

Unsteady Swirl Distortion in a Short Intake Under Crosswind Conditions

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Under crosswind operating conditions, the flow field of an aero-engine intake can be characterized by notable unsteady flow distortion. These distortions are typically associated with flow separation within the intake as well as with the ingestion of the ground vortex. This unsteady flow distortion can have a detrimental effect on the intake performance and potentially on the operability of the downstream compression system. Measurements of the unsteady velocity field within a model-scale intake under crosswind conditions were acquired using Stereo Particle Image Velocimetry (S-PIV). This work analyses the S-PIV data to quantify the unsteady flow distortion, as well as the characteristics of the ingested ground vortex, in a short intake under crosswind conditions. The swirl distortion metrics were calculated for a range of crosswind velocities and intake Mass Flow Capture Ratios (MFCR). The conditions at which the intake flow separates depend on crosswind velocity, ground clearance, the design of the intake, and on the MFCR. Flow characteristics of both low MFCR diffusion-driven, and high MFCR shock-induced separation were identified. The circumferential extent and intensity of the swirl distortion is strongly dependent on the crosswind velocity and mass flow rate. The swirl distortion caused by the diffusion-driven separation is greater than that due to the shock-induced separation. The diffusion-driven separation affects a larger portion of the intake Aerodynamic Interface Plane with greater time-averaged and peak distortion levels compared to shock-induced separation. The ground vortex characterization at the Aerodynamic Interface Plane showed a decreasing level of unsteadiness in vortex meandering with increasing MFCR.

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Nomenclature

$\tilde{m}$	=	corrected intake mass flow rate, kg/s
$\dot{m}$	=	intake mass flow rate, kg/s
A	=	area, m ²
AIP	=	Aerodynamic Interface Plane
D	=	diameter, m
H	=	intake centerline height from ground plane, m
h	=	vertical distance from lowest point of the highlight plane to ground, m
L	=	length, m
M	=	Mach number
$MFCR$	=	Mass Flow Capture Ratio
n	=	Vatistas' shape factor
P	=	static pressure, Pa
P_0	=	total pressure, Pa
R	=	radius, m
r	=	radius, m
Re_{Di}	=	Reynolds number per unit length, 1/m
SC	=	Swirl Coefficient
SI	=	Swirl Intensity, deg
T	=	static temperature, K
T_0	=	total temperature, K
u, v, w	=	Cartesian instantaneous velocities, m/s
U, V, W	=	Cartesian area averaged time averaged velocity components, m/s
V_∞	=	Crosswind velocity, kts and m/s
W, V_θ, V_r	=	cylindrical area averaged time averaged velocity components, m/s
w, v_θ, v_r	=	cylindrical instantaneous velocities, m/s
x, y, z	=	Cartesian frame of reference
x, θ, r	=	cylindrical frame of reference

Subscripts

∞	=	freestream
avg	=	average
c	=	relative to vortex core
hi	=	highlight
i	=	intake
is	=	isentropic quantity
max	=	maximum
min	=	minimum
ref	=	reference value
rms	=	root mean square
std	=	standard deviation
$wind$	=	relative to the crosswind

Operators

$\langle \rangle$	=	time average
$—$	=	area average
σ	=	standard deviation

Greek symbols

α	=	swirl angle, degrees
γ	=	ideal gas heat capacity ratio
Γ	=	circulation, m ² /s
μ	=	dynamic viscosity, kg/ms
ρ	=	density, kg/m ³

I. Introduction

MORE stringent performance and environmental considerations are driving the development of aircraft turbofan engines towards higher bypass ratios to improve propulsive efficiency and reduce fuel consumption ([1]-[3]). The consequent penalty in overall weight and drag associated with larger fan diameters can potentially be mitigated by shortening the intake. A short intake is expected to have reduced internal diffusion capabilities compared with conventional configurations and, therefore, may be more susceptible to flow distortion and high levels of unsteadiness, especially under crosswind conditions. There is also likely to be an increase in the aerodynamic coupling between the intake and the fan [4]. The performance of short intakes close to the ground in the presence of a crosswind can be strongly affected by multiple sources of unsteadiness, responsible for either total pressure or swirl distortion [5]. An ingested ground vortex and the flow separation which can arise on the windward side could be responsible for peak flow distortion events that can affect the engine stability even when the average distortion levels are below the acceptability threshold [6]. Therefore, it is of key importance to measure, assess and quantify the unsteady flow distortion and the level of unsteadiness for short intake configurations.

The evaluation of the crosswind ground vortex has been the focus of different experimental and computational studies over the past decades. Initial experimental and computational studies focused on the mechanisms of ground vortex formation ([7]-[9]) and on the relationship to the operating points and geometrical parameters of the intake ([10]-[12]). Murphy et al. [13] focused on the unsteady aspects of the ground vortex below the intake using Particle Image Velocimetry (PIV). The study quantified the vortex characteristics as well as the sensitivities to freestream velocity magnitude, direction, and the distance of the intake from the ground. Total pressure measurements at a nominal Aerodynamic Interface Plane (AIP) evaluated the effect of the ingested ground vortex and the intake separation on the intake performance descriptors. Based on the measurements from Murphy et al [13], Zantopp et al. [14] performed computational fluid dynamic investigations and compared the numerical results with the experimental data, assessing also the level of distortion inside the intake. Wang and Gursul [15] quantified unsteady aspects of the ground vortex using high-bandwidth PIV measurements to assess the vortex movement close to the ground and ahead of the intake. However, the intake flow swirl distortion was not measured.

The intake flow separation and the effect on both the intake performance and on the compressor system, have also been extensively investigated at high angles of attack, both experimentally ([16]-[20]) and numerically ([21]-[24]). Recent experimental studies have documented the different features which depend on the intake mass flow and on the magnitude of the crossflow, as illustrated in Fig. 1. With a constant crosswind velocity, the intake flow encompasses three different regimes as the intake mass flow increases; low-speed or diffusion-driven separation,

attached flow, and shock-induced separation ([25]-[26]). There can also be flow hysteresis ([27]-[28]). The effects of the low-speed separation, hysteresis, Reynolds number, and of different intake operating parameters on the performance of the intake were assessed with computational studies by Colin et al. [29], Zhang [30], Harjes et al. [31], and Burnazzi et al. [32]. However, these studies only focused on the quantification of the total pressure loss under crosswind conditions. Most of the previous experimental investigations were performed with intrusive measurement techniques, such as total pressure probes with low temporal and spatial resolution.

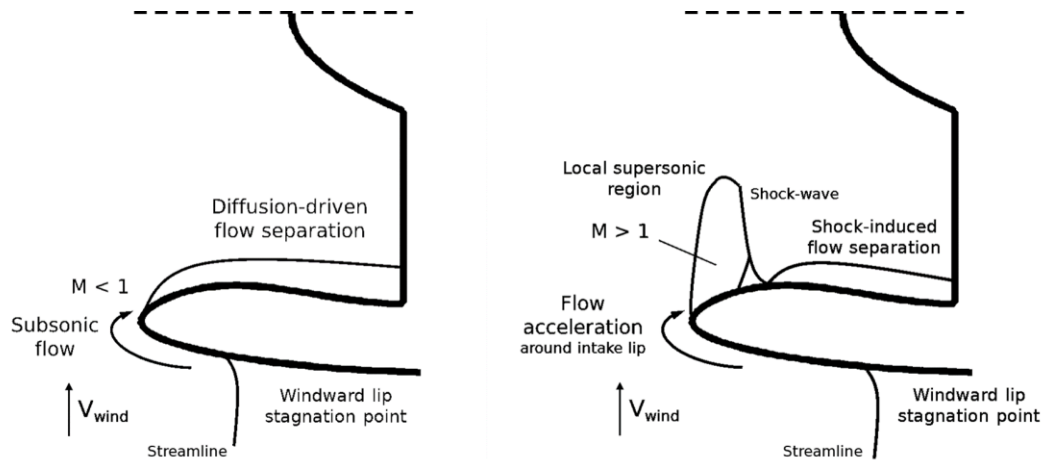


Fig. 1: Key flow features within an intake under crosswind: low-speed or diffusion-driven separation (left); high-speed or shock-induced separation (right).

The combined effect of both total pressure distortion and swirl distortion can have a greater adverse impact on the fan when they co-exist ahead of a fan face [5] [33]. While the methodology for assessing total pressure losses in intakes is relatively well established [34], the methodology to characterize unsteady swirl distortions is less mature. This is primarily due to the lack of high-quality measurements and hinders current understanding about the influence of the various types of swirl distortion on the behavior of a propulsion system. A novel aspect of the current work is the evidence that systematic, unsteady swirl distortion measurements can be acquired across a range of crosswind conditions using PIV. This enables the analysis of the dynamic swirl distortion across the full AIP for an aspirated intake of given geometry. The influence of the intake's geometrical characteristics remains beyond the scope of the current work. The work provides novel, high resolution measurements of the 3-component velocity field for a podded intake under crosswind conditions. The richness of the PIV measurements enables unsteady characterization of the key sources of swirl distortion typically encountered in podded intakes such as the ingested ground vortex and the intake lip separation. Focusing on these sources of swirl distortion, it is found that they have notably different unsteady characteristics which depend on the nature of the underpinning flow

separation mechanism across the operating range. The influence of different unsteady distortion signatures on the fan performance and stability is not well understood and there is an acknowledged need to improve distortion measurements as well as methods to evaluate swirl distortion. For example, novel ways of considering swirl distortion were recently introduced ([35] [36]) as a way of advancing the characterization of flow distortion. Although no fan rotor was used for this experiment, and hence the effect of fan suppression on the flow distortion were not included [36], the results demonstrate a novel approach to acquire and utilize high-quality measurements to better understand the complex aerodynamics for intakes in crosswind. This work sits within the wider context of the journey to improve understanding of intake flow distortion and the effect on the propulsion system, and it is envisaged that these methods would also be pertinent to the subsequent steps of investigating a configuration with a fan rotor.

II. Experimental set-up and Methods

A. Experimental facility and intake model

The experiments were conducted at the Low-Speed Tunnel of the German-Dutch Wind Tunnels (LST-DNW). The LST-DNW is a continuous, atmospheric, low-speed wind tunnel, with a 3.022 m x 2.25 m test cross section and a maximum achievable tunnel velocity (in empty conditions) of 80 m/s. A test rig was designed to accommodate the three-dimensional intake model operating in crosswind conditions with ground plane. A schematic of the intake installed within the tunnel's working section is shown in Fig. 2.

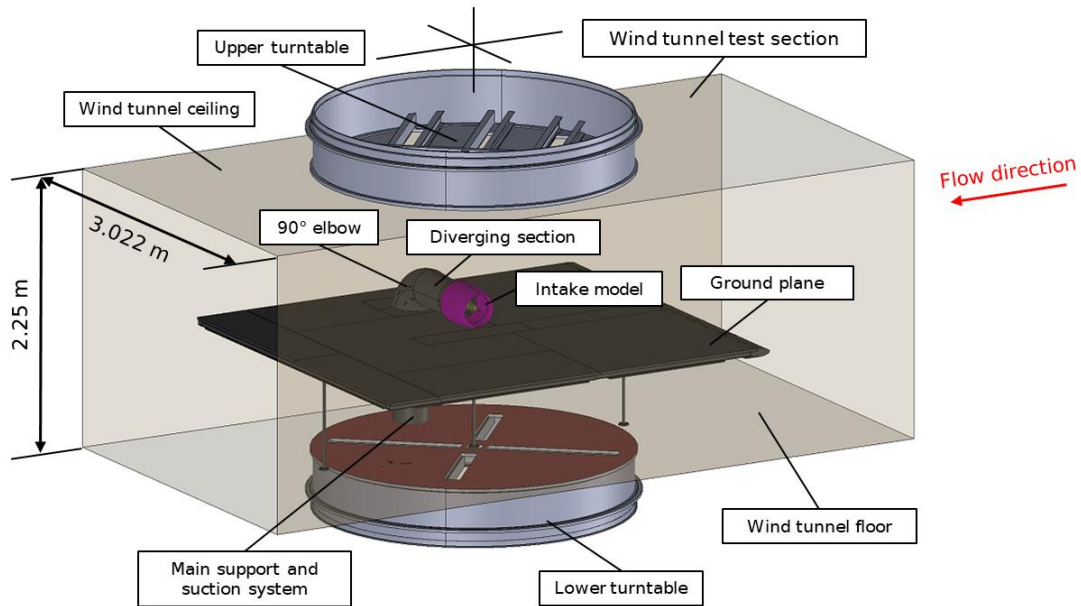


Fig. 2: Schematic of the LST-DNW wind tunnel test section with the model installed.

The intake model was located at the center of the test section and mounted on a 90-degree-bent duct to support the model and facilitate the suction system. A set of 4 suction pumps was used to drive the air flow through the intake model. The model and the suction pipe were placed on the LST floor turntable and oriented perpendicular to the incoming flow to reproduce crosswind conditions. The 4 suction pumps were calibrated against a bell mouth of known mass flow characteristics with an uncertainty of $\pm 0.5\%$. The ground plane had an elliptical (2:1) leading edge and spanned the full width of the wind tunnel test section.

The test article was a scaled short intake representative of a modern Very High Bypass Ratio configuration. The intake model was a 3D drooped and scarfed configuration with a conical center body. The vertical distance between the ground plane and the leading edge of the intake bottom lip (h) was $h/D_{hi} = 0.3$, where D_{hi} is the diameter of the intake highlight plane.

B. Instrumentation

The total pressure distribution at the Aerodynamic Interface Plane (AIP) was measured using 8 equi-spaced radial rakes with 10 Pitot probes on each rake, with the innermost located at $0.368R_i$ and the outermost at $0.985R_i$, where R_i is the intake radius at the intake exit section. The intake model was also equipped with 10 streamwise rows of 18-20 wall static pressure taps each, distributed around the lip at different azimuthal locations, that is 0° , 45° , 67.5° , 90° , 112.5° , 135° , 157.5° , 180° , 202.5° , and 270° . The range of the pressure sensors on the model rakes and on the lip was ± 100 kPa with a full-scale uncertainty of 0.1%. The free stream dynamic pressure and static pressure were measured with a Pitot-static probe located above the ground plane $5D_{hi}$ upstream of the intake model. The static and the dynamic pressure had an overall uncertainty of 0.4% and 0.14%, respectively. The average tunnel temperature had an overall uncertainty of 0.5K.

A schematic of the experimental arrangement and the PIV set-up is shown in Fig. 3. The PIV plane was illuminated by two Quantel Evergreen Nd:YAG lasers, which were located underneath the wind tunnel floor turntable (Fig. 3a). Velocity measurements were taken using a multi-camera optical set-up consisting of six LaVision Imager sCMOS cameras with a sensor resolution of 2560×2160 px². The camera lenses were Canon lenses with a focal length of 100mm. The cameras were positioned outside the test section to avoid interference flow through and around the intake model (Fig. 3b). The flow was seeded with di-ethyl-hexyl-sebacate (DEHS) particles of 1 micrometer median diameter. PIV measurements with a velocity field acquisition frequency of 15 Hz were taken at two crossflow planes within the intake. These were located upstream of the notional fan face at $-0.017D_i$ and $-0.058D_i$ respectively (Fig. 3c), where D_i is the intake inner diameter. Each resulting PIV dataset consisted of a sequence of 1,000 snapshots across a plane of size 250×250 mm². LaVision's DaVis 11 software

was used for PIV image processing and the calculation of the velocity fields. The final achieved spatial resolution was 1.5mm in both directions, which corresponded to a total of 18,000 3-dimensional velocity vectors across each measurement plane [36].

