

Unsteady flow interactions and ground plane proximity in a coupled compact intake-fan in crosswind[☆]

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ABSTRACT

The assessment of the crosswind flow separation and resulting intake flow distortion can be a key consideration for the design of viable large civil aeroengines. Under crosswind conditions, the intake aerodynamics are strongly influenced by both the fan and the ground plane. However, the impact of key design parameters, such as ground clearance, on the intake flow distortion is not fully understood. This study investigates the effects of a large variation in ground clearance on the intake-fan unsteady aerodynamics using Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations of a fully coupled rotating fan stage. The work includes an assessment of the unsteady swirl distortion and the unsteady peak distortion events. The findings show that increased ground clearance can have adverse effects on the intake flow distortion. Gross separation can occur at lower crosswind velocities which arise at the intake lower quadrant due to mass flow redistribution. Conversely, the gross separation on the windward side of the intake occurs at a greater crosswind velocity for an increased ground clearance. However, this separation also exhibits greater levels of the azimuthal extent of the unsteady intake swirl distortion compared to the baseline configuration. Overall, intake designs should be assessed at the expected ground clearance as the flow distortion and the onset of separation can vary substantially.

1. Introduction

The design of aero-engine intakes is a key aspect in reducing cruise fuel consumption by minimizing cruise drag and mass of the overall propulsion system. Compact intakes can offer benefits by reducing the nacelle wetted area and mass (Peters et al., 2015). However, such benefits are accompanied by challenges related to off-design conditions, such as high incidence and crosswind operations (Cao et al., 2017). For these operating conditions, and depending on the intake geometry and curvature distributions (Coschignano et al., 2019; O'Pray et al., 2022; Boscagli et al., 2023), subsonic adverse pressure gradients (Piovesan et al., 2024) and shock boundary layer interactions (Boscagli et al., 2023; Castillo Pardo et al., 2025; Lobbuono et al., 2024; Pardo et al., 2024; Boscagli et al., 2023; Piovesan et al., 2024) can lead to boundary layer separations that arise on the intake lip and diffuser surface. These separations can potentially cause flow distortion and degrade the performance of the fan and the overall propulsion system (Castillo Pardo et al., 2025); (Page et al., 2018). Additionally, the impact of features such as the ground vortex (GV), upstream perturbations from the fan, and intake flow unsteadiness remain insufficiently understood. In the literature there are examples of the analysis of the high incidence operations (Cao et al., 2017; Coschignano et al., 2019; O'Pray et al., 2022); (Carnevale et al., 2017, 2018; Vadlamani et al., 2019; Gunn et al., 2021),

while there is still a substantial gap in understanding the impact of the effect of crosswind velocity on the onset of intake separation and flow distortion when the intake-ground and intake-fan interactions are considered.

In crosswind operations, the conditions under which the intake flow separates are influenced by the crosswind velocity (V_{cw}) and mass flow capture ratio (MFCR, Eq. (1))

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

where m_f is the intake mass flow, ρ_∞ is the freestream density, and A_{hi} is intake highlight area, defined as the projected frontal area of the geometric boundary between the intake lip and external nacelle forebody (Fig. 1). Piovesan et al (Piovesan et al., 2024) investigated the intake aerodynamics for different combinations of MFCR and V_{cw} using Particle Image Velocimetry (PIV) measurements within an aspirated turbofan intake. Two distinct types of separation were identified on the windward side of the intake, one related to subsonic diffusion (low MFCR) and a shock-induced separation (high MFCR). At low MFCR, the separation occurs on the internal diffuser surface downstream of the lip. At high MFCR, the flow accelerates over the lip to produce a locally supersonic flow with a terminating shock that interacts with the boundary layer and can result in a shock induced separation (Piovesan et al., 2024; Boscagli

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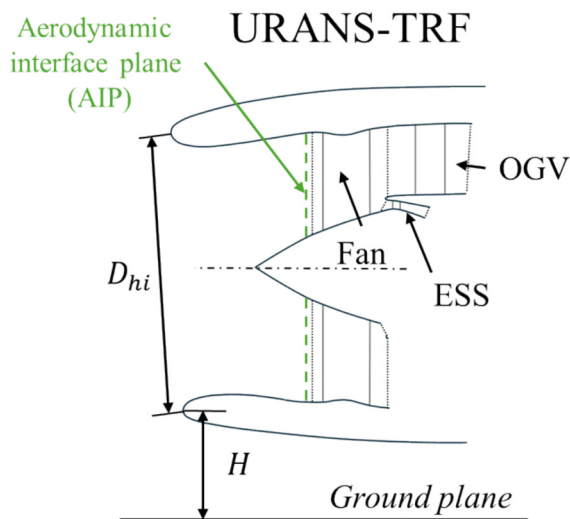


Fig. 1. Schematic representation of intake-fan configuration.

et al., 2022; Castillo Pardo et al., 2025; Vadlamani and Tucker, 2019). These are critical considerations to understand the operational limits of an intake in crosswind conditions. The separated regions are characterised by total pressure losses and extensive flow distortion which have the potential to act as initiators of fan stall and rotating flow instabilities (Zhang and Vahdati, 2019; Awes et al., 2020; Zhang, 2019).

