified. Nonetheless, in this type of clustering where no labelling is available, tuning of the hyperparameters is empirical and must be checked for every database whose underlying physics substantially differs. From the definition provided in [5], “A vortex is a connected region where $R \neq 0$ ”, it is evident that $k \approx 2$. However, it would be desirable for ϵ to be as low as possible (in terms of the resolution, h). For the results in this study, the hyperparameters of the DBSCAN applied in the ‘Peak Rortex Map’ are $k = 2$, $\epsilon = 3h$, while those in the vortex identification are $k = 2$, $\epsilon = 2h$ for both databases. An elliptical shape was selected to characterise the region given that it accommodate complex vortical structures that can be identified in

real world problems. The scaling factor is empirically determined, with a value of 1.5 providing sufficient margin to accurately identify the primary vortex within this relatively noise-free dataset. However, in scenarios involving more complex phenomena, such as interactions or densely packed structures, the scaling factor can be adjusted or tailored to achieve optimal performance for specific applications. Although circulation is a vorticity-based metric, it is used for comparison because of its extensive presence in the literature. In this work the use of discretised circulation (Eq. 10) is justified as a mean to avoid any assumption on the cluster shape.

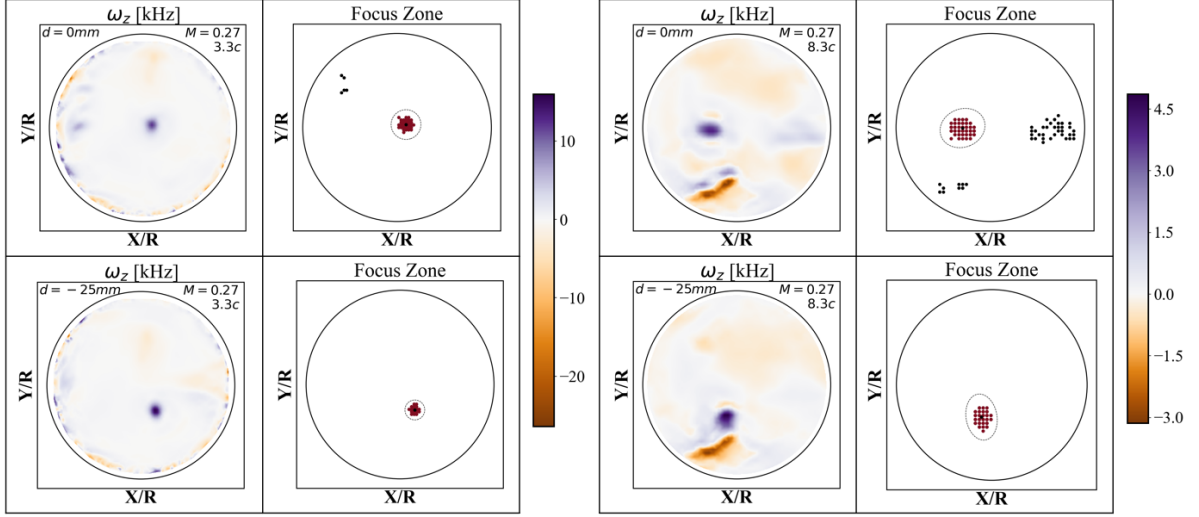
4. RESULTS AND DISCUSSION

4.1 Half Delta Wing Vortex

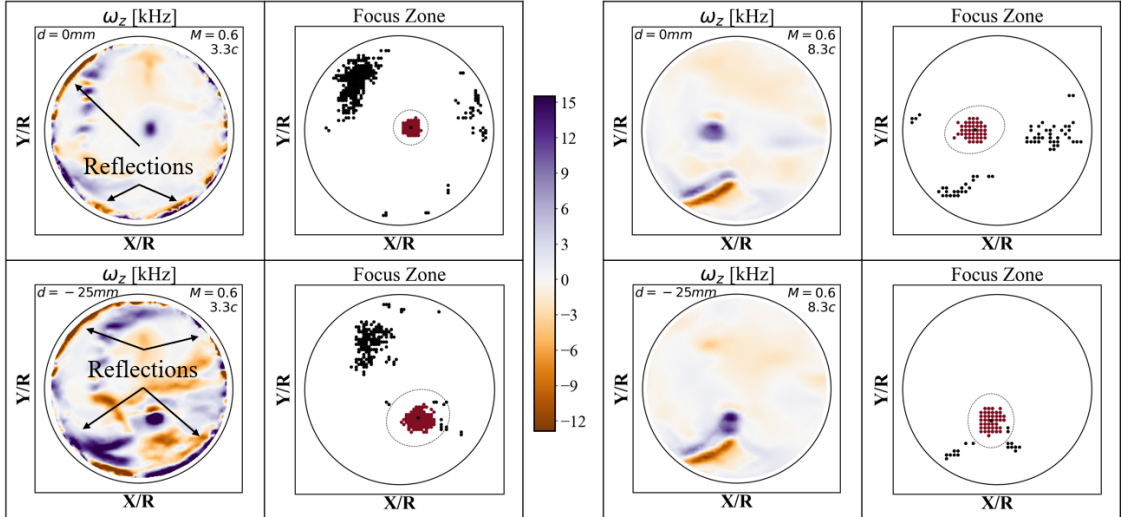
The presented findings offer valuable insights into the vortex structure, intensity, and persistence under varying conditions of the angle of attack (AoA), immersion ratio (ξ), and Mach number (M), based on experimental measurements of the half-delta wing. Fig. 9a illustrates the average vertical in-plane velocity component for all the cases with $AoA = -12^\circ$. The cases with $AoA = -6^\circ$ were discarded given that there was no coherent vortical structure at any of the downstream positions measured. The expected influence of immersion is evident, and manifests as the vertical displacement of the vortex. While visualizations alone do not provide conclusive evidence



(a) Average vertical in-plane velocity for both M_{ref} , immersion and downstream distance at $AoA = -12^\circ$.