Fig. 3: Experimental arrangement and schematic of PIV set-up: a) schematic view of the test rig (intake and ground plane); b) PIV cameras set-up (front-view); c) PIV measurements on the two vertical planes inside the intake.

The intake aerodynamics under crosswind conditions, with a ground clearance of $h/D_{hi} = 0.3$, was investigated for different values of free stream velocity (V_∞) and intake mass flow rate ($\dot{m}$). The range of operating conditions was first investigated by varying the freestream velocity at a fixed intake mass flow, and subsequently by varying the intake mass flow at a fixed crosswind velocity. The former data sets investigated the intake response to a mass flow variation encompassing different operating conditions characterized by diffusion-driven and shock-induced separation. The second set studied the effects of the crosswind velocity magnitude, which eventually leads to shock-induced separation, on the intake performance. The effect of increasing and decreasing mass flow

on the separation and reattachment hysteresis was also investigated. The crosswind velocity ranged between 2.5 kts (1.3 m/s) and 43 kts (22.1 m/s).

The intake Mass Flow Capture Ratio $MFCR$ was defined according to [37] as follows:

$$MFCR = \frac{A_{\infty}}{A_{hi}} = \frac{\dot{m}}{\rho_{\infty} V_{\infty} A_{hi}} \quad (1)$$

The intake flow conditions in terms of mass flow rate during the test were set as a percentage of a reference value corresponding to the maximum mass flow rate achievable through the intake and dictated by the suction pumps.

The intake Reynolds number per unit length Re_{D_i} was defined in terms of the freestream velocity V_{∞} and the intake inner diameter D_i as follows:

$$Re_{D_i} = \frac{\rho_{\infty} V_{\infty}}{\mu} \quad (2)$$

To prevent early laminar separation, boundary layer trips were used on the outer side of the intake surface. The test matrix of the flow conditions investigated is summarized in Table 1.

Table 1 Investigated test matrix.

Case	Ground clearance h/D_{hi}	Crosswind velocity V_{∞} [kts]	MFCR	Reynolds number per unit length $Re_{D_i} \cdot 10^{-6}$ [1/m]
1a	0.3	15	5.7 – 17.8	0.5
1b	0.3	15	17.2 – 7.8	0.5
2	0.3	20	4.4 – 13.2	0.7
3a	0.3	3.5 - 30	76.8 – 8.8	0.1 – 1.0
3b	0.3	4 - 43	56.5 – 5.2	0.1 – 1.4

D. Data analysis methods

The PIV velocity fields were analyzed to evaluate the flow distortion across the range of operating conditions. The velocity results had a spatial resolution of 1.5 mm^2 in both directions which yielded approximately 18,000 velocity vectors across the measurement plane. Flow statistics were calculated using 1,000 flow snapshots acquired per operating point. The analysis of the flow non-uniformities focused on the quantification of distortion and unsteadiness by means of a range of parameters derived from industrial practice [38], as well as the methodological approach established in previous works ([39]-[42]). The definition of the swirl distortion descriptors commonly used to assess the flow angularity distortion is based on a ring and rake approach ([33]). The Aerodynamic Interface Plane (AIP) is divided into several radial rings and circumferential sectors. To perform the quantitative assessment of the swirl distortion, a polar grid of 288 circumferential and 49 radial points was used. The points were equi-spaced circumferentially, with a radial spacing to provide an equal area distribution. The Delaunay triangulation method was used to interpolate the PIV data onto the grid points. For the current analysis, the data was considered within the region $0.3R_{AIP} < r < 0.96R_{AIP}$ to avoid spurious PIV data near the surfaces of the center body and intake walls.

The conventional swirl coefficient based on the most distorted 60° sector $SC60$ ([43]-[44]) and the swirl intensity parameter SI [33], associated to the magnitude of the swirl, were considered to quantify the swirl distortion. The Swirl Coefficient $SC60$ is defined as the ratio of $\max(|\overline{v_{\theta,60}}|)$, the maximum average circumferential velocity in a section of 60° , to the area-average axial velocity at the AIP, $\overline{w_{AIP}}$:

$$SC60 = \frac{\max(|\overline{v_{\theta,60}}|)}{\overline{w_{AIP}}} \quad (3)$$

Swirl Intensity (SI) is a quantification of the swirl distortion, based on the swirl angle distribution on the ring-by-ring basis illustrated earlier, where the swirl angle α is defined as the angle between the circumferential velocity and the axial direction velocity:

$$\alpha = \tan^{-1} \left(\frac{v_\theta}{w} \right) \quad (4)$$

Following previous approaches outlined in ([39]-[42]), the swirl angle distribution was divided in positive θ_i^+ and negative angle θ_i^- regions and the swirl sector (SS) elements, which represent the azimuthally average positive and negative swirl angle, were defined as:

$$SS_i^+ = \frac{1}{\theta_i^+} \int_{\theta_i^+}^{\theta_i^+} \alpha(\theta)_i d\theta \quad (5)$$

$$SS_i^- = \frac{1}{\theta_i^-} \int_{\theta_i^-}^{\theta_i^+} \alpha(\theta)_i d\theta \quad (6)$$

The sign of the swirl angle α was positive in the clockwise direction, looking downstream.

The radial swirl intensity SI , which corresponds to the average of the absolute value in each ring i , and the overall swirl intensity $\bar{SI}$, corresponding to the average value on the plane, were then defined as:

$$SI_i = \frac{SS_i^+ \theta_i^+ + |SS_i^-| \theta_i^-}{360} \quad (7)$$

$$\bar{SI} = \frac{1}{N} \sum_{i=1}^N (SI)_i \quad (8)$$

where N is the number of rings.

The pressure distributions on the intake surface were evaluated in terms of isentropic Mach number, defined as follows:

$$M_{is} = \sqrt{\frac{2}{\gamma - 1} \left[\left(\frac{P_{0,\infty}}{P} \right)^{(\gamma-1)/\gamma} - 1 \right]} \quad (9)$$

where $P_{0,\infty}$ is the tunnel total pressure and P is the static pressure on the intake surface.

For each crosswind configuration, the ground vortex characteristics were calculated from the AIP velocity distributions obtained with SPIV measurements. The characteristics of the ground vortex in terms of strength and core size were calculated using the Vorticity Disk Method [13]. The centre of the ground vortex was identified using the peak out-of-plane vorticity $|\omega_x|$. Vorticity data was linearly interpolated onto a polar grid with a maximum radius of $r_{max}/D_i = 0.25$ comprising $I_{max} = 150$ radial and $J_{max} = 261$ circumferential points, centered in the vortex core. The vorticity was then integrated over circular areas of increasing radial distance from the center of the vortex, computing a distribution of the circulation Γ as a function of radial distance as follows:

$$\Gamma_i = \int \omega_x dA_{i,j} = \sum_{j=1}^{J_{max}} \omega_{i,j} A_{i,j} \quad (10)$$

where:

$$A_{i,j} = \begin{cases} \frac{\pi}{J_{max}} \left(\frac{r_{i+1,j}}{2} \right)^2, & \text{if } i = 1 \\ \frac{\pi}{J_{max}} \left[\left(\frac{r_{i+1,j} - r_{i,j}}{2} + r_{i,j} \right) - \left(\frac{r_{i,j} - r_{i-1,j}}{2} + r_{i-1,j} \right) \right]^2, & \text{if } i > 1 \end{cases} \quad (11)$$

The circumferentially averaged swirl velocity $V_{v,\theta}$ was then calculated as a function of the radial distance and the size of the vortex r_c was determined by the radial position of the peak swirl velocity $V_{v,\theta}^{max}$. The vortex core radius r_c was normalized by the intake radius r_i , so that $r^* = r_c/r_i$, and the non-dimensional circulation of the ground vortex core Γ_c at the AIP was considered to be the circulation up to the core extent r_c . Since the free-stream velocity is a parameter that influences the interaction between the incoming flow and the internal flow and therefore the amount of vorticity ingested inside the intake, the vortex core circulation was also normalized by the intake diameter D_i and the free-stream velocity V_∞ :

$$\Gamma^* = \frac{\Gamma}{D_i V_\infty} \quad (12)$$

The Vatistas' shape factor n was calculated by using a least squares fit of the velocity distribution:

$$\frac{V_{v,\theta}}{V_{v,\theta}^{max}} = 2^{\frac{1}{n}} \left[\frac{r^*}{(1 + r^{*2n})^{\frac{1}{n}}} \right] \quad (13)$$

The statistics of the vortex core characteristics were calculated to quantify the level of unsteadiness of the ingested ground vortex. The vortex meandering amplitude a_M , defined in [15] as follows:

$$a_M = \sqrt{\frac{(\sum (x_i - x_c)^2 + (y_i - y_c)^2)}{N}} \quad (14)$$

was also calculated, where N is the number of snapshots x_i and x_c are the coordinates of instantaneous and time-averaged inlet vortex locations in the direction of crosswind, and y_i and y_c are the coordinates of the instantaneous and time-averaged inlet vortex locations in the direction perpendicular to the transverse flow in the AIP plane. The vortex meandering amplitude is a useful parameter that can be used to quantify the ground vortex variation with respect to the average location when data with sufficient resolution in time to perform a frequency analysis are not available, as in the present case where low-bandwidth PIV data was acquired. Although the ground vortex was expected to arise in all of the test configurations only a small weak and intermittent vortex was present, making the vortex characterization not possible. For some configurations characterized, by a strong ground vortex, it was not possible to get reliable PIV measurements in the vortex core due to condensation or poor seeding.

The experimental uncertainty on wind tunnel velocity and $MFCR$ were estimated using the method for the propagation of errors outlined by Taylor [45]. For the typical operating condition of 15 kts (7.7 m/s) and 20 kts (10.3 m/s) crosswind, the uncertainty on the freestream velocity was 2% and the uncertainty on $MFCR$ was $\pm 0.02 MFCR$.

III. Results and Discussion

A. Flow field at the Aerodynamic Interface Plane

As observed experimentally ([25]-[26]) and numerically ([29]-[30]), the mechanisms responsible for intake flow separation in crosswind can be either diffusion-driven or shock-induced (Fig. 1). Consequently, it is of key importance to identify the flow regime at which the intake is operating and to classify the separation mechanism responsible for the distortion. Based on previous studies, the conceptual map shown in Fig. 4 classifies the intake flow regimes at different operating conditions as a function of the crosswind velocity and mass flow rate in terms of $MFCR$.

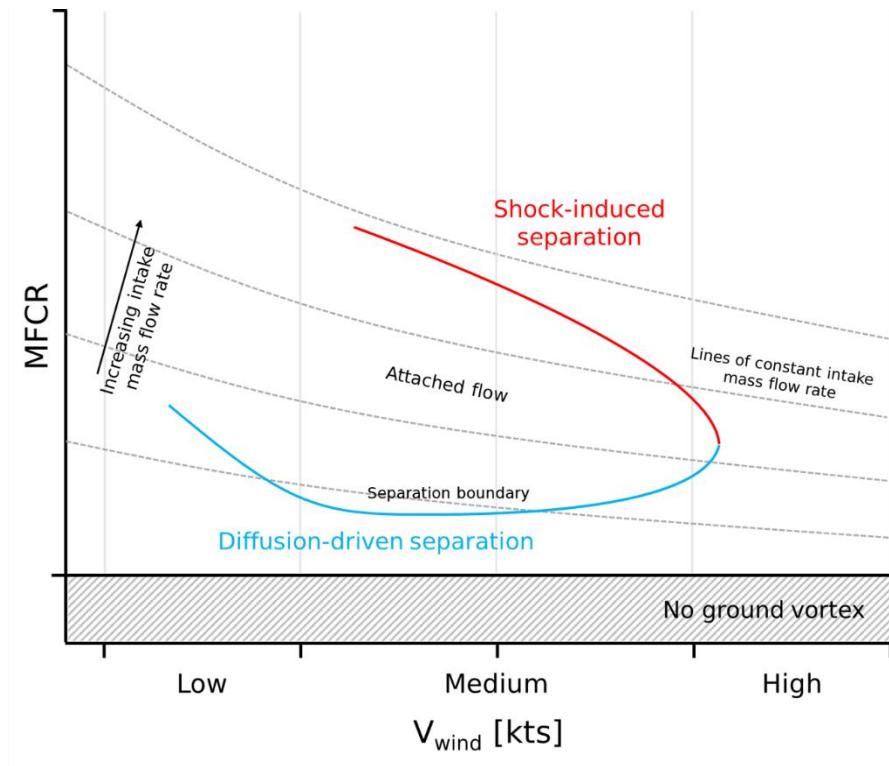


Fig. 4: Schematic of intake aerodynamic characteristics in crosswind.

Considering the intake operating conditions at a constant crosswind velocity and increasing $MFCR$, the two separation limits which indicate the boundaries of diffusion-driven and shock-induced separation regimes can be postulated, based on the total pressure distortion metrics ([29]-[30]) and on the static pressure distributions on the intake surface. For the low-speed, diffusion-driven separation, after the initial acceleration around the intake lip (Fig. 1, left), there is a deceleration within the intake and the boundary layer separates forming a large area of reversed flow. At higher mass flow rates, the flow is strongly accelerated around the lip until it becomes locally supersonic (Fig. 1, right). This generates a shockwave which is sufficient potent to cause the separation of the

boundary layer. Between these two separation limits, the flow remains fully or mostly attached over the lip and the diffuser. The value of $MFCR$ at which the idealized far upstream captured stream-tube theoretically extends to the ground is considered as an indicative limit value for the ground vortex formation for a given ground clearance. The criterion assumes no interaction between the stream tube and the ground plane or the approaching boundary layer. This is indicated by a horizontal line in Fig. 4. Below this value of the $MFCR$ no vortex forms. For this configuration, based on a simple circular cross-section of the upstream ingested freestream stream-tube, the limiting $MFCR$ is 2.6. Since the $MFCR$ is a function of both crosswind magnitude and mass flow rate (Eq. 1), the lines at constant mass flow rate are also indicated in Fig. 4. For all the test configurations, the separation within the intake was assessed by considering the reversed flow regions based on the time-averaged axial velocity at the Aerodynamic Interface Plane (AIP), normalized by the reference out-of-plane velocity $W_{ref} = \langle \bar{w} \rangle_{AIP} = \frac{1}{A} \int_A \langle w(r, \theta, t) \rangle dA$. To distinguish the flow mechanisms responsible for the separation, the pressure distributions on the intake surface in terms of isentropic Mach number were also considered.

The variation of the normalized axial velocity, $\langle w \rangle / \langle \bar{w} \rangle_{AIP}$, at the AIP plane with increasing Mass Flow Capture Ratio ($MFCR$) is shown in Fig. 5 at a fixed crosswind velocity of 15 kts (7.7 m/s) (Case 1a in Table 1). The analysis in terms of axial velocity distributions was previously reported in Kempaiah et al. [36]. Although discussed in [36], this dataset serves as the baseline for the subsequent analysis in this paper and, therefore, is briefly described here. As noted in Kempaiah et al. [36], the key observations were that as the ingested mass flow is increased, the intake flow goes from an initial separated condition ($MFCR = 5.7$) to an attached condition ($MFCR = 11.1$) and then separates again ($MFCR > 16.3$). Due to the non-axisymmetric geometrical features of the intake and the presence of the ground plane, the separated region is biased towards the top-half of the AIP on the windward side. As the mass flow capture ratio increases from 5.7 to 9.4, the size of the distorted region noticeably decreases both radially and circumferentially, until the flow reattaches at $MFCR = 11.1$. As the $MFCR$ is further increased from 14.7 to 16.3, the flow separates again. The radial extent of the separated region modestly reduces between $MFCR = 16.3$ to $MFCR = 17.8$, while the circumferential extent slightly increases, starting around the top-dead-center of the intake. This change in the topology of the separated region is attributed to the different nature of the identified separation mechanisms. Diffusion-driven separation is responsible for a wider region of reversed flow, whereas shock-induced separation is more localized around the location where the shock arises. In this case, the bulk of the flow has more momentum due to the higher blockage within the intake, which further explains the reduced radial extent of the region of reversed flow.