In addition to intake flow separation, intake-ground interactions can give rise to other flow features that can affect the intake aerodynamics. The ground vortex (GV) forms due to the interaction of the captured stream tube and the ground plane (Murphy and MacManus, 2011; Mishra et al., 2012; Nichols et al., 2022; Dupuy, 2022; Courtine et al., 2022; Zhang et al., 2024; Rao et al., 2022; Zantopp et al., 2010). This results in a vortex that is ingested by the intake and generates swirl and total pressure loss as well as circumferential and radial distortion at the Aerodynamic Interface Plane (AIP, Fig. 1) (Murphy and MacManus, 2011; Rao et al., 2022). The ground vortex formation typically depends on the MFCR, which needs to be greater than a critical value that depends on the freestream conditions and ground clearance (Murphy and MacManus, 2011; Mishra et al., 2012).

Previous work (Murphy and MacManus, 2011) indicates that the ground clearance significantly impacts the formation, position and strength of the ground vortex. The intake ground clearance, along with the approaching boundary layer thickness and freestream Mach number can notably affect the vortex strength (Murphy and MacManus, 2011). As ground clearance decreases, the interaction between the intake stream tube and the ground intensifies, which can lead to an increase in the ground vortex strength and the associated level of distortion (Murphy and MacManus, 2011; Mishra et al., 2012). A trailing vortex (TV) may also develop on the leeward side due to the asymmetry of the captured stream tube and further contribute to unsteady distortion and swirl variations at the AIP (Mishra et al., 2012; Zantopp et al., 2010).

For shorter and more compact intakes, the aerodynamic coupling between intake and fan becomes increasingly important. The proximity of the fan can modify the intake flow field through both steady and unsteady mechanisms. Previous work shows that the fan can positively influence intake performance under high incidence by redistributing mass flow and accelerating flow at the fan tip which can alleviate the local adverse pressure gradients and move the separation to higher angles of attack (Cao et al., 2017). However, Boscagli et al. (2022, 2023) showed that unsteady fan effects, such as unsteady pressure waves, can propagate upstream and interact with the shock front on the intake lip. This can trigger a separation at lower crosswind velocities for powered (intake-fan coupled) configurations compared to aspirated (intake-only) ones. Previous studies (Castillo Pardo et al., 2025; Pardo et al., 2024) of

conventional and short intakes under crosswind conditions highlight that the fan proximity can suppress the intake flow separation in shorter intakes but may increase swirl variation in the separated region, particularly for counter-rotating configurations. However, for shorter configurations, it was also shown that a gross separation may not reattach upstream of the fan face due to the more aggressive diffusers (Castillo Pardo et al., 2025).

Previous studies have examined the influence of intake-ground plane interaction on the formation and strength of the ground vortex (Murphy and MacManus, 2011; Mishra et al., 2012; Nichols et al., 2022; Dupuy, 2022; Courtine et al., 2022; Zhang et al., 2024; Rao et al., 2022; Zantopp et al., 2010). However, these studies have not explored the impact of ground clearance on intake separation mechanisms or the resulting unsteady swirl distortion. In addition, the previous work did not consider powered configurations with coupled intake-fan arrangements as the analysis of the effect of ground clearance was restricted to aspirated intakes. It is important to note that the present study does not focus on the formation of the ground vortex as there is a considerable body of literature that already addresses these aspects (Murphy and MacManus, 2011; Mishra et al., 2012; Nichols et al., 2022; Dupuy, 2022; Courtine et al., 2022; Zhang et al., 2024; Rao et al., 2022; Zantopp et al., 2010). The analysis is focused on a range of V_{cw} at a constant mass flow which is pertinent to analyses for intake design and the identification of intake flow separation boundaries (Boscagli et al., 2023; Boscagli et al., 2022; Loboano et al., 2024; Castillo Pardo et al., 2025). The requirement on the maximum tolerable pure crosswind V_{cw} for take-off conditions depends on the particular aircraft applications. However, within the open literature previous studies have used a V_{cw} of 35kts as typical reference conditions for pure crosswind condition (Castillo Pardo et al., 2025; Pardo et al., 2024); consequently, this study spanned a range of V_{cw} from 22 to 36kts. In these conditions, and for the ground clearances assessed in this work, the ground vortex is always ingested by the intake.

This current study builds upon previous research and methodologies that investigated unsteady intake-fan interactions under crosswind conditions (Boscagli et al., 2022, 2023; Loboano et al., 2024). While prior work (Loboano et al., 2024) analysed the intake flow separation, and spectral characteristics of distortion, the key contribution of this study lies in the identification of the intake separation mechanisms and the swirl distortion due to significant changes in ground clearance. The unsteady swirl distortion is assessed using a blade incidence tracking method that quantifies both the intensity and azimuthal extent of peak swirl distortion events (Migliorini et al., 2022). This method is applied for the first time to a full-scale compact intake, providing new insights into its aerodynamic behaviour.

2. Methodology

2.1. Intake design and computational grid

The in-house Tool for Intake Design (TIDE) (Christie et al., 2017; Christie et al., 2019) method was used to design the intake geometry. A 3D non-axisymmetric intake was generated using a parametric approach based on iCST curves. The full-scale configuration consisted of a compact intake with a length-to-fan-diameter ratio (L_{in}/D_{fan}) of 0.4 (Loboano et al., 2024). A significant variation in ground clearance was evaluated for $H/D_{hi}=0.25$ and $H/D_{hi}=0.44$, where H denotes the height of the bottom lip above the ground and D_{hi} is the highlight diameter (Fig. 1). A multiblock fully structured 3D mesh consisting of 4.5×10^7 nodes was used. This comprised an intake mesh of 1.0×10^7 nodes generated with ICEM (ANSYS Inc., 2015) (Fig. 2) and a fan stage mesh of 3.5×10^7 nodes generated with a proprietary meshing tool. The wall boundary layer was resolved with a $y^+ \approx 1$. The computational domain (Fig. 3) was approximately a quarter-sphere with a radius about 30 times the fan diameter, based on (Lee et al., 2018). Static pressure far-field boundary conditions were applied at the freestream, while the intake, fan cowl, spinner, and ground plane were modelled as no-slip walls