(b) Vorticity and vortical region at $AoA = -12^\circ$ and $M_{ref} = 0.27$.



(c) Vorticity and vortical region at $AoA = -12^\circ$ and $M_{ref} = 0.60$.

Figure 9: Flow properties from S-PIV measurements. Red-coloured represents high-density region, black low-density region of peak Rortex values. The dotted line is the vortical region identified by the method described in Section 2 for cases with $AoA = -12^\circ$.

regarding vortex intensity, circulation measurements suggest relative strength values that are not directly comparable to prior studies in the literature. This is because of the presence of a contracting section between the vortex generator and the measurement planes. Prior studies on vortex evolution through contracting ducts in these type of ducts indicate that the circulation levels might be higher than in a constant-diameter duct due to the vortex intensification in these scenarios [23]. These observations indicate that future investigations into vortex dynamics should focus on high AoA values.

Regarding vortex identification, the employed methodology effectively isolates the primary vortex despite the presence of experimental noise. Fig. 9b and 9c illustrates the vorticity and the region of the vortex located by the method for $M_{ref} = 0.20$ and 0.60 respectively in the upstream plane. No other iterations outcomes are shown given that they are discarded by the algorithm as they are not relevant structures. Finally, with respect to the downstream measurement distances, the results confirm that the vortex persists even at $AoA = 12^\circ$, remaining detectable up to 8.3 chord lengths downstream. This finding suggests that the vortex retains sufficient coherence for further downstream development analysis, thereby reinforcing its relevance in aerodynamic applications.

4.2 Application to civil aero-engine intake under crosswind conditions

Upon successful performance in the isolated vortex database, the proposed method was applied to a civil intake under crosswind conditions. Two cases defined by the fan rotational speed are employed. The first case presented is the high MFCR one. It is characterised by a ground vortex at the bottom, and a diffusion-driven separation region. The second case, at low MFCR, is characterised by a diffusive vortex at the bottom.