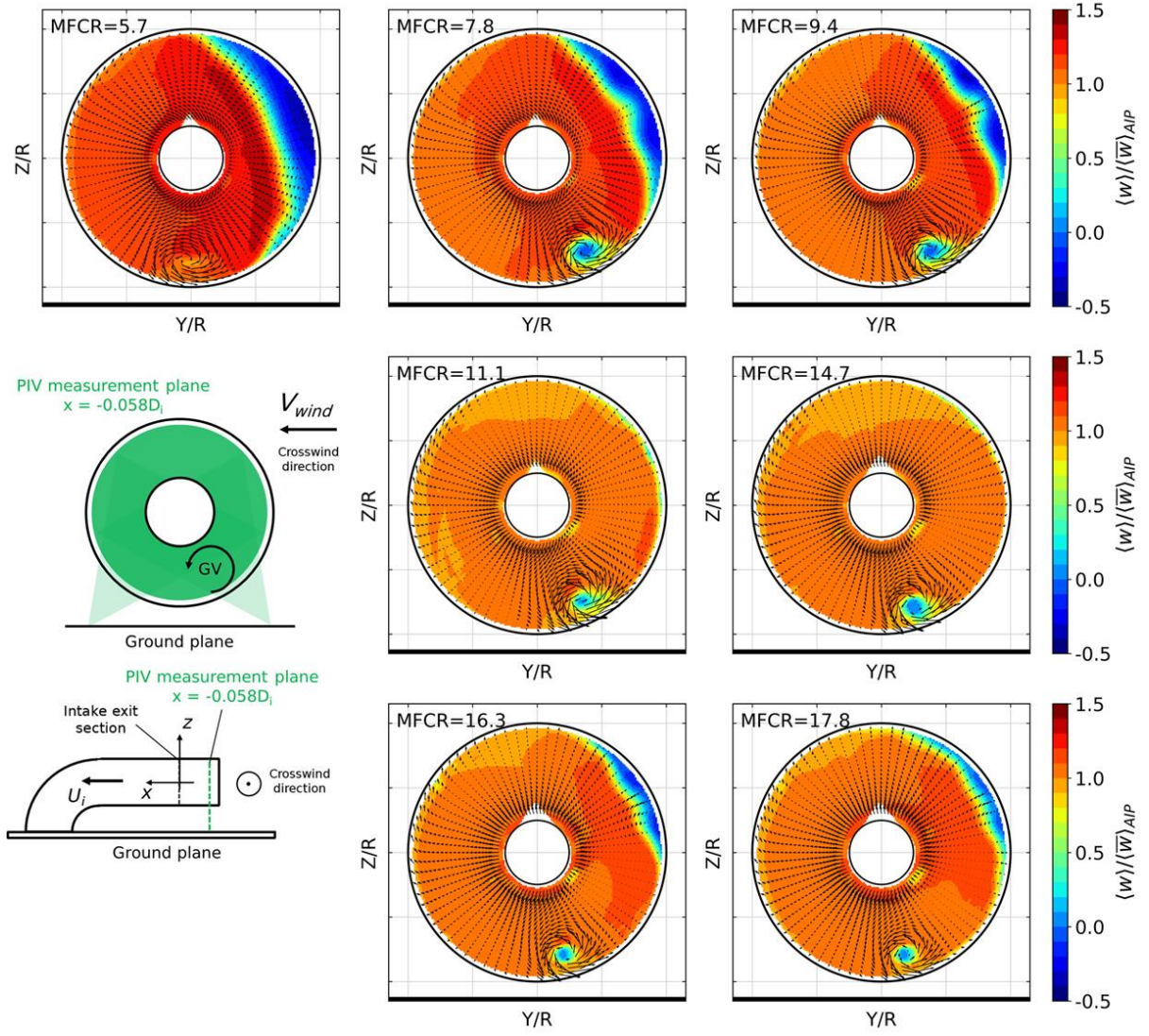


Fig. 5: PIV measured time-averaged normalized axial velocity at the AIP with increasing Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 15 kts (7.7 m/s). Crosswind direction from right to left. View looking downstream. Figure adapted from [36].

Similar flow behavior, for which the two separation limits corresponding to diffusion-driven and shock separation boundaries can be identified, is reported in previous experimental ([25]-[26]) and numerical studies ([30]), although the details of the AIP velocity field was not previously measured. The isentropic Mach number distributions on the intake surface (Fig. 6 and Fig. 7) distinguish the different nature of the separation occurring in these cases and help to identify the separation boundaries sketched in Fig. 4. The contours of the time-averaged isentropic Mach number on the unwrapped surface of the intake in Fig. 6 and Fig. 7 derive from the linear interpolation of the static pressure taps measurements on the surface of the intake. The axial coordinate x^* is normalized such that $x^* = (x - x_{hi})/L_i$, where x is the axial coordinate of each static pressure tap, and x_{hi} is the

axial coordinate of the highlight plane, and L_i is the length of the intake at the top-dead centre. For $MFCR = 9.4$ (Fig. 6a), which is the operating point just before the reattachment of the intake flow at $MFCR = 11.1$ (Fig. 6b), the peak isentropic Mach numbers are subsonic all around the intake surface and confirm the diffusion-driven nature of the separation. At $MFCR = 14.7$ the peak isentropic Mach numbers are supersonic, but the intake flow is still attached (Fig. 7a). At $MFCR = 16.3$ the separation is caused by the presence of a shockwave, located approximatively at 67.5° (Fig. 7b). Overall, at low $MFCR$ s ($MFCR = 5.7, 7.8$, and 9.4), the separation is diffusion-driven, while at high $MFCR$ s ($MFCR = 16.3$ and 17.8), the separation is shock-induced. At $MFCR = 11.1$ and $MFCR = 14.7$, the time-average flow is attached and mostly uniform.

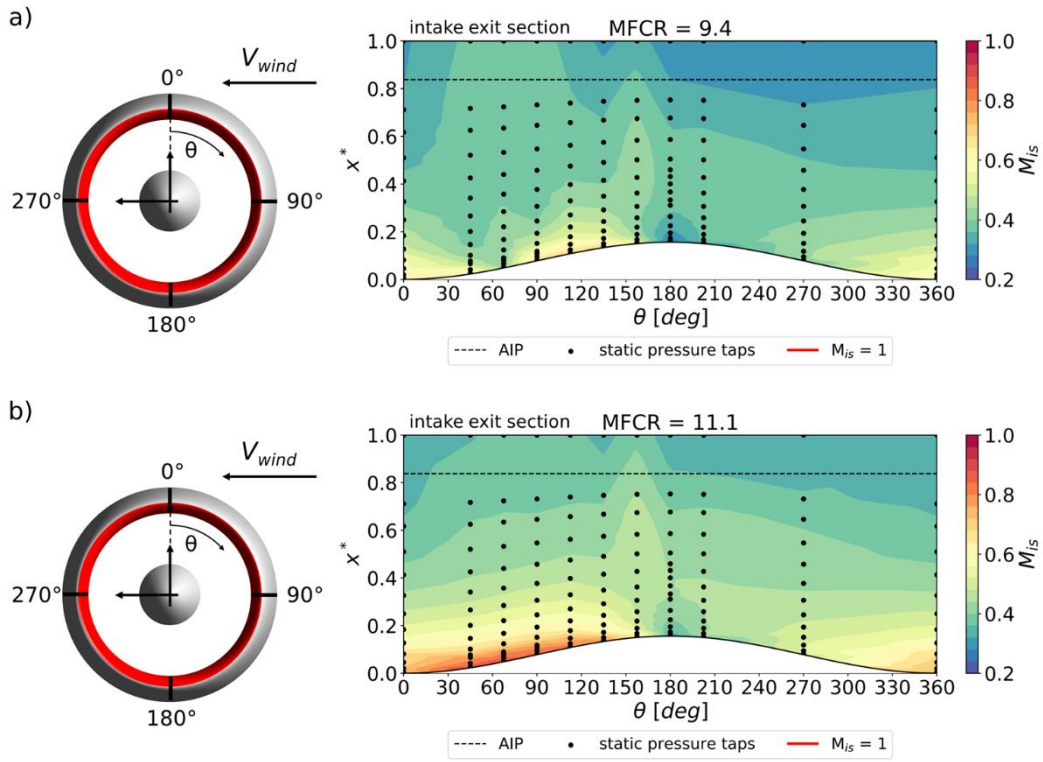


Fig. 6: Measured isentropic Mach number distribution around the intake surface: a) diffusion-driven separation ($MFCR=9.4$); b) reattachment point ($MFCR=11.1$).

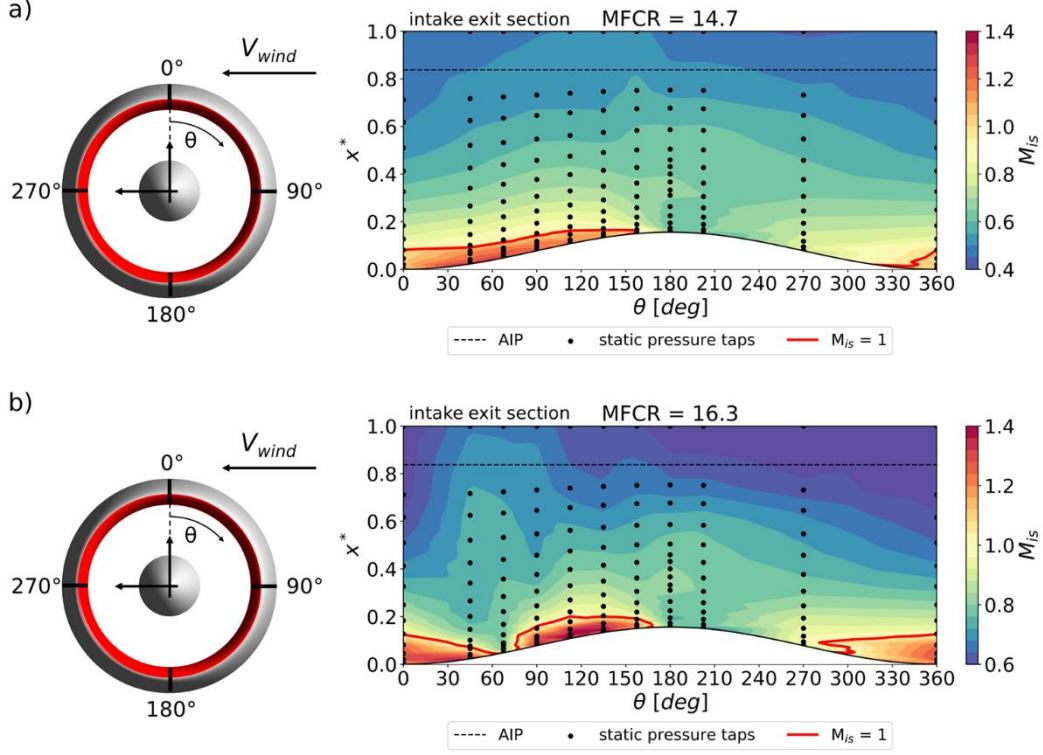


Fig. 7: Measured isentropic Mach number distribution around the intake surface: a) attached condition ($MFCR=14.7$); b) shock-induced separation ($MFCR=16.3$).

The non-dimensional time-averaged circumferential velocity $\langle v_\theta \rangle / \langle \bar{w} \rangle_{AIP}$, radial velocity $\langle v_r \rangle / \langle \bar{w} \rangle_{AIP}$, and swirl angle $\langle \alpha \rangle$ distributions were also determined for each configurations to examine the effect of the flow separation and of the ingested ground vortex. The distributions of $\langle v_\theta \rangle / \langle \bar{w} \rangle_{AIP}$ are generally similar for the range of $MFCRs$ (Fig. 8). The maximum and minimum circumferential velocities are at the lower part of the AIP around the area affected by the ingested ground vortex, while the circumferential velocity distribution in the region affected by reversed flow ($MFCR = 5.7, 7.8, 9.4$ and $MFCR = 16.3$ and 17.8 , Fig. 5) is broadly unaffected by the separation itself. In addition, on the downwind side centred around $\theta = 315^\circ$, there is a consistent clockwise circumferential velocity which is possibly associated with the non-uniformity of the ingested stream-tube.

The general topology of the non-dimensional time-averaged radial velocity $\langle v_r \rangle / \langle \bar{w} \rangle_{AIP}$ distributions (Fig. 9) shows that with increasing $MFCR$ the radial velocity distortions are similarly associated with the ingested ground vortex. the radial velocity distribution is broadly unaffected by the presence of the windward separation ($MFCR = 5.7, 7.8, 9.4$ and $MFCR = 16.3$ and 17.8 , Fig. 5).

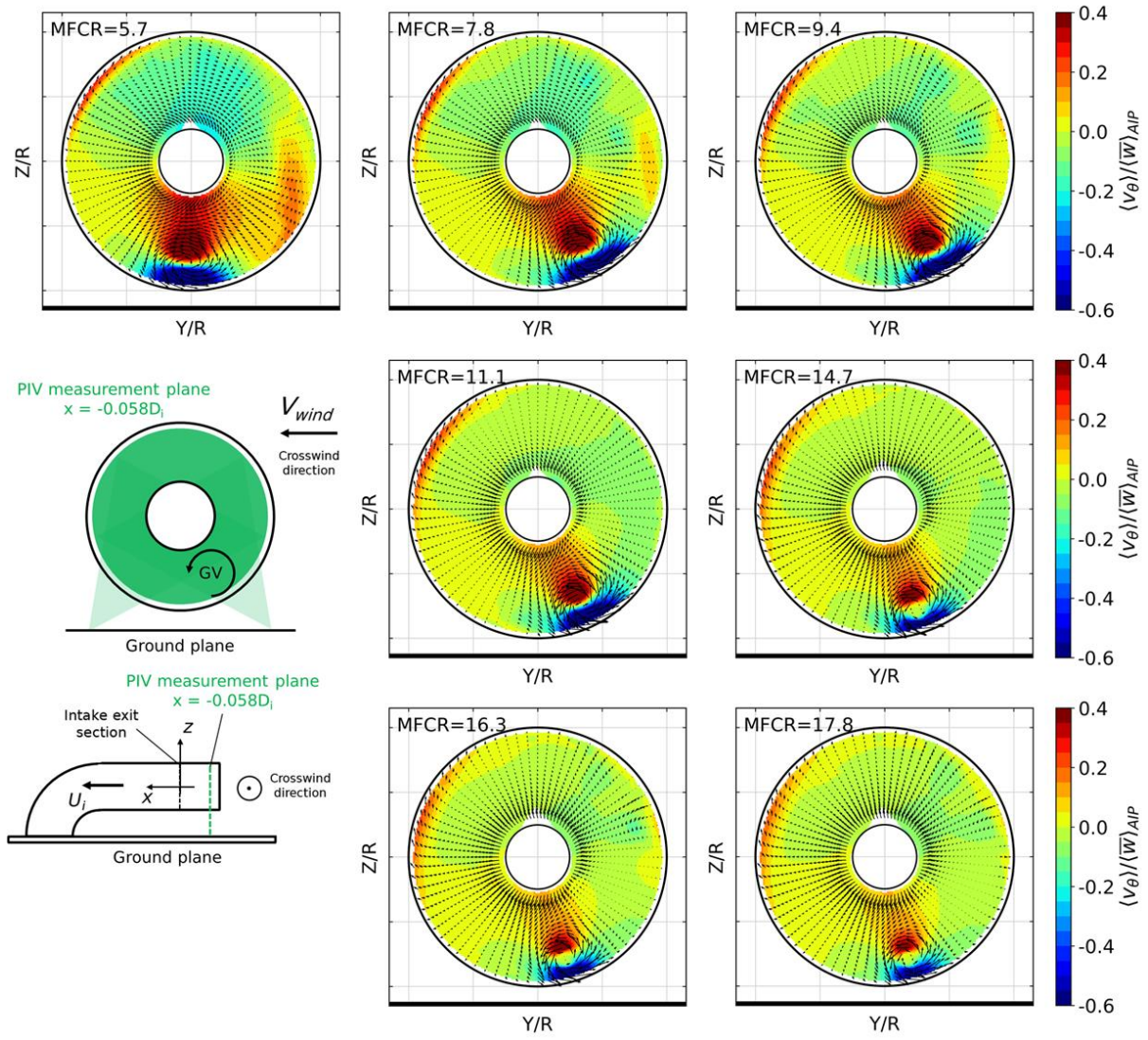


Fig. 8: Time-averaged non-dimensional circumferential velocity component $\langle v_\theta \rangle / \langle \bar{w} \rangle_{AIP}$ distributions at the AIP for increasing Mass Flow Capture Ratio (MFCR) at 15 kts (7.7 m/s). Crosswind direction from right to left. View looking downstream.