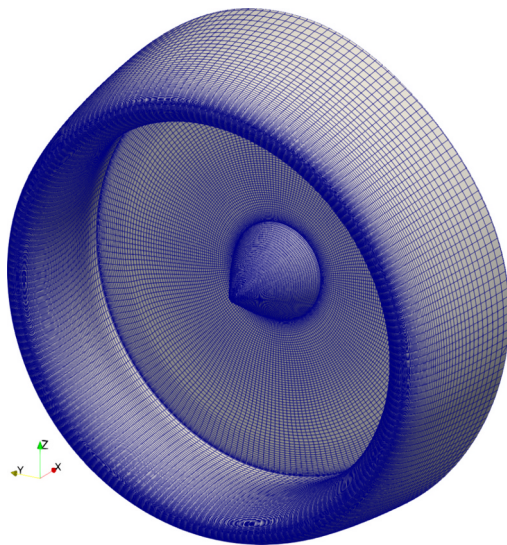


Fig. 2. Detail of intake surface mesh.

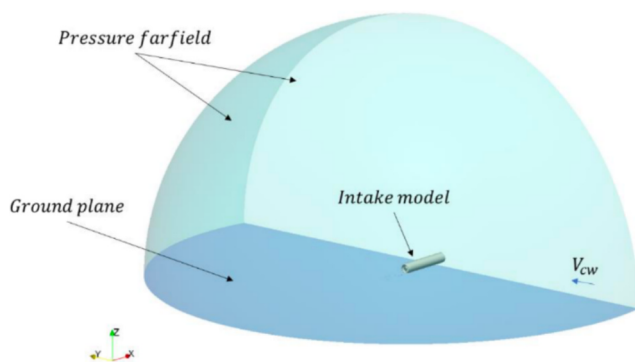


Fig. 3. Computational domain (Lobuono et al., 2024).

(based on (Boscagli et al., 2022)).

2.2. Solver and coupled intake-fan CFD analysis

The simulations were conducted using a proprietary Navier Stokes code, which is an unstructured finite volume solver (Moinier, 1999; Almendral-Fernandez et al., 2018). Convective fluxes were evaluated using a Roe approximate Riemann solver with a second-order MUSCL reconstruction (Crumpton et al., 1997). To limit numerical dispersion around discontinuities such as shock waves, a pseudo-Laplacian blending approach (Misev and Hills, 2018) was employed to switch smoothly between first- and second-order reconstruction. Viscous fluxes were discretised using second-order central differencing, and gradients were evaluated using a Green–Gauss method (Misev and Hills, 2018). Time advancement was performed using an implicit second-order backward-difference scheme (Almendral-Fernandez et al., 2018).

The aerodynamic interaction between the intake and the fan was investigated using an unsteady fully coupled computational model of the intake-fan configuration. The work followed the methodology outlined by Boscagli et al. (2022, 2023). This technique utilized an unsteady Reynolds Averaged Navier-Stokes (URANS) approach with a full annulus rotating fan, referred to as URANS-Time Resolved Fan (URANS-TRF). The computational capabilities for the turbomachinery were validated by Boscagli et al (Boscagli et al., 2022) using a single stage arrangement of a research fan in isolation.

In this work, the simulation setup included an intake coupled with the research fan stage, featuring a single passage Outlet Guide Vane

(OGV) and Engine Sector Stator (ESS) blades (Fig. 1, Fig. 4). A sliding plane boundary condition (Almendral-Fernandez et al., 2018) was implemented at the interface between the stationary and rotating parts (Fig. 4). Neighbouring subdomains were extended normal to the interface to create a one-cell overlap, so each subdomain had an internal surface and a corresponding extruded external surface. Values of the primitive variables on an external surface were obtained by interpolating from the internal surface of the adjacent subdomain. This sliding-plane treatment was used for the unsteady RANS simulations to account for the aerodynamic interactions, the changing relative reference frame and the motion of the blade row. A mixing-plane boundary condition (Denton, Jan. 1992) was applied between the fan-OGV and fan-ESS regions (Fig. 4). Constant mass flow rates were set at the OGV and ESS exits (Fig. 4).

Building on previous computational analyses of intakes with body-force fan models (Carnevale et al., 2017; Vadlamani et al., 2019; Cao et al., 2017), the Spalart-Allmaras (SA) turbulence model with a vorticity- and strain-based production term was applied (Spalart and Allmaras, 1992). The URANS-TRF simulations were conducted with a computational timestep corresponding to a frequency that was 60 times greater than blade passing frequency (f_{bp}). This value was comparable to that used in previous work and was considered sufficient to capture the distortion wavelength and frequency in the relative frame of reference (Carnevale et al., 2017). Data sampling occurred every 12 timesteps, yielding a sampling frequency ratio of $f_s/f_{bp} = 5$. A frequency resolution of $f_{res}/f_{bp} \sim 0.01$ was achieved (Lobuono et al., 2024). After an initial transient equivalent to 4 fan revolutions, a total physical time to complete at least 6 fan revolution was computed to ensure adequate resolution of the dominant low-frequency unsteadiness associated with the separation and shock–boundary-layer interaction (SBLI). This was characterised by frequencies below the blade-passing frequency and comparable with the one engine revolution (Lobuono et al., 2024). A CFL number of order unity was maintained in the near-wall and shock-interaction regions. The unsteady simulations were initialised from a steady RANS solution for which the iterative convergence was a reduction of flow residuals by five orders of magnitude. For the iterative convergence of the subsequent URANS computations, there was a reduction of residuals of about two orders of magnitude for each time-step along with the stabilisation of mass flow at the OGV and ESS outlets to the prescribed values. Wall resolution was maintained at $y^+ \sim 1$, with sufficient refinement across the boundary layer and shock-interaction regions to capture the relevant compressible-flow features.