The results of the iterations performed by the algorithm on the high MFCR case are shown in Fig. 8. In the first iteration, the ground vortex was accurately detected (Fig. 10a). The second iteration highlighted a region in the plane that, despite exhibiting a uniform peak Rortex distribution, was revealed through individual snapshots to be an aggregation of smaller vortices. This corresponds to the diffusion-driven separation region (Fig. 10b). This observation is significant because it suggests that the method may be capable of capturing the physics-based formation of vortices. However, further studies on vortex structures generated through different mechanisms are required to confirm this hypothesis. The final iteration identified a zone that is discarded owing to its low strength relative to the other detected areas.

The results for the low MFCR case indicate that the vortex structures exhibit transient behaviour, with lim-

ited persistence over time (Fig. 11), which is characteristic of a highly diffused flow. Nevertheless, the method successfully isolates the vortices, with a clear displacement observable throughout the analysis. This effectiveness is largely due to the non-sensitive-to-noise mathematical modeling utilised, which enables reliable detection of vortices even in the presence of significant diffusion. However, given the dynamic nature of the flow and transient characteristics of the structures, further research is required to refine the tracking of vortices over time, particularly in terms of simultaneously identifying and monitoring multiple structures. Enhancing the method is necessary to improve its robustness in dealing with such complex, time-dependent scenarios.

5. CONCLUSIONS

This paper presents an unsupervised, automatic, flow-agnostic cluster-based tracking algorithm designed to segment vortex-dominated fields. By integrating the physics-informed Rortex method with density-based clustering techniques, the proposed framework offers a novel and effective approach for analysing and characterizing complex vortex structures. The methodology was successfully validated using two distinct datasets, demonstrating its flexibility and robustness.

Despite its advantages, the use of unsupervised DBSCAN introduces challenges, particularly in the manual tuning of hyperparameters, which may introduce user-bias. This limitation becomes particularly pronounced in flow fields characterized by highly diffused vortices or shedding phenomena. Future research will focus on exploring alternative clustering techniques and extending the framework to enable the temporal tracking of vortex structures, thereby enhancing its applicability and reducing reliance on manual adjustments.

Compared with existing methodologies, the proposed approach distinguishes itself through its fully data-driven clustering mechanism, which circumvents the need for predefined thresholds and heuristic criteria. These advancements have significant implications for fluid dynamics research, providing a systematic and adaptable tool for analysing intricate flow structures. The impact of this framework extends beyond high-Reynolds-number aerodynamic applications to any domain requiring precise vortex identification.

Future work will focus on enhancing the method with time-tracking capabilities to identify and monitor vortex evolution, enabling the analysis of vortex creation and dissipation processes, particularly in the cases discussed in Section 4.2. Techniques involving shape factor and