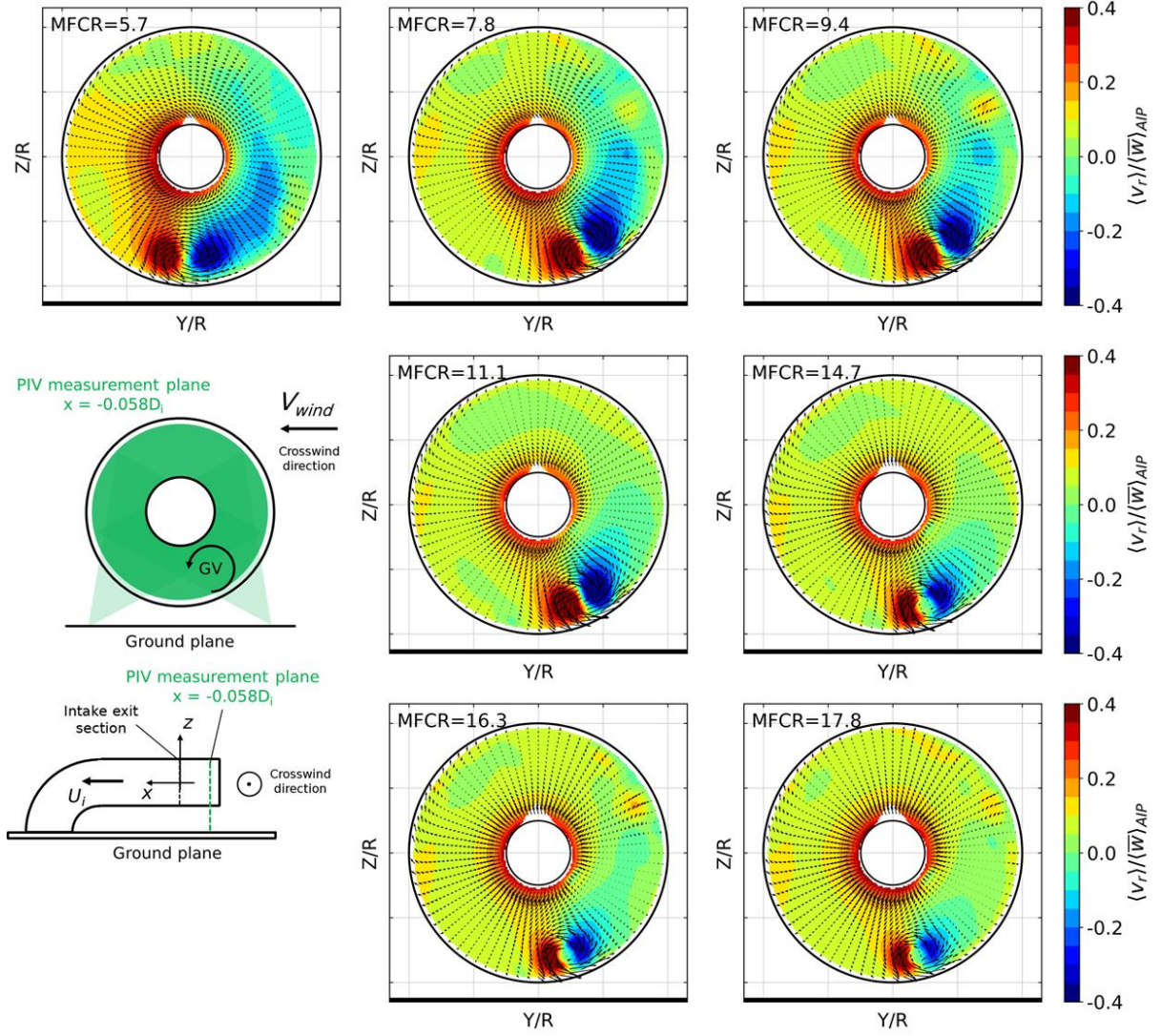


Fig. 9: Time-averaged non-dimensional radial velocity component $\langle v_r \rangle / \langle \bar{w} \rangle_{AIP}$ distributions at the AIP for increasing Mass Flow Capture Ratio (MFCR) at 15 kts (7.7 m/s). Crosswind direction from right to left. View looking downstream.

The time-averaged swirl angle distributions are shown in Fig. 10. For the two attached flow conditions at $MFCR = 11.1$ and 14.7 (Fig. 5), the distributions of α are primarily dominated by the circumferential velocity (Fig. 8) and the presence of the ingested ground vortex. For $MFCR = 16.3$ and 17.8 , which correspond to shock-induced separation conditions (Fig. 5 and Fig. 10), the extent of the region affected by the ground vortex is reduced, along with the magnitude of the time-averaged swirl angle. In these cases, the separation on the windward side of the intake, apart being responsible of some localized region of high and low values of α on the upper half of the plane, has only a modest effect on the swirl angle distribution. This is somehow expected, since the region of reversed flow caused by the shock induced separation at the intake lip is localized to the upper part of the AIP

and is not very extensive (Fig. 5). Of particular interest, are the swirl angle distributions for $MFCR = 5.7, 7.8,$ and 9.4 , which are characterized by a diffusion-driven separation (Fig. 5). The time-averaged α distributions are notably different to the ones at $MFCR = 16.3$ and 17.8 with a much larger region of high swirl angles, both positive and negative, roughly matching the extents of the reversed flow region (Fig. 5). Since the corresponding time-averaged circumferential velocity distributions (Fig. 8) do not show significant levels of circumferential velocity around the region encompassed by the separation, the swirl angle in the upper part of the AIP is therefore mainly due to the axial velocity deficits.

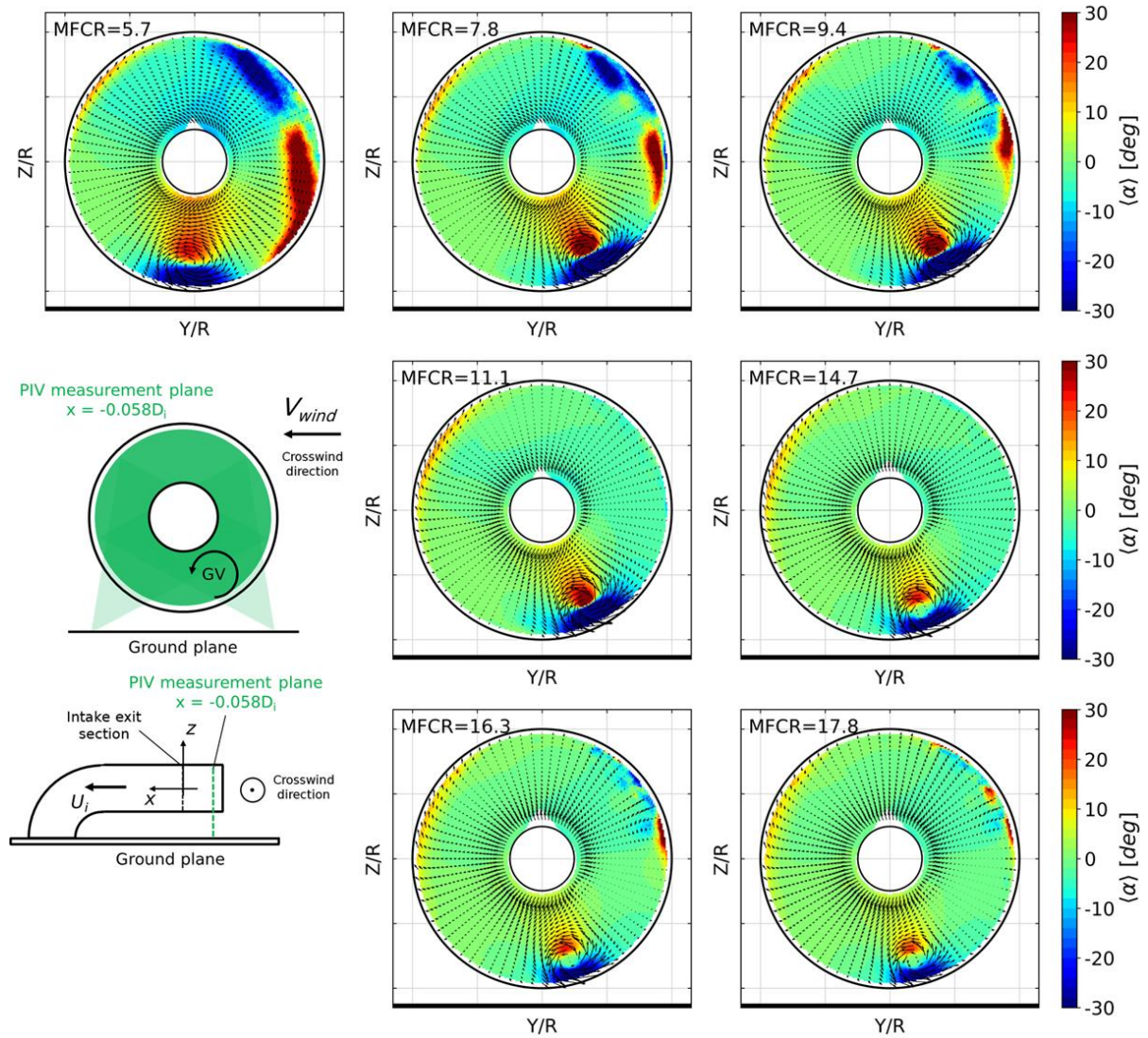


Fig. 10: Time-averaged swirl angle $\langle \alpha \rangle$ distributions at the AIP for increasing Mass Flow Capture Ratio (MFCR) at 15 kts (7.7 m/s). Crosswind direction from right to left. View looking downstream.

For a crosswind of 15 kts (7.7 m/s), a decreasing sweep of $MFCR$ was also used to investigate the presence of hysteresis (Case 1b in Table 1). Despite small differences in the radial and circumferential extents of the separation, the values of $MFCR$ at which the intake reattaches, and separates were broadly the same with no indication of hysteresis. As the crosswind increased from 15 kts (7.7 m/s) to 20 kts (10.3 m/s) (Case 2 in Table 1), the normalized axial velocity distributions at the AIP (Fig. 11) show that the flow separation inside the intake is present for all $MFCR$ s across the range from 4.4 to 13.2. With increasing $MFCR$ at 20 kts (10.3 m/s), the intake gradually moves from a regime characterized by low-speed separation ($MFCR = 4.4, 6.1, 7.4, 8.8$ and 10.1) to a condition of high-speed separation ($MFCR = 11.2, 12.5$, and 13.2). As considered in the schematic in Fig. 4, the boundary enclosing the attached intake flow regimes shrinks as the crosswind velocity is increased. A clear boundary distinguishing the low-speed and high-speed separation regimes cannot be easily discerned.

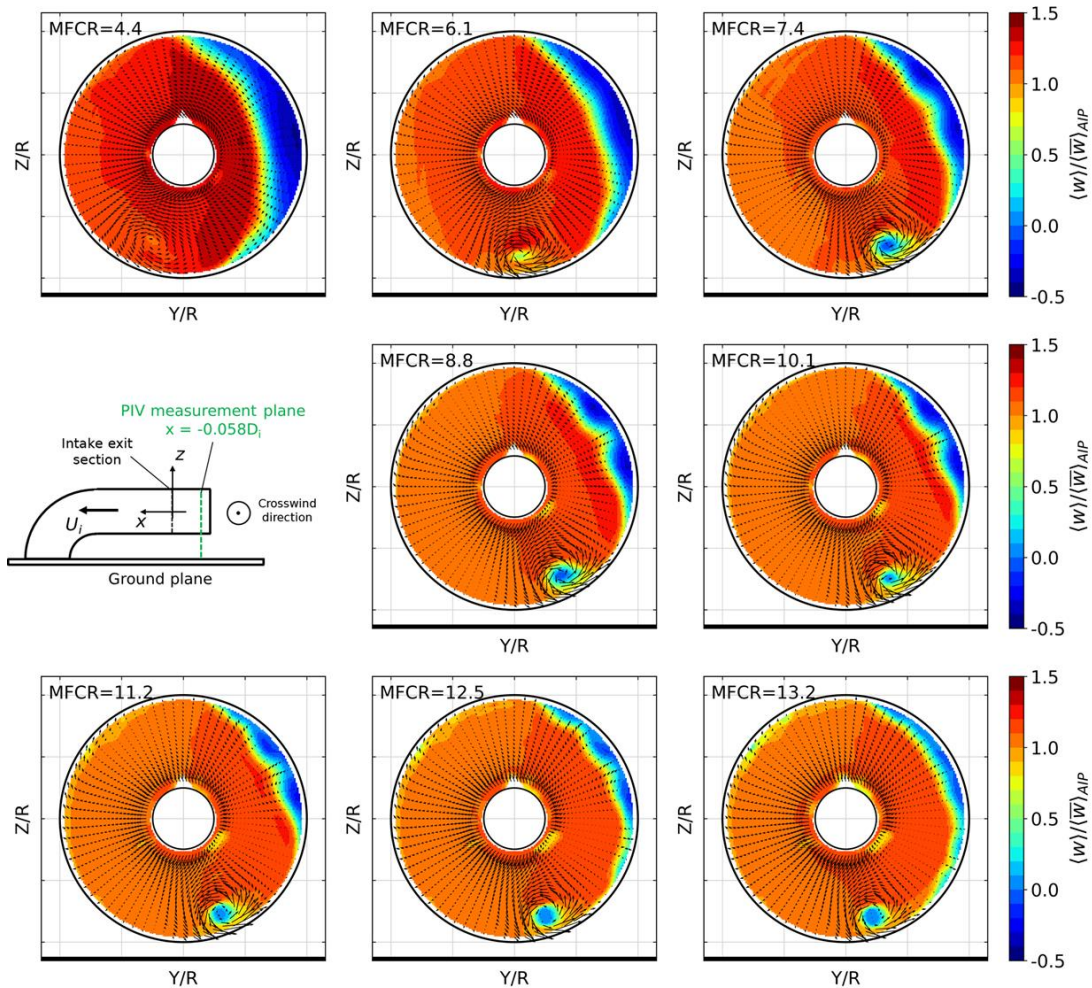


Fig. 11: PIV measured time-averaged normalized axial velocity at the AIP with increasing Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 20 kts (10.3 m/s). Crosswind direction from right to left. View looking downstream.