2.3. CFD validation

The CFD methodology was based on previous grid independence and validation studies (Boscagli et al., 2022). These results were validated against experimental data (Boscagli et al., 2022) and reported here for completeness (Fig. 5; Fig. 6 a-b).

A first study was centred around a non-axisymmetric intake config-

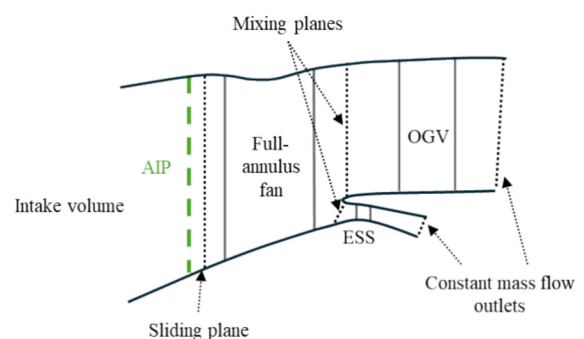


Fig. 4. Schematic representation of fan stage volumes and boundary conditions.

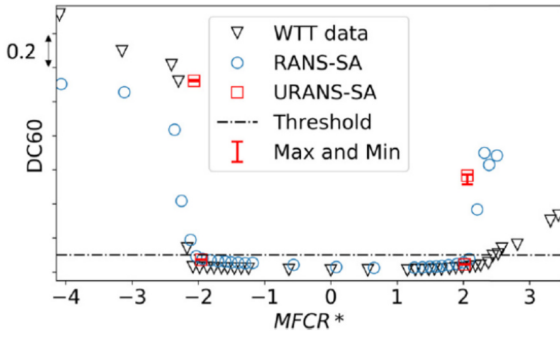


Fig. 5. DC60 as a function of MFCR* for model scale aspirated intake in crosswind. RANS and URANS results compared to Wind Tunnel Test (WTT) (Boscagli et al., 2022).

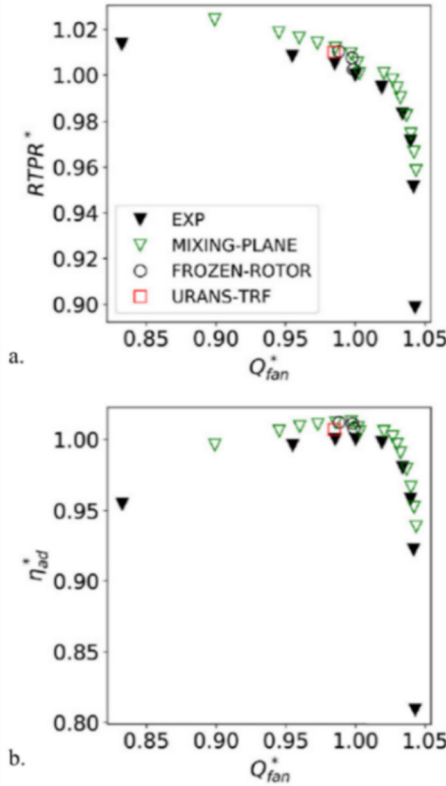


Fig. 6. (a.) Normalised rotor total pressure ratio (RTPR*) and (b.) normalised rotor adiabatic efficiency (η^*_{ad}) as a function of normalised fan capacity (Q^*_{fan}). Steady RANS Mixing-Plane and Frozen-Rotor (FR) and URANS Time Resolved Fan (TRF) comparison against experimental data (EXP) (Boscagli et al., 2022).

uration without a fan or ground plane in crosswind. The mass flow was varied to achieve a variation of MFCR. Steady RANS with Spalart-Allmaras (SA) model was applied on grids of 6.8×10^6 , 10.8×10^6 , and 35.2×10^6 nodes. Total pressure distortion and loss at the AIP were quantified using inlet pressure ratio (IPR, Eq. (2)) and DC60 (Eq. (3)), and the critical crosswind velocity was defined by the DC60 threshold. In Eq. (2), $\overline{P}_{0,AIP}$ is the area-averaged total pressure at the AIP and $P_{0,WTT}$ is the wind tunnel inlet total pressure. In Eq. (3), $\overline{P}_{0,60}$ and $\overline{q}_{AIP}$ denote the area-averaged values of lowest total pressure in a 60° sector and dynamic head.

$$IPR = \frac{\overline{P}_{0,AIP}}{P_{0,WTT}} \quad (2)$$

$$DC60 = \frac{\overline{P}_{0,60} - \overline{P}_{0,AIP}}{\overline{q}_{AIP}} \quad (3)$$

Grid level 2 (10.8×10^6) provided sufficient accuracy with a grid convergence index (GCI) of 0.014% for IPR and 5.6% for DC60 when compared to level 3 grid. The MFCR was referred to a reference attached condition ($MFCR_{ref}$) and redefined as $MFCR^* = MFCR - MFCR_{ref}$. Based on the measurements, an open separation occurred at low MFCR in subsonic flow conditions ($MFCR^* \sim -2.2$, Fig. 5), while transonic flow with shock induced separation arose at high MFCR ($MFCR^* \sim 2.4$, Fig. 5). Steady RANS predicted the critical MFCR in the transonic regime with $\sim 6\%$ accuracy and within $\pm 1\text{--}2\%$ for unsteady RANS (Boscagli et al., 2022).