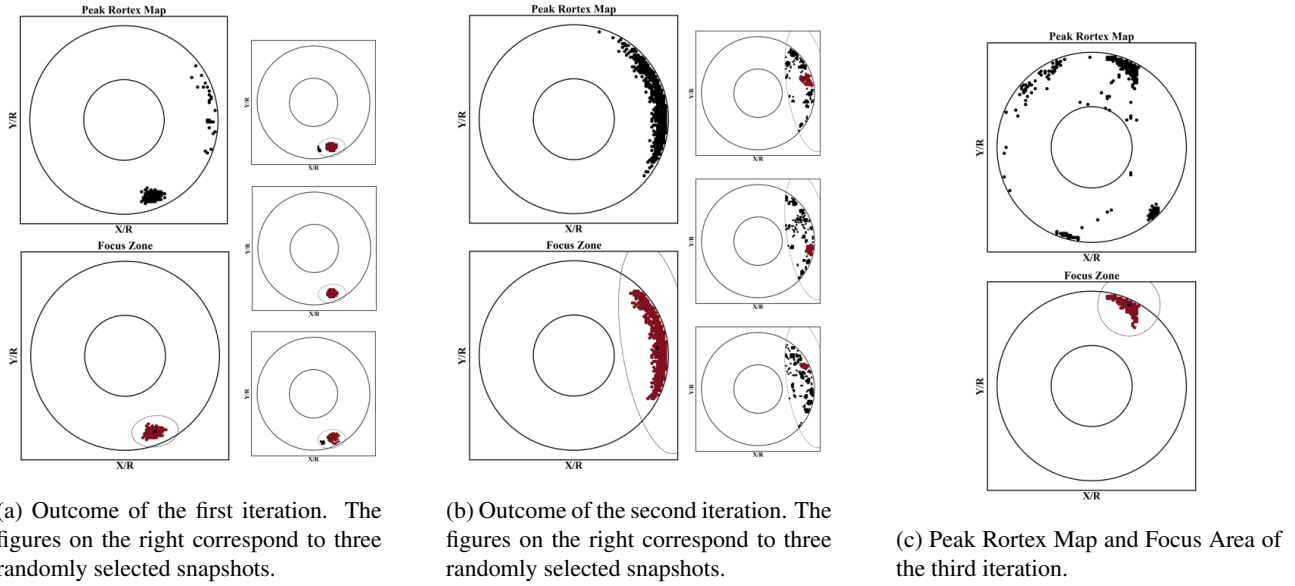


Figure 10: Structures identified by the automatic cluster-based algorithm on the data corresponding to a typical short-intake under crosswind conditions in the presence of the ground plane at high MFCR.

distance-criteria will be considered to improve detection accuracy in high-diffusion scenarios.

Overall, the framework facilitates the identification, tracking, and circulation computation of vortical structures across diverse flow conditions, making it particularly relevant to industries concerned with flow diagnostics, prediction, and control. By offering a scalable and robust approach, this methodology contributes to advancing state-of-the-art in vortex analysis.

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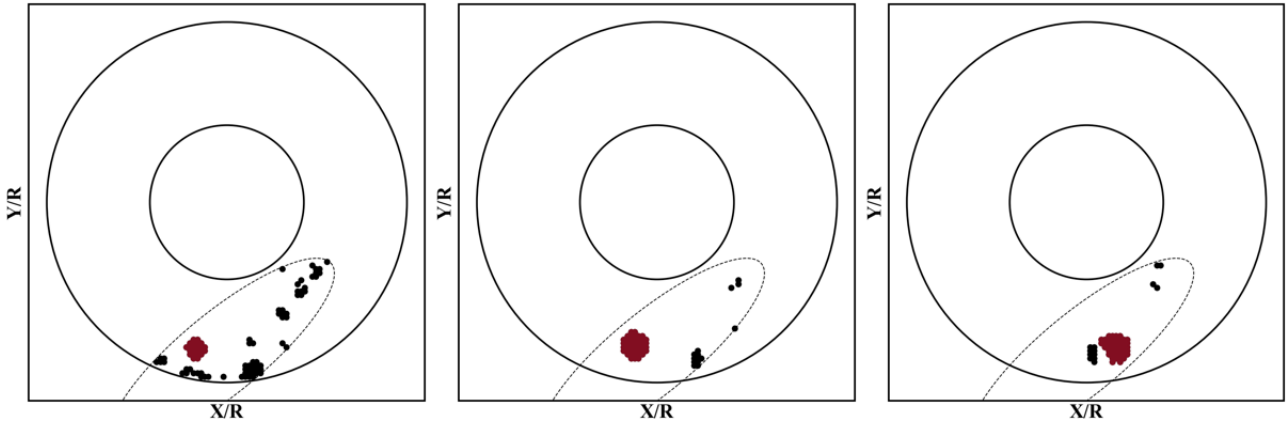


Figure 11: Ground vortex identification in three consecutive snapshots by the method at low MFCR. Illustration of main structure displacement over time.

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Cluster-based tracking method for the identification and characterisation of vortices

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