In previous studies ([13]-[15]), the intake aerodynamics were investigated by varying the crosswind velocity at a constant value of the mass flow rate. This was to observe the unsteady characteristics of the ground vortex below and in front of the intake. In the present study, the aerodynamic behavior of the intake was also investigated for a range of crosswind velocities with the intake mass flow rate set to either the maximum value or 86% of the maximum value, respectively (Case 3a and Case 3b in Table 1). These configurations are schematically illustrated in Fig. 4, where for a specified mass flow rate ($\dot{m}$), the $MFCR$ reduces as V_∞ increases. Depending on the combination of $\dot{m}$ and V_∞ , the variation in $MFCR$ could result in the intake being attached or separated in either of the two flow regimes. The variation of the normalized axial velocity at the AIP with the crosswind velocity at the maximum mass flow rate through the intake (Case 3a in Table 1) highlights the onset of the separation (Fig. 12). In this case, the crosswind velocity varies between 3.5 kts (1.8 m/s) and 30 kts (15.4 m/s) and the corresponding $MFCR$ ranges from 76.8 to 8.8. The intake goes from an attached and mostly uniform regime to a shock-induced flow regime (Fig. 12), as indicated by the isentropic Mach number distributions along the intake surface. At low crosswind velocities, nominally 3.5 kts (1.8 m/s) and 6 kts (3.1 m/s), with $MFCR = 76.8$ and $MFCR = 43.4$, respectively, the time-averaged flow around the intake lip is attached and mostly uniform, with no signs of flow separation, apart from a small region of low velocity along the windward side of the intake at $V_\infty = 6$ kts (3.1 m/s). Moreover, for $V_\infty = 3.5$ kts (1.8 m/s) and $V_\infty = 6$ kts (3.1 m/s), the time-averaged axial velocity deficit associated with the ground vortex is barely visible due to the relatively weak vortex, which is also confirmed in the time-average circumferential velocity distributions. As the crosswind velocity increases to $V_\infty = 11$ kts (5.7 m/s and $MFCR = 23.9$), despite no reversed flow in the time-averaged flow field, a wider region of low axial velocity starts to emerge on the upper windward quarter indicating the flow diffusion on the way towards separation. As the crosswind velocity is further increased to $V_\infty = 14$ kts (7.2 m/s and $MFCR = 18.0$) and above, from $V_\infty = 18$ kts (9.3 m/s and $MFCR = 14.5$) to $V_\infty = 30$ kts (15.4 m/s and $MFCR = 8.8$), the intake separates on the windward side, and the size of the distorted region increases, extending from the top dead center to almost the bottom dead center of the intake. Along with a larger area of separated flow, as the crosswind velocity is increased, the size and strength of the ingested ground vortex also increase. In this arrangement with a fixed mass flow rate, Murphy et al. [13] showed that the ground vortex typically increases in strength until it gets close to the blow away $MFCR$ at which point it no longer forms. For this fixed mass flow configuration, the ground vortex idealized blow away $MFCR$ corresponds to a crosswind velocity of 100 kts (around 51 m/s). The azimuthal extent of the windward lip separation does increase with $MFCR$ to the point where at the maximum crosswind velocity of $V_\infty = 30$ kts (15.4 m/s and $MFCR = 8.8$), the two regions of low axial velocity distortion are contiguous.

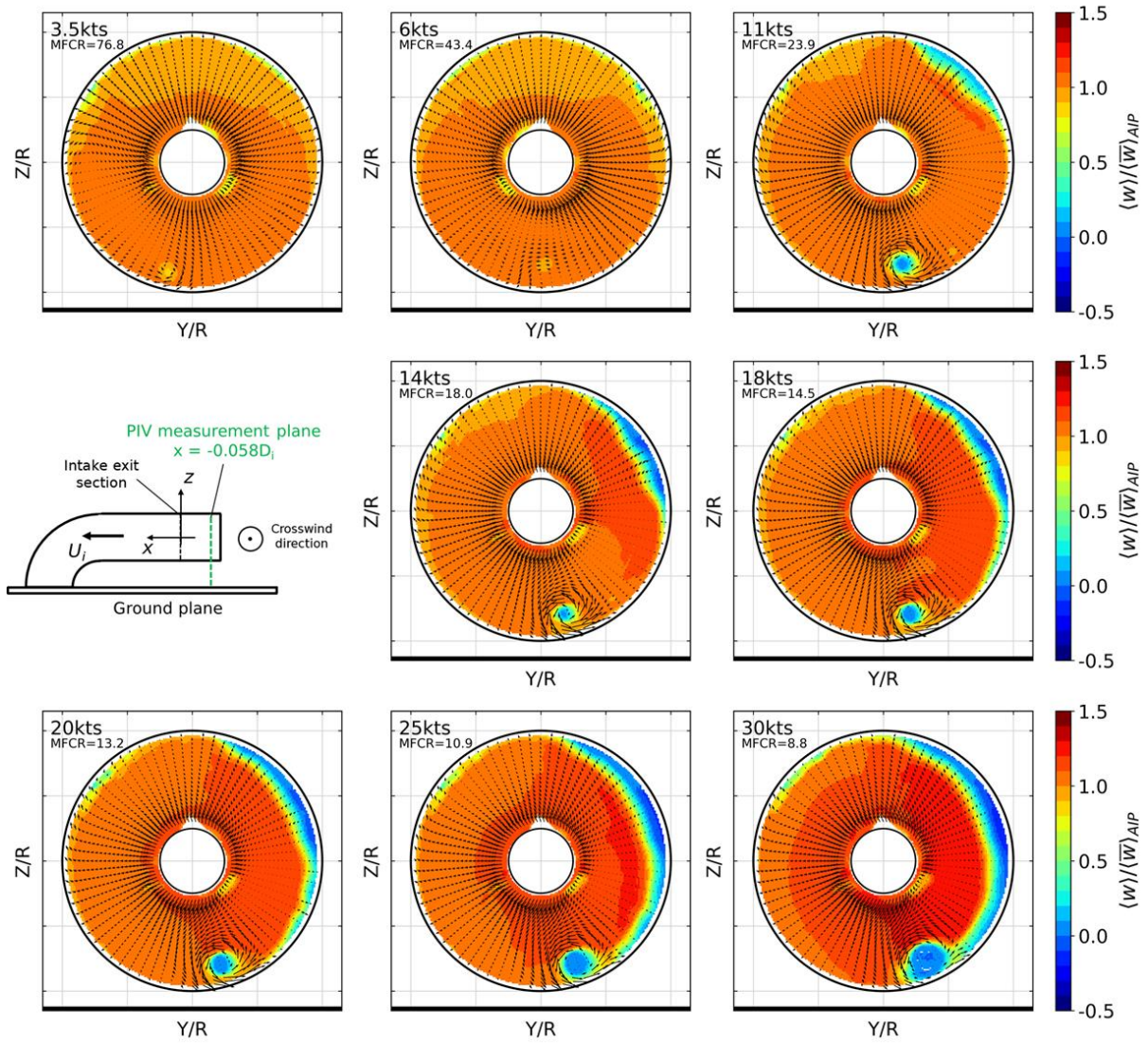


Fig. 12: PIV measured time-averaged normalized axial velocity at the AIP with crosswind velocity for a fixed maximum intake mass flow rate. Crosswind direction from right to left. View looking downstream.

At a mass flow rate through the intake equal to 86% of the maximum value (Case 3b in Table 1), the normalized axial velocity distributions at the AIP with varying V_∞ are broadly similar to the ones for the configuration at the maximum mass flow. The results are not presented for the sake of brevity. It was noted that for this reduced value of the mass flow rate, the intake separation occurred at a greater crosswind magnitude of $V_\infty = 18$ kts (9.3 m/s and $MFCR = 12.3$) compared to the case at the maximum mass flow rate. As illustrated in Fig. 12 for a fixed lower intake mass flow, as V_∞ increases, and $MFCR$ reduces the region of attached flow changes and the mechanisms of the separation depend on which separation boundary the intake crosses first. In light of these considerations, the measured intake aerodynamic behavior at the different operating conditions is mapped in Fig. 13. The performance map classifies the intake operating points and the intake flow regimes as a function of the

crosswind velocity and the $MFCR$, with the approximated separation boundary identified from the analysis of the time-averaged flow topology and the surface isentropic Mach number distributions.

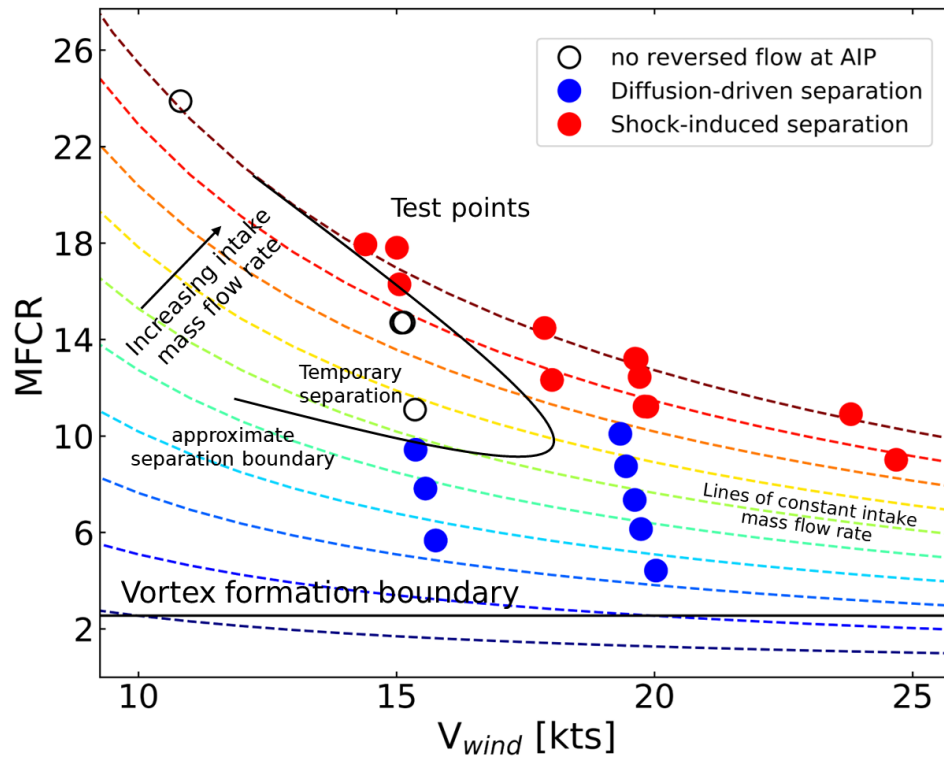


Fig. 13: Experimental intake performance map under crosswind conditions for $h/D_{hi} = 0.3$.

B. Unsteady flow analysis and swirl distortion assessment

The high levels of time-averaged swirl angle and the presence of reversed flow at the AIP can adversely affect the operability of the downstream axial compression system. Although this is an aspirated intake, and the coupling of the intake with a fan may reduce the distortion slightly ([48]-[50]), it is useful to evaluate the unsteady nature of the distorted flow. For each operating condition, the root mean square of the axial velocity fluctuations and the standard deviation of the swirl angle highlight the intensity of the fluctuations in the flow and the regions of the AIP more affected by the unsteadiness of the velocity field. A measure of the magnitude of the unsteadiness in axial velocity is given in Fig. 14, in terms of the distributions of the non-dimensional out-of-plane velocity fluctuations at the AIP for increasing $MFCR$ at 15 kts (7.7 m/s).

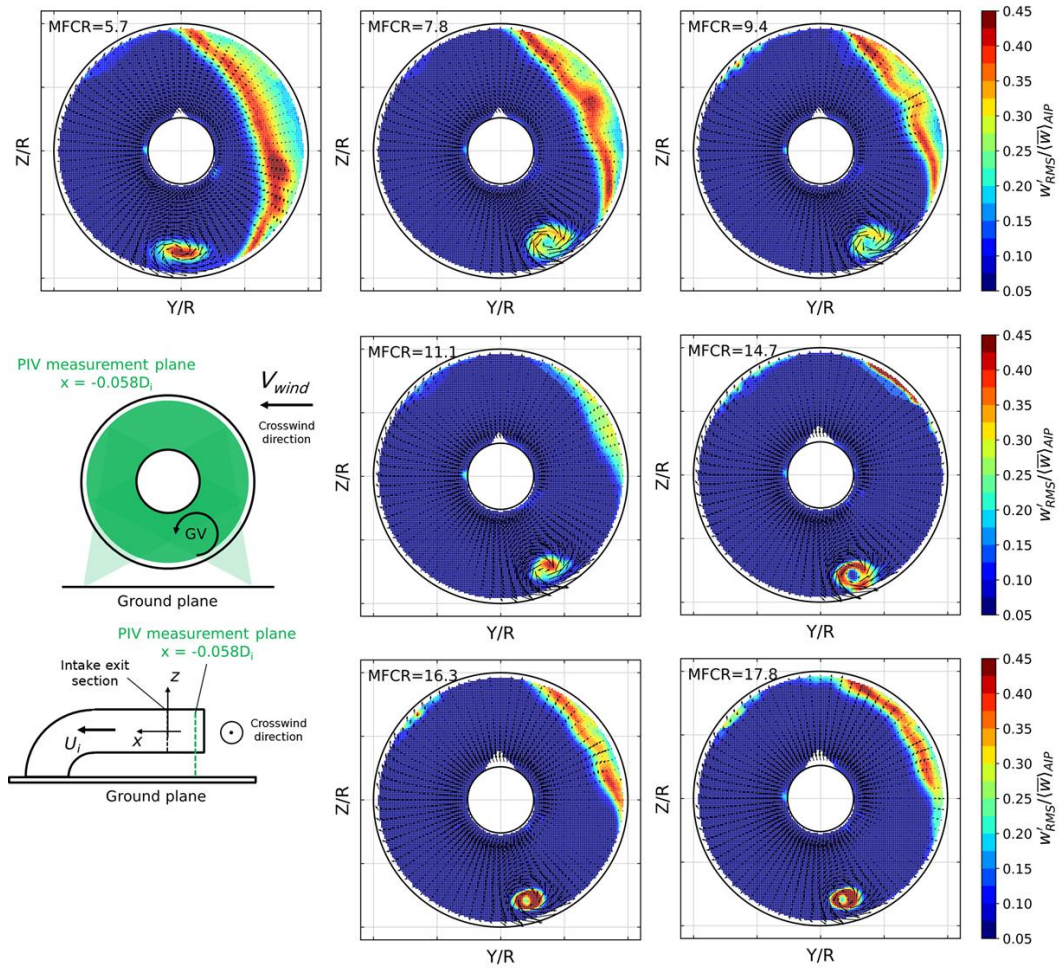


Fig. 14: Distributions of the non-dimensional out-of-plane velocity fluctuations $w'_{RMS}/\langle \bar{w} \rangle_{AIP}$ at the AIP with increasing Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 15 kts (7.7 m/s).

Crosswind direction from right to left. View looking downstream.

For low values of $MFCR$ from $MFCR = 5.7$ to 9.4 , that is for intake operating conditions characterized by a diffusion driven separation (Fig. 5), the extensive regions of unsteady out-of-plane velocity fluctuations $w'_{RMS}/\langle\bar{w}\rangle_{AIP}$, are associated with the windward separation and the ingested ground vortex. For $MFCR = 5.7$, the distribution of $w'_{RMS}/\langle\bar{w}\rangle_{AIP}$ shows a local maximum at the bottom of the separated region, for which the boundaries are highlighted in the time-averaged non-dimensional velocity distributions in Fig. 5. Another local maximum of out-of-plane velocity fluctuations is associated with the ingested ground vortex. As the $MFCR$ is increased to 7.8 and 9.4 , the region of greatest unsteadiness associated with the separation is less extensive, with peak values, although not notably reduced, located in the upper part of the AIP. Based on the time-averaged non-dimensional velocity distributions (Fig. 5) as the $MFCR$ is further increased to $MFCR = 11.1$ and 14.7 the intake is attached. However, from Fig. 14, in the distribution of the velocity fluctuations at $MFCR = 11.1$ there is evidence of a region of peak unsteadiness suggesting the presence of flow separation. This is due to a rare temporary separation which arises in specific PIV snapshots (Fig. 15). In this case, it is a low-speed diffusion separation mechanisms and highlights a more stochastic aspect of the onset and decay of the separated region at these intermediate $MFCR$ s between the low-speed diffusion boundary and the shock induced separation boundary.