The solver underwent additional validation on a single-stage turbomachinery configuration including a single passage fan, Outlet Guide Vane (OGV), and Engine Sector Stator (ESS) using mixing plane boundary conditions (Fig. 6 a-b) (Boscagli et al., 2022). Grid convergence used three levels with 4.4×10^6 , 8.2×10^6 , and 16.2×10^6 nodes, and grid level 1 (4.4×10^6) achieved a GCI below 0.05% for the rotor total pressure ratio (RTPR) and adiabatic efficiency (η_{ad}). Full-annulus unsteady RANS with sliding-plane boundaries were applied at the fan peak efficiency point ($Q^*_{fan} \sim 1.0$, Fig. 6 a-b). Unsteady simulations spanned multiple fan revolutions with 60 time-steps per blade-passing time. The values of Q_{fan} , RTPR and η_{ad} were normalized with the experimental values at fan peak efficiency point and referred as Q^*_{fan} , RTPR* and η^*_{ad} respectively. At the peak efficiency point ($Q^*_{fan} \sim 1.0$, Fig. 6 a-b), the deviations from the experimental results were below 0.01 in RTPR and 1.2% in η_{ad} for the different CFD models (Boscagli et al., 2022).

These results quantified the CFD solver capabilities for intake aerodynamic in crosswind and fan performance analyses. Overall, the SA turbulence model was considered to be sufficiently adequate for the analyses carried out in this study.

2.4. Data analysis

The distribution of aerodynamic quantities was assessed at the Aerodynamic Interface Plane (AIP, Fig. 1, Fig. 4), and on the unwrapped intake surface. The isentropic Mach number M_{isen} and axial wall shear stresses τ_{wx} were investigated on the intake surface. M_{isen} was calculated with eq. (4), where $P_{0\infty}$ is the freestream total pressure, P the local static pressure and γ the ratio of specific heats.

$$M_{isen} = \sqrt{\frac{2}{\gamma - 1} \left[\left(\frac{P_{0\infty}}{P} \right)^{\frac{\gamma - 1}{\gamma}} - 1 \right]} \quad (4)$$

The variation of swirl angle was assessed based on the velocity triangles shown in Fig. 7. The swirl and relative swirl angles were evaluated with Eq. (5) and (6), where V_θ and V_{ax} are the tangential and axial components of the absolute velocity, U is the blade speed (Eq. (7)), and the term $V_\theta - U = W_\theta$ is the relative tangential velocity (Fig. 7). V_θ and W_θ are positive in the same direction of U ; α , β and are positive in the clockwise direction, which is the same of the fan rotational speed ω [rad/s] (Fig. 8).

$$\alpha = \tan^{-1}(V_\theta/V_{ax}) \quad (5)$$

$$\beta = \tan^{-1}((V_\theta - U)/V_{ax}) \quad (6)$$

$$U = \omega r \quad (7)$$

Considering this sign convention for β , the blade incidence angle i was calculated with Eq. (8), where β_m is the blade metal angle (Fig. 7). The variation of blade incidence angle Δi (Eq. (9)) was determined with reference to the nominal values of incidence i_{nom} . This was evaluated with a circumferential average of i from a steady single passage fan

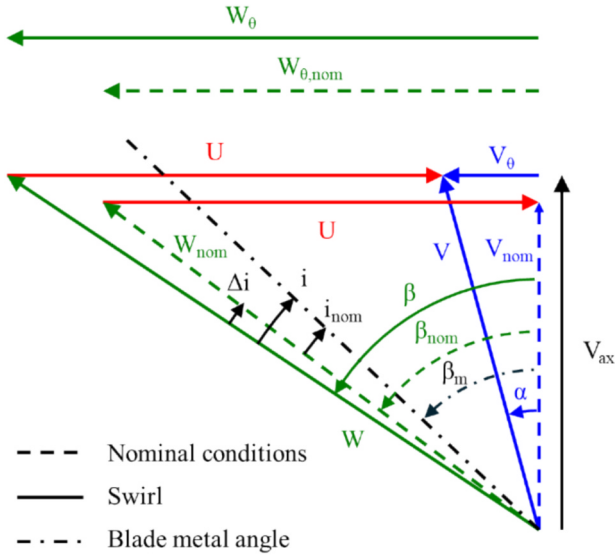


Fig. 7. Velocity triangles for nominal (dashed) and swirl (solid) conditions and indication of fan blade metal angle (based on (Migliorini et al., 2022)).

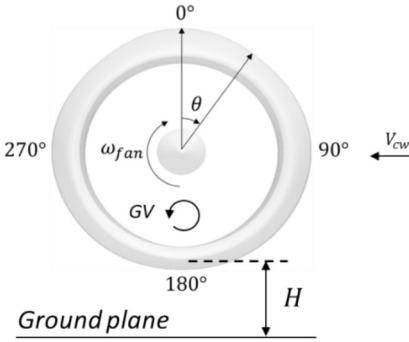


Fig. 8. Intake crosswind configuration.

computation.

$$i = \beta_m - \beta \quad (8)$$

$$\Delta i = i - i_{nom} \quad (9)$$

Δi was tracked for each blade and across the radial extent at the AIP. The method was outlined by Migliorini et al. (2022) and defined a swirl distortion event as a strictly positive or strictly negative interval of $\Delta i(t)$ (Fig. 9 a). Each distortion event was characterised by a duration t_e and an average value $\langle \Delta i \rangle_e$. For each distortion event, the peak Δi_{peak} was identified. A distortion event was classified as a peak distortion event if the condition of Eq. (10) was satisfied (Fig. 9 b). The standard deviation of blade incidence is denoted with $\sigma(i)$.

$$\exists t_j \in [t_0, t_0 + t_e] \mid |\Delta i(t_j)| > \langle \Delta i \rangle_e + \frac{\sigma(i)}{2} \quad (10)$$

For each distortion peak event, the peak intensity was the maximum value Δi_{peak} and the duration of the peak event t_{peak} was defined by the time interval in which $|\Delta i| \geq 0.5|\Delta i_{peak}|$. The choice of this value was based on previous studies which introduced this approach (Migliorini et al., 2022). It was used in the study as a way of highlighting the differences in unsteady flow distortion that are not evident in conventional metrics. However, it is acknowledged that further research is needed to calibrate the threshold values that are pertinent to the response of the fan. The duration of the peak distortion event was expressed in terms of azimuthal exposure ϕ as defined in Eq. (11).

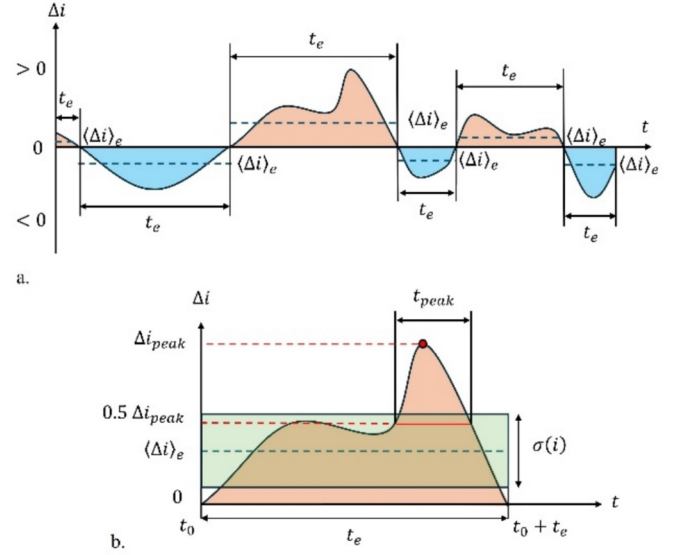


Fig. 9. (a.) Time variation of Δi and blade distortion events; (b.) peak distortion event (based on (Migliorini et al., 2022)).

$$\phi [^\circ] = \omega t_{peak} \times \frac{180^\circ}{\pi} \quad (11)$$

3. Results

3.1. Intake separation characteristics

The intake separation characteristics and the effect of crosswind velocity and ground clearance were investigated with the analysis of both the instantaneous and time averaged distributions of $PR = P_0/P_{0,\infty}$ at the AIP (Fig. 10, Fig. 11, Fig. 14, Fig. 15) and M_{isen} on the intake surface (Fig. 12, Fig. 13, Fig. 16, Fig. 17).

For a relatively low ground clearance of $H/D_{hi} = 0.25$ the flow is predominately attached up to a crosswind velocity of $V_{cw} = 28$ kts (Fig. 10 a, Fig. 11 a, Fig. 12 a-b, Fig. 13 a) and there is no large total pressure losses at the AIP. However, two specific regions of local separation are observed on the intake surface (Fig. 12 a-b, Fig. 13 a). A first type of separation (A1) arises from the shock boundary layer interaction at $\theta = 150^\circ$. Additional local pockets of separation (B) are associated with the effect of the unsteady fan static pressure pulses on the boundary layer of the intake diffuser (Lobbuono et al., 2024). These pressure pulses originate from the fan shocks and propagate upstream. Previous studies (Boscagli et al., 2023) suggested that these local perturbations could propagate upstream to the front shock and exacerbate shock-boundary layer interactions. However, this is not observed in the current study which is for a different intake design. Instead, the pressure pulses primarily affect the flow in the diffuser, indicating that the fan unsteady

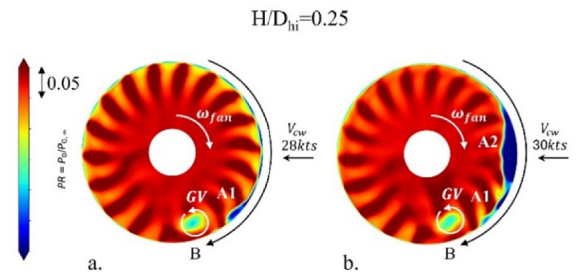


Fig. 10. Snapshot of intake total pressure ratio for (a.) $V_{cw} = 28$ kts, $H/D_{hi} = 0.25$, (b.) $V_{cw} = 30$ kts, $H/D_{hi} = 0.25$.

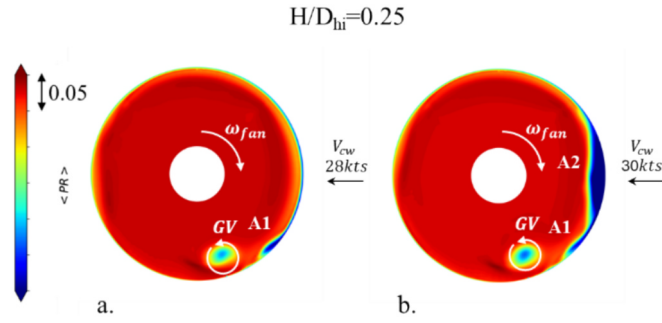


Fig. 11. Time averaged intake total pressure ratio for (a.) $V_{cw}=28kts$, $H/D_{hi}=0.25$, (b.) $V_{cw}=30kts$, $H/D_{hi}=0.25$.