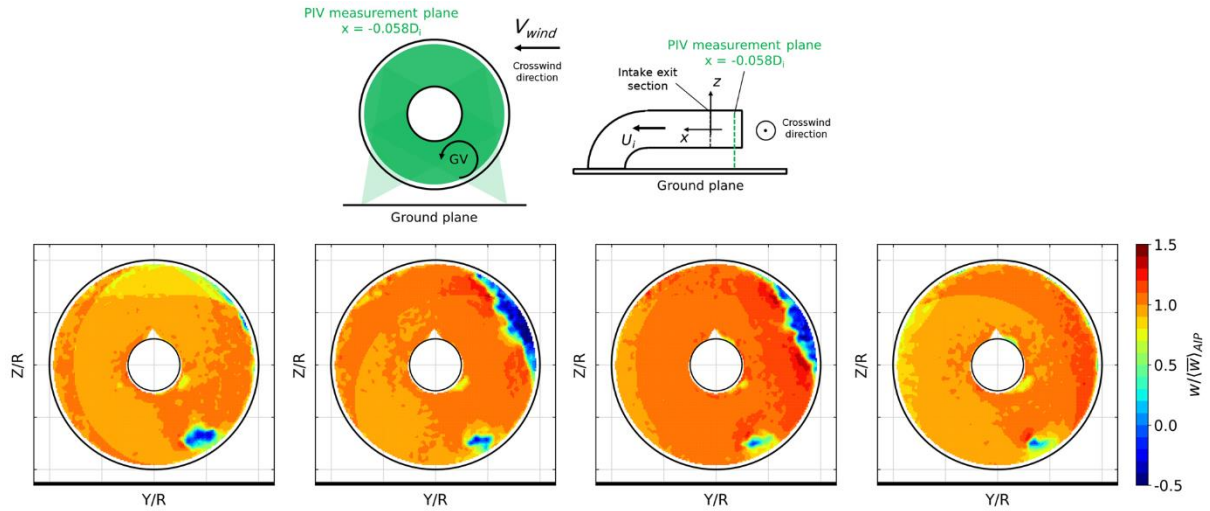


Fig. 15: Snapshots of axial velocity distributions $w/\langle\bar{w}\rangle_{AIP}$ at the AIP ($MFCR = 11.1$, 15 kts) showing the intake separation and reattachment. Crosswind direction from right to left. View looking downstream.

As the $MFCR$ increases to 16.3 and 17.8 for shock-induced separation conditions, the out-of-plane velocity fluctuations exhibit high values of $w'_{RMS}/\langle\bar{w}\rangle_{AIP}$. The local peak values, associated with flow separation, are comparable to those in diffusion-driven separation cases, but with reduced circumferential and radial extent. The fluctuations of the swirl angle σ_α with increasing $MFCR$ are shown in Fig. 16. The high swirl regions characterized

by high levels of unsteadiness are localized around the ground vortex core, especially at low $MFCR$ (from $MFCR = 5.7$ to 11.1), and in the separation in the top-half of the intake, when present (from $MFCR = 5.7$ to 9.4 and from $MFCR = 16.3$ to 17.8). While the values across the rest of the AIP remain relatively low, the large region of reversed flow introduces high peaks of swirl angle unsteadiness, indicative of large spatial and temporal variations that are greater than the time-averaged values (Fig. 10).

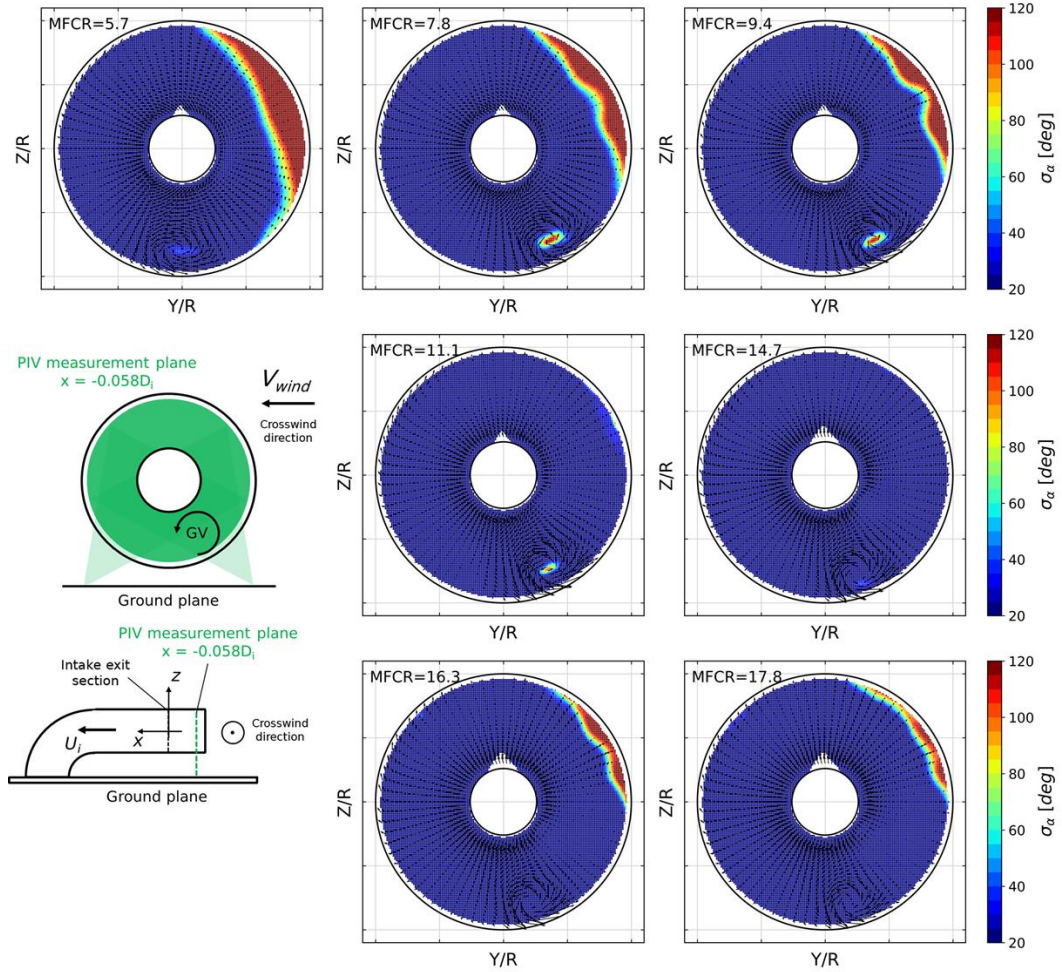


Fig. 16: Distributions of the swirl angle fluctuations σ_α at the AIP with increasing Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 15 kts (7.7 m/s). Crosswind direction from right to left.

View looking downstream.

The S-PIV data at the AIP provides a uniquely rich dataset and highlights the considerable advance relative to conventional low spatial resolution measurement methods. It has shown the substantial variations in the flow field and complex nature of the distorted flow. It is useful to extend the analysis to an assessment of the swirl distortion descriptors. Although the statistics of the main distortion descriptors provides a quantitative description of the average level of distortions, it is of key importance to consider the variability of the distortion parameters and the

peak distortion events. The heat maps introduced by Gil Prieto et al [41] simultaneously illustrate the relationship between two distortion metrics for the entire set of snapshots acquired during the PIV measurements, highlighting the range and trend between different descriptors and the occurrence of distortion events associated with the unsteady aspects of the flow that a simple statistical analysis does not address. The joint-Probability Density Function (j-PDF) cloud maps are plotted considering the swirl coefficient and the area-average swirl intensity. For the evaluation of the joint-PDF, the range of the descriptors is discretized into equi-spaced partitions which led to a resolution of 0.01 and 0.4° for $SC60$ and $\bar{SI}$, respectively. The joint-PDF is non-dimensionalized by the descriptors limit.

At a fixed crosswind of 15 kts (7.7 m/s) and increasing $MFCR$ (Case 1a in Table 1), Fig. 17 shows that the signature of the unsteady swirl descriptors depends on the $MFCR$. For the diffusion-driven separated case at $MFCR = 5.7$, there is a notable variation in both $SC60$ as well as $\bar{SI}$. As the $MFCR$ is increased to 17.8, the average and unsteady variation in $SC60$ monotonically decreases, while the time-averaged and maximum swirl intensity $\bar{SI}$ are greater for the cases where the flow is separated compared with the attached ones ($MFCR = 11.1, 14.7$). This shows that separation can generate high peaks of distortion that affect intake performance and potentially give rise to distortion events significantly different from the time-averaged values. In cases with diffusion-led flow separation (from $MFCR = 5.7$ to 9.4), the average and peak $SC60$ values are greater than those associated with time-averaged attached flow ($MFCR = 11.1$ and 14.7) and shock-induced separation ($MFCR = 16.3$ and 17.8). Interestingly, the statistical values of the swirl coefficient $SC60$ for the cases characterized by shock-induced separation ($MFCR = 16.3$ and 17.8) are lower not only than those associated with diffusion-driven separation, but also than those associated with time-averaged attached flow field. Considering that the $SC60$ parameter (Eq. 4), is an indicator of the level of the circumferential non-uniformities in the flow, this trend of the $SC60$ statistics suggests that the circumferential distortion is not primarily affected by the mechanisms of the separation, but by the presence of the ground vortex. The values of the overall swirl intensity $\bar{SI}$ are higher at low $MFCRs$ (from 5.7 to 9.4) compared to the ones for separated cases at high $MFCRs$ ($MFCR = 16.3$ and 17.8), due to a wider region of reversed flow (Fig. 10). For the separated cases at low $MFCRs$ ($MFCR = 5.7, 7.8$, and 9.1) the peaks of $\bar{SI}$ are between 2 and 4 times higher than the maximum values for the shock-induced separation cases ($MFCR = 16.3$ and $MFCR = 17.8$). This emphasizes a greater impact on intake distortion and flow unsteadiness of low $MFCR$ cases with diffusion-driven separation compared with the cases at high $MFCRs$, with shock-induced separation.

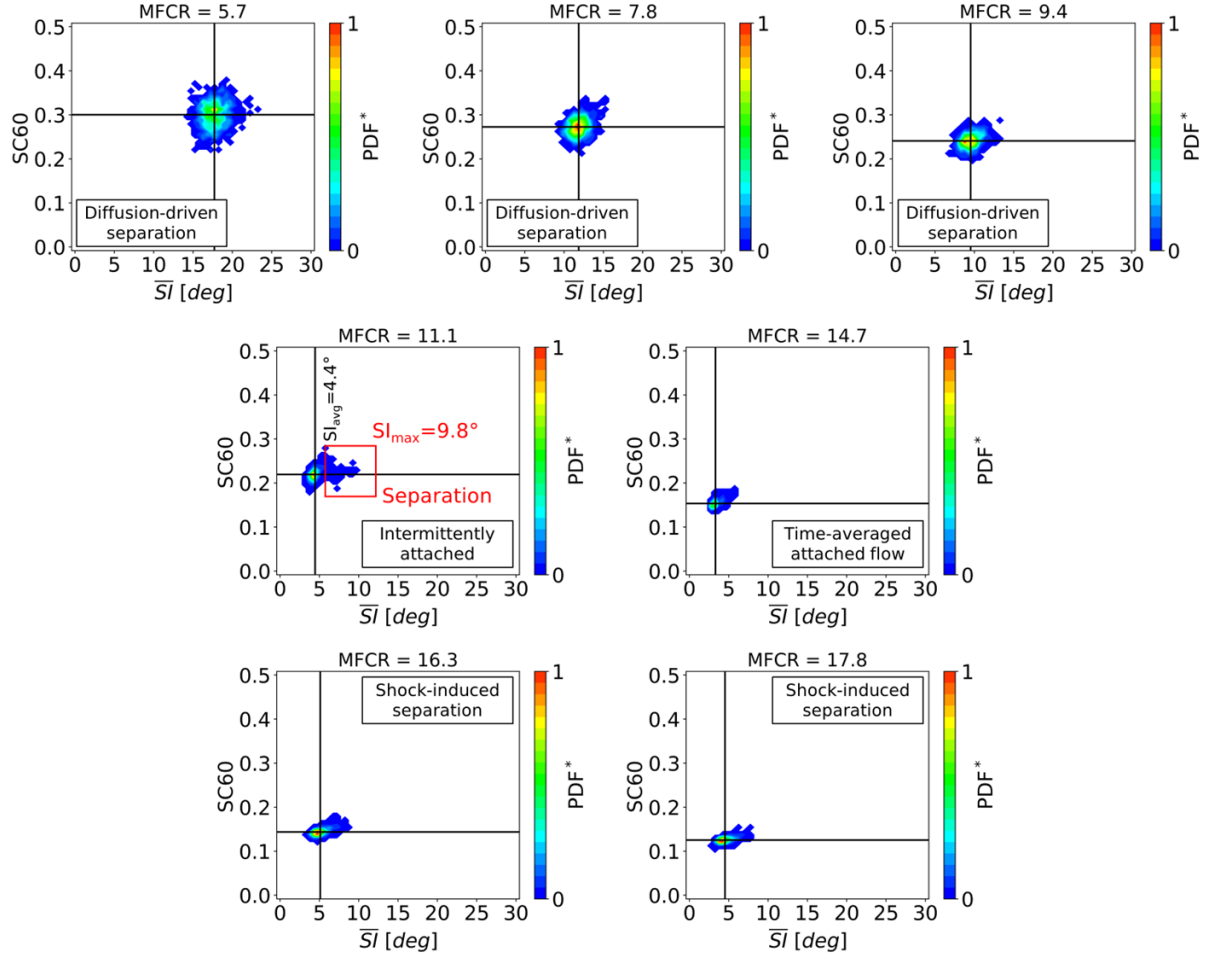


Fig. 17: SC_{60} - $\overline{SI}$ j-PDF distributions at the AIP for a fixed crosswind velocity of 15 kts (7.7 m/s) with varying Mass Flow Capture Ratio (MFCR).

The effect of the diffusion-driven separation on the performance of the intake in terms of SI and SC_{60} is also reflected on the radial distribution of the swirl intensity across the AIP (Fig. 18), where the average swirl intensity in each ring SI is plotted for each radial position, as a function of time. The diffusion-driven separated cases, combined with the ground vortex ($MFCR = 5.7, 7.8$, and 9.1), affect a bigger region of the AIP compared with the shock-induced separation cases ($MFCR = 16.3$ and 17.8). The swirl distortion spans from the outer surface of the intake up to 70% of the AIP in the worst case ($MFCR = 5.7$), reducing to 80% for the separated case just before the reattachment ($MFCR = 9.1$), with peak values above 40° and around 30° respectively. For the shock-induced separation cases ($MFCR = 16.3$ and 17.8) the peak SI is reduced to between 20 and 25° and the separation affects a smaller portion of the AIP plane compared to diffusion-driven separated cases.