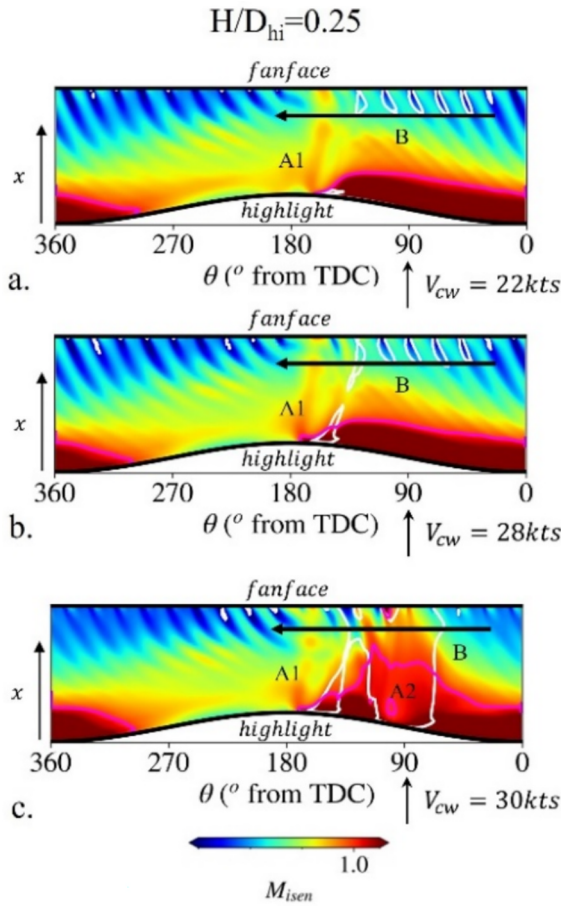


Fig. 12. Snapshot of M_{isen} on the unwrapped intake surface with isoline of $M_{isen}=1$ (magenta), and axial wall shear stresses $\tau_{wx}=0$ (white) for $H/D_{hi}=0.25$ at (a.) $V_{cw}=22kts$, (b.) $V_{cw}=28kts$, (c.) $V_{cw}=30kts$.

effects may depend on the intake design. From $V_{cw}=22kts$ to $28kts$ the axial extent of the shock-driven separation increases until this starts to merge with the subsonic diffusion separations. For a crosswind velocity of $V_{cw}=30kts$, a second large windward separation arises from the lip (A2 in Fig. 10 b, Fig. 11 b, Fig. 12 c, and Fig. 13 b). This extends towards the AIP and results in a notable loss in total pressure (Fig. 10 b, Fig. 11 b).

Notable differences in the separation onset arise when the ground clearance is increased from 0.25 (Fig. 10, Fig. 11, Fig. 12, Fig. 13) to 0.44 (Fig. 14, Fig. 15, Fig. 16, Fig. 17). For $H/D_{hi}=0.44$, the gross lip separation develops on the bottom lip at $V_{cw} \geq 24kts$ (A1 in Fig. 14 b-c, Fig. 15 a, Fig. 16 b-c and Fig. 17 b). The different origin of the intake

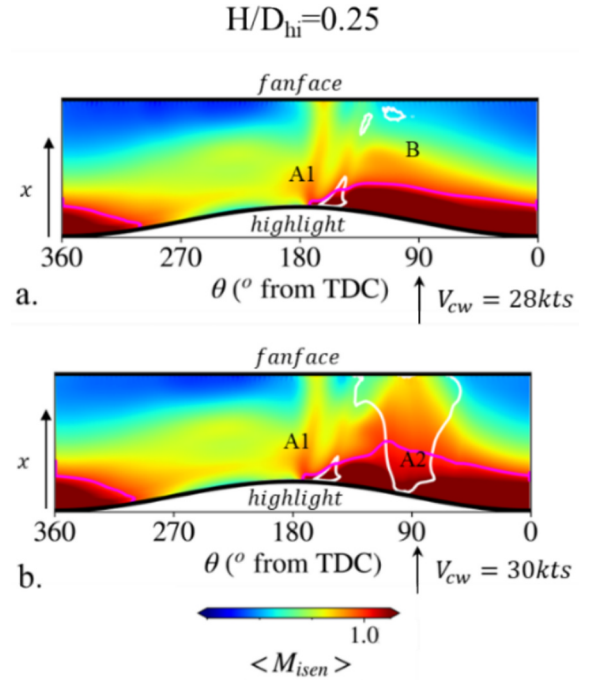


Fig. 13. Time averaged M_{isen} on the unwrapped intake surface with isoline of $\langle M_{isen} \rangle = 1$ (magenta), and axial wall shear stresses $\langle \tau_{wx} \rangle = 0$ (white) for $H/D_{hi}=0.25$ at (a.) $V_{cw}=28kts$, (b.) $V_{cw}=30kts$.