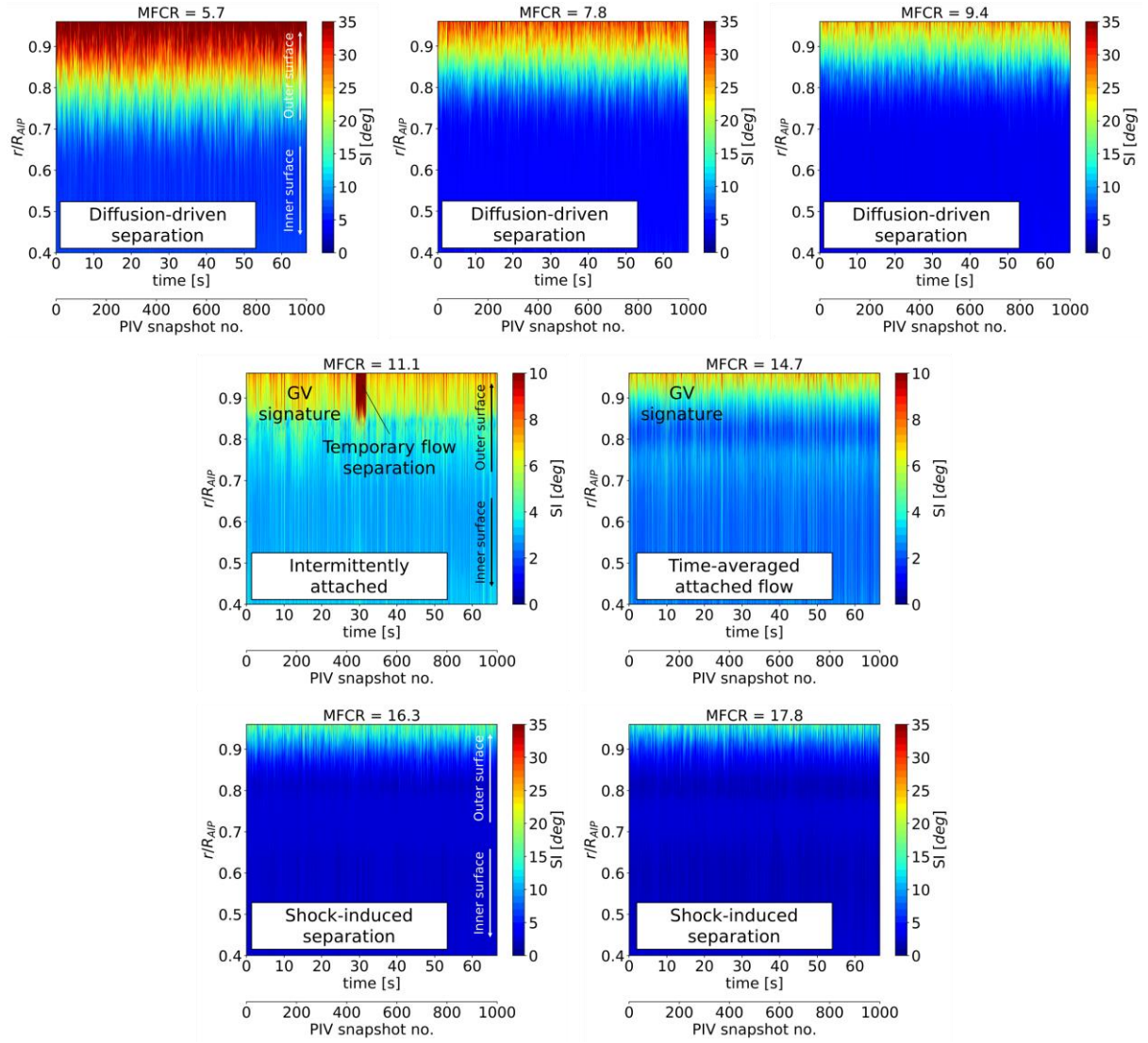


Fig. 18: Distributions of swirl intensity (SI) as a function of the AIP radius and time for a fixed crosswind velocity of 15 kts (7.7 m/s) between MFCR=5.7 (diffusion-driven separation) and MFCR=17.8 (shock-induced separation).

C. Ground vortex characterization

In previous experimental studies, the focus of the analysis of the ground vortex (GV) was on the determination of its the unsteady characteristics either on a plane underneath the intake [13] or on a plane ahead of the intake [15]. The unique aspect of these experiments enables a quantitative assessment of the GV characteristics across the AIP ahead of the fan face. A first assessment of the unsteady ground vortex behavior was previously presented by Kempaiah et al. [36] for a dataset at a fixed crosswind velocity of 15 kts (7.7 m/s). In this past work it was established that for high MFCR, the ingested vortex oscillates within a narrower area, suggesting a decreasing level of unsteadiness in the vortex core location across the plane. For a higher crosswind speed of 20 kts (10.3 m/s), the instantaneous locations of the ingested ground vortex core are shown in Fig. 19 as a function of MFCR. The time-averaged vortex center is indicated by the black marker, while the colors represent the probability, intended as the frequency of occurrence expressed as a percentage of the population, of the ingested vortex to be located at each point on the plane.

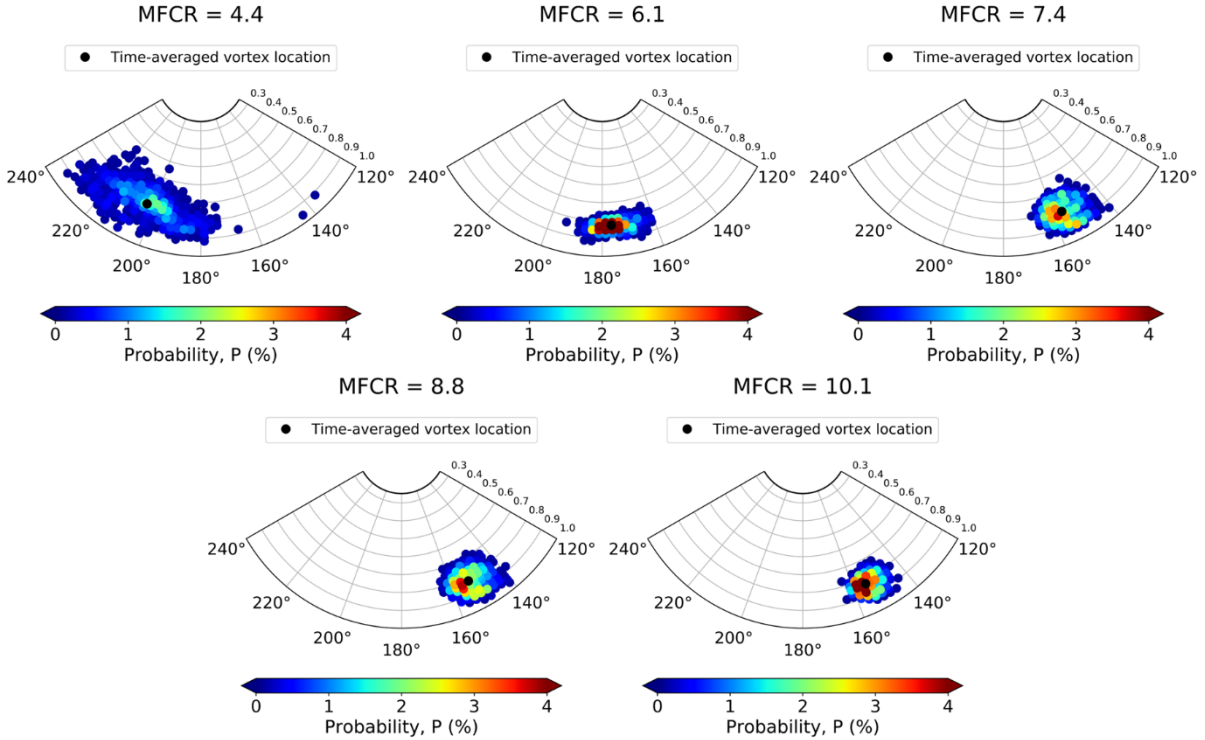


Fig. 19: Distribution of instantaneous ground vortex locations at the AIP as a function of Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 20 kts (10.3 m/s).

With increasing *MFCR*, the single anti-clockwise vortex increases in strength and moves azimuthally towards the windward side of the intake (Fig. 19). Previous investigations ([13] and [15]) showed that, for a fixed intake mass flow and increasing crosswind velocity, the ground vortex underneath the intake and at the inlet entrance is highly

unsteady and the level of unsteadiness increases as the $MFCR$ decreases. Across the range of $MFCR$ from 4.4 to 10.1, the radial position of the ingested ground vortex core does not change notably, being confined in a region between 0.6 and $0.9R_{AIP}$. As $MFCR$ increases, the time-averaged and the instantaneous azimuthal positions reduce from about a θ of 210° to 150° as the ground vortex moves towards the windward side. At the lowest $MFCR$ of 4.4, the vortex moves around on the plane with a relatively wide circumferential area around the time averaged location, with corresponding low values of probability, indicating a high level of unsteadiness. The azimuthal variation of the ground vortex position in this case is about 60° . As the $MFCR$ increases to 6.1 and 7.4 this azimuthal variation in vortex position reduces to about 40° and then further to about 20° for $MFCR = 8.8$ and 10.1. As the $MFCR$ is increased from 4.4 to 10.1, the levels of probability associated with the instantaneous ground vortex core location increase, suggesting a decrease in the amount of unsteadiness. In order to quantify the level of the unsteadiness of the ingested vortex, the variation of the vortex position is considered in terms of a meandering ([15]) relative to the time average location for both datasets at 15 kts (7.7 m/s) in Table 2 and 20 kts (10.3 m/s) in Table 3. The normalized vortex meandering is defined as the root mean square of the distance of the vortex core to the time average location and evaluated as a non-dimensional amplitude $a_M^* = a_M/D_i$. As reported in Table 2 and Table 3, the level of unsteadiness decreases as the $MFCR$ increases. This is in line with previous findings ([13] and [15]) for vortex positions either in front or underneath the intake. As the $MFCR$ is decreased by either reducing the intake mass flow rate or increasing the crosswind velocity, the intake operating point moves towards the limit value at which the ground vortex is blown away (see boundary in Fig. 13). These conditions, as shown in Fig. 19, are characterized by high levels of unsteadiness.

Table 2 Normalized vortex meandering amplitude a_M^* as a function of Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 15 kts (7.7 m/s).

	MFCR=5.7	MFCR=7.8	MFCR=9.4	MFCR=11.1
a_M/D_i	0.055	0.046	0.042	0.031

Table 3 Normalized vortex meandering amplitude a_M^* as a function of Mass Flow Capture Ratio (MFCR) for a fixed crosswind velocity of 20 kts (10.3 m/s).

	MFCR=4.4	MFCR=6.1	MFCR=7.4	MFCR=8.8	MFCR=10.1
a_M/D_i	0.091	0.036	0.043	0.041	0.031

The variations, as a function of the *MFCR*, of the ground vortex parameters in terms of normalized vortex core radius and vortex core circulation, both in peak magnitude and level of unsteadiness, are shown in Fig. 20 and Fig. 21 for a crosswind velocity of 15 kts (7.7 m/s) and 20 kts (10.3 m/s), respectively. Considering the non-dimensional circulation $\Gamma^* = \Gamma / D_i V_\infty$, the strength of the ground vortex intensifies with increasing *MFCR*, both in time-averaged and peak values. Since the crosswind velocity is constant and the mass flow rate through the intake is increased, the amount of vorticity ingested increases with the *MFCR*, due to the greater interaction between the captured stream-tube and the ground plane. The time-average values of Γ^* ranges from 1.47 to 3.42 for the range of *MFCRs* investigated at 15 kts (7.7 m/s) and from 1.05 to 3.36 at 20 kts (10.3 m/s), respectively. The peak values are between 3.07 (*MFCR* = 5.7) and 4.90 (*MFCR* = 11.1) for the case at 15 kts (7.7 m/s) and between 3.08 (*MFCR* = 4.4) and 4.72 (*MFCR* = 10.1) for the case at 20 kts (10.3 m/s). As the *MFCR* is increased the normalized vortex core $r_c^* = r_c / r_i$ remains broadly constant, with time-averaged values between 7% at *MFCR* = 5.7 and 11% at *MFCR* = 11.1 for the case at 15 kts (7.7 m/s) and between 6% at *MFCR* = 4.4 and 12% at *MFCR* = 10.1 for the case at 20 kts (10.3 m/s). It is also of interest to note that for both the non-dimensional circulation and the normalized vortex core radius, the level of unsteadiness, evaluated by means of the standard deviation, remains broadly constant across the range of *MFCRs*, suggesting no increase in the variability of the vortex core strength and vortex core radius. The time-averaged Vatistas' shape factor ranged between 0.90 (*MFCR* = 5.7) and 1.37 (*MFCR* = 11.1) for the case at 15 kts (7.7 m/s) and between 0.93 (*MFCR* = 4.4) and 1.40 (*MFCR* = 10.1) for the case at 20 kts (10.3 m/s), respectively.

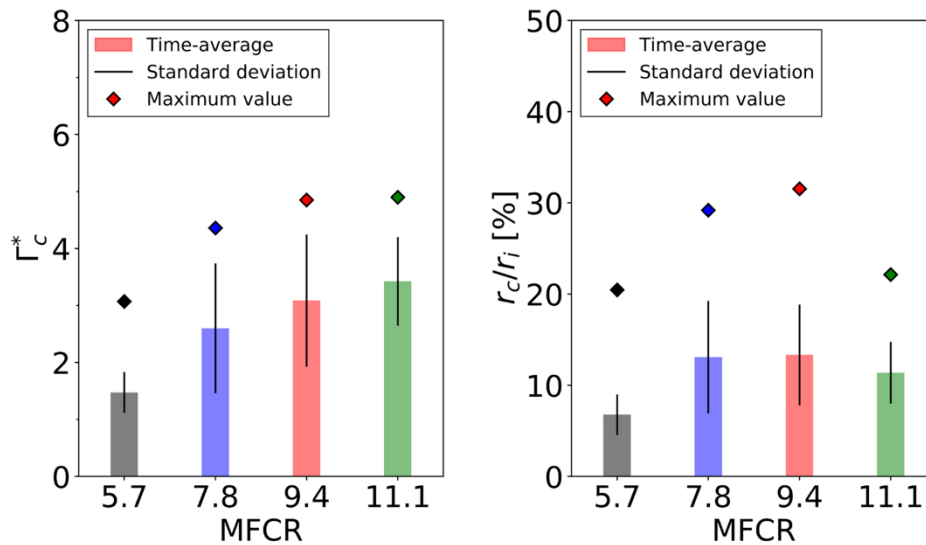


Fig. 20: Time average values and statistics of a) normalized vortex core circulation Γ^* and b) normalized vortex core radius, for varying *MFCR* at a fixed crosswind velocity of 15 kts (7.7 m/s).

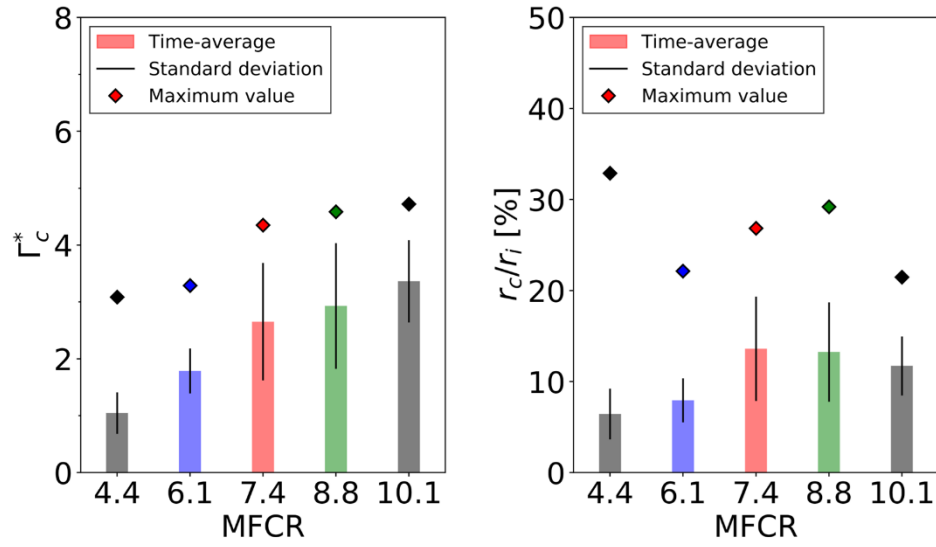


Fig. 21: Time average values and statistics of a) normalized vortex core circulation Γ^* and b) normalized vortex core radius, for varying MFCR at a fixed crosswind velocity of 20 kts (10.3 m/s).

IV. Conclusions

This study presents the analysis of non-intrusive unsteady velocity and swirl distortion measurements within a short aero-engine intake under crosswind conditions. The configuration is pertinent to very high bypass ratio engines. The measurements were conducted in an industrial wind tunnel environment which demonstrated the viable use of non-intrusive techniques in such settings for propulsion integration measurements. This was never demonstrated before and is a notable advance in the state of the art. In general, both total pressure and swirl distortion are pertinent in terms of the effect on the propulsion system. However, the focus of this work is on the less studied and less understood velocity and swirl distortion. The high spatial resolution and time-variant PIV data allowed for the characterization of intake swirl distortion caused by the ground vortex and intake separation with an unprecedented level of synchronous spatial resolution. The non-dimensional time-averaged velocity fields at the AIP, combined with the static pressure distributions on the intake surface, were used to classify the intake operating regime and to assess the nature of the distortion based on the underpinning flow separation mechanism; either diffusion or shock-driven. The two different separation mechanisms result in different levels of axial velocity and swirl angle distortion. Operating points characterized by diffusion-driven separation exhibit greater peak levels of swirl distortion and fluctuations over a wider area of the AIP compared to shock-induced separation. The analysis of the ground vortex characteristics showed that, the strength and radius of the vortex increases with *MFCR*, while the level of unsteadiness reduces. In addition, the measurements showed a mode of operation whereby the flow was found to be temporarily separated, which was not clearly established or quantified previously. This operating mode includes a primarily attached flow, with modest levels of distortion, but also instantaneous, extreme distortion events driven by diffusion separation. Overall, although the intake was aspirated and did not include a fan rotor coupled with the intake, which can affect the flow distortion, the successful measurement of the underpinning aerodynamic characteristics of the ground vortex, shock- and diffusion-induced separation, and the associated distortion classifications are an advance beyond the previous state of the art and lay the foundations for future assessments of coupled intake/fan configurations.

Acknowledgements and data access statement

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The underpinning data cannot be made available due to confidentiality restrictions.

References

- [1] Birch, N. T., "2020 Vision: The Prospects for Large Civil Aircraft Propulsion," *The Aeronautical Journal*, Vol. 104, No. 1038, 2000, pp. 347–352. <https://doi.org/10.1017/S0001924000063971>
- [2] Hughes, C., Van Zante, D., and Heidmann, J., "Aircraft Engine Technology for Green Aviation to Reduce Fuel Burn," 2011. <https://doi.org/10.2514/6.2011-3531>
- [3] Owens, R., Hasel, K., and Mapes, D., "Ultra High Bypass Turbofan Technologies for the Twenty-First Century," 1990. <https://doi.org/10.2514/6.1990-2397>
- [4] Boscagli, L., Christie, R., MacManus, D., and Piovesan, T., "Aerodynamics of a Short Intake in Crosswind," *Aerospace Science and Technology*, Vol. 129, 2022, p. 107826. <https://doi.org/10.1016/j.ast.2022.107826>
- [5] Cousins, W. T., "History, Philosophy, Physics, and Future Directions of Aircraft Propulsion System/Inlet Integration," 2004. <https://doi.org/10.1115/GT2004-54210>
- [6] Bowditch, D., and Coltrin, R., "A Survey of Inlet/Engine Distortion Compatibility," 1983. <https://doi.org/10.2514/6.1983-1166>
- [7] Siervi, F. De, Viguiet, H. C., Greitzer, E. M., and Tan, C. S., "Mechanisms of Inlet-Vortex Formation," *Journal of Fluid Mechanics*, Vol. 124, No. 1, 1982, p. 173. <https://doi.org/10.1017/S0022112082002456>
- [8] Shin, H. W., Cheng, W. K., Greitzer, E. M., and Tan, C. S., "Inlet Vortex Formation Due to Ambient Vorticity Intensification," *AIAA Journal*, Vol. 24, No. 4, 1986, pp. 687–689. <https://doi.org/10.2514/3.9330>
- [9] Shin, H. W., Greitzer, E. M., Cheng, W. K., Tan, C. S., and Shippee, C. L., "Circulation Measurements and Vortical Structure in an Inlet-Vortex Flow Field," *Journal of Fluid Mechanics*, Vol. 162, No. 1, 1986, p. 463. <https://doi.org/10.1017/S0022112086002124>
- [10] Liu, W., Greitzer, E. M., and Tan, C. S., "Surface Static Pressures in an Inlet Vortex Flow Field," *Journal of Engineering for Gas Turbines and Power*, Vol. 107, No. 2, 1985, pp. 387–393. <https://doi.org/10.1115/1.3239738>

- [11] Nakayama, A., and Jones, J. R., “Correlation for Formation of Inlet Vortex,” AIAA Journal, Vol. 37, No. 4, 1999, pp. 508–510. <https://doi.org/10.2514/2.743>
- [12] Brix, S., Neuwerth, G., and Jacob, D., “The Inlet-Vortex System of Jet Engines Operating near the Ground,” 2000. <https://doi.org/10.2514/6.2000-3998>
- [13] Murphy, J. P., and MacManus, D. G., “Ground Vortex Aerodynamics under Crosswind Conditions,” Experiments in Fluids, Vol. 50, No. 1, 2011, pp. 109–124. <https://doi.org/10.1007/s00348-010-0902-4>
- [14] Zantopp, S., MacManus, D., and Murphy, J., “Computational and Experimental Study of Intake Ground Vortices,” The Aeronautical Journal, Vol. 114, No. 1162, 2010, pp. 769–784. <https://doi.org/10.1017/S0001924000004255>
- [15] Wang, Z., and Gursul, I., “Unsteady Characteristics of Inlet Vortices,” Experiments in Fluids, Vol. 53, No. 4, 2012, pp. 1015–1032. <https://doi.org/10.1007/s00348-012-1340-2>
- [16] Boldman, D., Iek, C., Hwang, D., Larkin, M., and Schweigher, P., “Effect of a Rotating Propeller on the Separation Angle of Attack,” 1993. <https://doi.org/10.2514/6.1993-17>
- [17] Motycka, D. L., “Reynolds Number and Fan/Inlet Coupling Effects on Subsonic Transport inlet Distortion,” Journal of Propulsion and Power, Vol. 1, No. 3, 1985, pp. 229–234. <https://doi.org/10.2514/3.22785>
- [18] Larkin, M. J., and Schweiger, P. S., “Ultra High Bypass Nacelle Aerodynamics,” No. NASA CR-189149, 1992.
- [19] Schulze, S., Kähler, C., and Radespiel, R., “On Stalling Flow-Through Nacelles and Powered Inlets at Take-Off Conditions,” 2008. <https://doi.org/10.2514/6.2008-789>
- [20] Schulze, S., and Kaehler, C. J., “Analysis of the Flow in Stalling Engine Inlet Models with Different Visualization and Measurement Techniques,” *Second Symposium "Simulation of Wing and Nacelle Stall"*, 2010, pp. 1–12.
- [21] Probst, A., Schulze, S., Radespiel, R., and Kähler, C. J., “Numerical and Experimental Investigation of a Stalling Flow-Through Nacelle,” Notes on Numerical Fluid Mechanics and Multidisciplinary Design, Vol. 112, 2010, pp. 537–544. https://doi.org/10.1007/978-3-642-14243-7_66
- [22] Probst, A., Schulze, S., Kähler, C. J., and Radespiel, R., “Reynolds-Stress Modelling of Subsonic and Transonic Inlet Stall Compared to Measurements,” Third Symposium “Simulation of Wing and Nacelle Stall”, Braunschweig, 21. - 22. June 2012, pp. 1–13.

- [23] Probst, A., Schulze, S., Radespiel, R., and Kähler, C. J., “Numerical Simulation of Engine-Inlet Stall with Advanced Physical Modelling Compared to Validation Experiments,” *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Vol. 121, 2013, pp. 565–573. https://doi.org/10.1007/978-3-642-35680-3_67
- [24] Kennedy, S., Robinson, T., Spence, S., and Richardson, J., “Computational Investigation of Inlet Distortion at High Angles of Attack,” *Journal of Aircraft*, Vol. 51, No. 2, 2014, pp. 361–376. <https://doi.org/10.2514/1.C031789>
- [25] Quémard, C., Garçon, F., and Raynal, J., “High Reynolds number air intake tests in the ONERA F1 and S1MA wind tunnels,” *Workshop on airframe engine integration at DLR*, DLR, Mar. 1996, Braunschweig, France.
- [26] Lecordix J., Mullender A., Lecossais E., Godard J., and Hepperle M., “Hybrid laminar flow nacelle design,” *ICAS Proceedings*. 20: 504–520.
- [27] Hall, C., and Hynes, T., “Measurements of Intake Separation Hysteresis in a Model Fan and Nacelle Rig,” Vol. 22, 2002. <https://doi.org/10.2514/6.2002-3772>
- [28] Hall, C., and Hynes, T., “Nacelle Interaction with Natural Wind Prior to Take-Off,” Vol. 21, 2002. <https://doi.org/10.2514/6.2002-3773>
- [29] Colin Y., Aupoix B., Boussuge J.-F., and Chanez, P., “Numerical Simulation and Analysis of Crosswind Inlet Flows at Low Mach numbers,” *8th International Symposium on Experimental and Computational Aerothermodynamics of Internal Flows* Lyon, Jul 2007, Lyon, France.
- [30] Zhang, M., “Numerical Investigation of Nacelle Intake Flow Distortion at Crosswind Conditions,” *32nd Congress of the International Council of the Aeronautical Sciences, ICAS 2021*, 2021, pp. 1–11.
- [31] Harjes, L., Bode, C., Grubert, J., Frantzheld, P., Koch, P., and Friedrichs, J., “Investigations of Jet Engine Intake Distortions Caused by Crosswind Conditions,” *Journal of the Global Power and Propulsion Society*, Vol. 4, 2020, pp. 48–62. <https://doi.org/10.33737/jgpps/118875>
- [32] Burnazzi, M., Probst, A., and Steger, M., “Hybrid RANS/LES of an Isolated Engine Nacelle with Crosswind Using an Unstructured CFD Solver,” *Notes on Numerical Fluid Mechanics and Multidisciplinary Design*, Vol. 143, 2020, pp. 347–356. https://doi.org/10.1007/978-3-030-27607-2_28
- [33] “A Methodology for Assessing Inlet Swirl Distortion,” *Society of Automotive Engineers, SAE Aerospace Information Report 5686*, 2022.
- [34] “Inlet Total-Pressure Distortion Considerations for Gas-Turbine Engines,” *Society of Automotive Engineers, SAE Aerospace Information Report 1419D*, 2023.

- [35] Migliorini, M., Zachos, P. K., and MacManus, D. G., “Novel Method for Evaluating Intake Unsteady Flow Distortion,” *Journal of Propulsion and Power*, 2021, pp. 1–13. <https://doi.org/10.2514/1.b38127>
- [36] Kempaiah, K. U., Piovesan, T., Zachos, P. K., Michaelis, D., Gebbink, R., van Rooijen, B., Prieto, D. G., MacManus, D., Sciacchitano, A., and Sheaf, C., “High-Resolution Turbofan Intake Flow Characterization by Automated Stereoscopic-PIV in an Industrial Wind Tunnel Environment,” *Measurement Science and Technology*, Vol. 35, No. 2, 2024, p. 025210. <https://doi.org/10.1088/1361-6501/ad0ea0>
- [37] Seddon, J., and Goldsmith, E., “Intake Aerodynamics, Second Edition,” American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 1999. <https://doi.org/10.2514/4.473616>
- [38] Bouldin, B., and Sheoran, Y., “Inlet Flow Angularity Descriptors Proposed for Use With Gas Turbine Engines,” 2002. <https://doi.org/10.4271/2002-01-2919>
- [39] Zachos, P. K., MacManus, D. G., Prieto, D. G., and Chiereghin, N., “Flow Distortion Measurements in Convoluted Aeroengine Intakes,” *AIAA Journal*, Vol. 54, No. 9, 2016, pp. 2819–2832. <https://doi.org/10.2514/1.J054904>
- [40] MacManus, D. G., Chiereghin, N., Gil Prieto, D., and Zachos, P., “Complex Aero-Engine Intake Ducts and Dynamic Distortion,” 2015. <https://doi.org/10.2514/6.2015-3304>
- [41] Gil-Prieto, D., Zachos, P., MacManus, D. G., and Tanguy, G., “Convoluted Intake Distortion Measurements Using Stereo Particle Image Velocimetry,” 2016. <https://doi.org/10.2514/6.2016-3560>
- [42] Gil-Prieto, D., MacManus, D. G., Zachos, P. K., and Bautista, A., “Assessment Methods for Unsteady Flow Distortion in Aero-Engine Intakes,” *Aerospace Science and Technology*, Vol. 72, No. January, 2018, pp. 292–304. <https://doi.org/10.1016/j.ast.2017.10.029>
- [43] Guo, R. W., and Seddon, J., “The Swirl in an S-Duct of Typical Air Intake Proportions,” *Aeronautical Quarterly*, Vol. 34, No. 2, 1983, pp. 99–129. <https://doi.org/10.1017/S0001925900009641>
- [44] Guo, R. W., and Seddon, J., “Swirl Characteristics of an S-Shaped Air Intake with Both Horizontal and Vertical Offsets,” *Aeronautical Quarterly*, Vol. 34, No. 2, 1983, pp. 130–146. <https://doi.org/10.1017/S0001925900009653>
- [45] Taylor, J. R., “An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements,” University Science Books, 1996.
- [46] Trapp, L. G., and Girardi, R., “Evaluation of Engine Inlet Vortices Using CFD,” 2012. <https://doi.org/10.2514/6.2012-1200>

- [47] Mishra, N., MacManus, D., and Murphy, J., “Intake Ground Vortex Characteristics,” Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, Vol. 226, No. 11, 2012, pp. 1387–1400. <https://doi.org/10.1177/0954410011424092>
- [48] Lee, K.-B., Wilson, M., and Vahdati, M., “Effects of Inlet Disturbances on Fan Stability,” *Journal of Engineering for Gas Turbines and Power*, Vol. 141, No. 5, 2019, pp. 1–11. <https://doi.org/10.1115/1.4042204>
- [49] Cao, T., Vadlamani, N. R., Tucker, P. G., Smith, A. R., Slaby, M., and Sheaf, C. T. J., “Fan–Intake Interaction Under High Incidence,” *Journal of Engineering for Gas Turbines and Power*, Vol. 139, No. 4, 2017, pp. 1–10. <https://doi.org/10.1115/1.4034701>
- [50] Carnevale, M., Wang, F., Green, J. S., and Di Mare, L., “Lip Stall Suppression in Powered Intakes,” *Journal of Propulsion and Power*, Vol. 32, No. 1, 2016, pp. 161–170. <https://doi.org/10.2514/1.B35811>



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