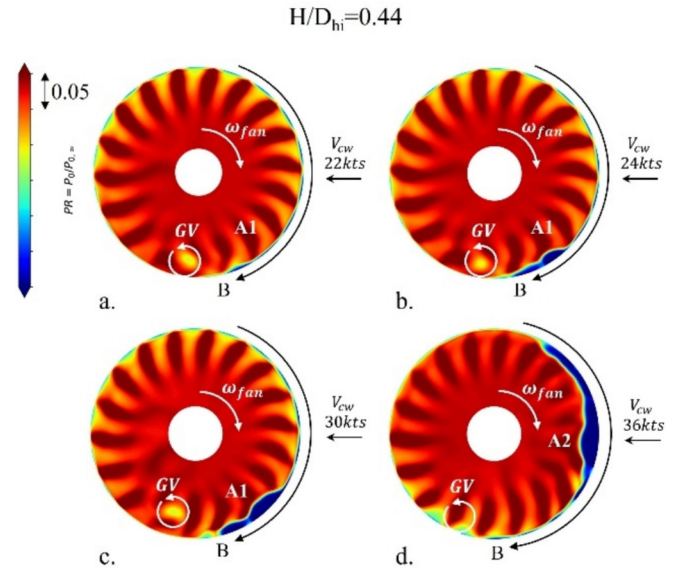


Fig. 14. Snapshot of intake total pressure ratio for $H/D_{hi}=0.44$ at (a.) $V_{cw}=22kts$, (b.) $V_{cw}=24kts$, (c.) $V_{cw}=30kts$, (d.) $V_{cw}=36kts$.

separation is associated with a change in mass flow distribution and an increase in the intake lip loading at the bottom dead centre region (at $\theta \sim 180^\circ$). For example, for the high ground clearance ($H/D_{hi}=0.44$) and $V_{cw}=22kts$ (Fig. 16 a) the sonic line extends up to $\theta=200^\circ$ and the peak of M_{isen} is highly supersonic at $\theta=180^\circ$. Conversely, the flow around the bottom lip is subsonic for $H/D_{hi}=0.25$ (Fig. 12 a). However, as expected, the onset of gross separation on the windward side is improved for $H/D_{hi}=0.44$ and arises at a higher crosswind velocity of $36kts$ (A2 in Fig. 14 d, Fig. 15 b, Fig. 16 d, Fig. 17 b) compared to $H/D_{hi}=0.25$. With higher ground clearance, the windward side has a reduced lip loading as more flow is redirected toward the bottom region of the intake.

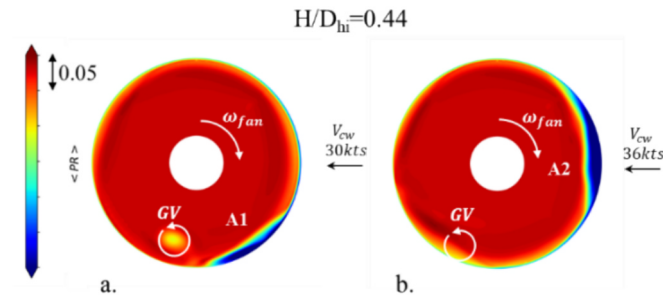


Fig. 15. Time averaged of intake total pressure ratio for $H/D_{hi}=0.44$ at (a.) $V_{cw}=30kts$, (b.) $V_{cw}=36kts$.

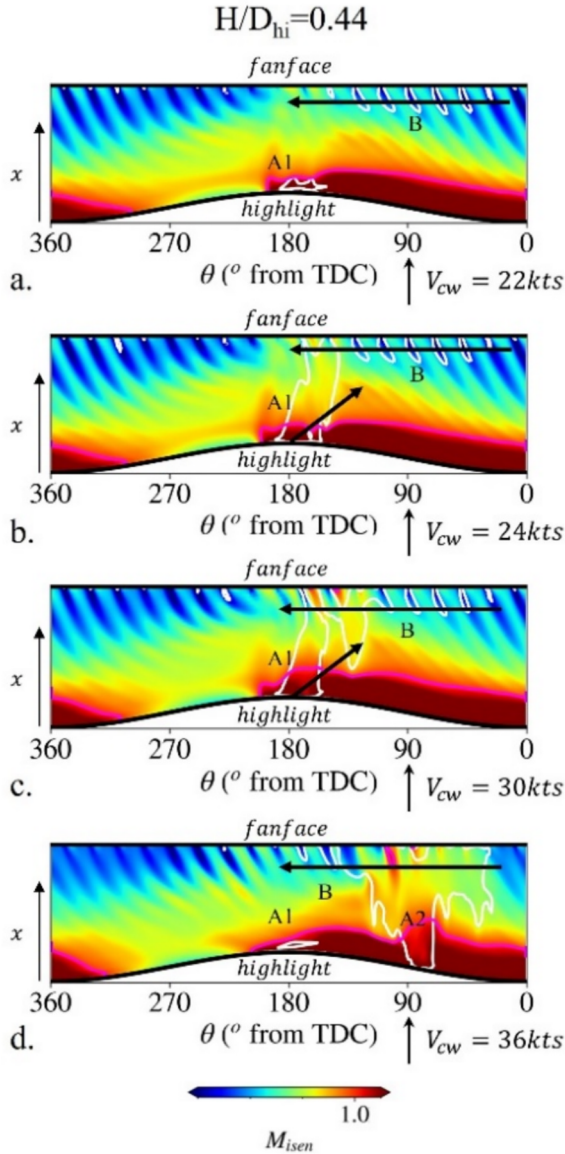


Fig. 16. Snapshot of M_{isen} on the unwrapped intake surface with isoline of $M_{isen}=1$ (magenta), and axial wall shear stresses $\tau_{wx}=0$ (white) for $H/D_{hi}=0.44$ at (a.) $V_{cw}=22kts$, (b.) $V_{cw}=24kts$, (c.) $V_{cw}=30kts$, (d.) $V_{cw}=36kts$.

However, once flow separation occurs on the windward separation at $V_{cw}=36kts$, this becomes dominant, while the separation in the lower region mostly reattaches.

A previous study (Lobuono et al., 2024) related to this work shows

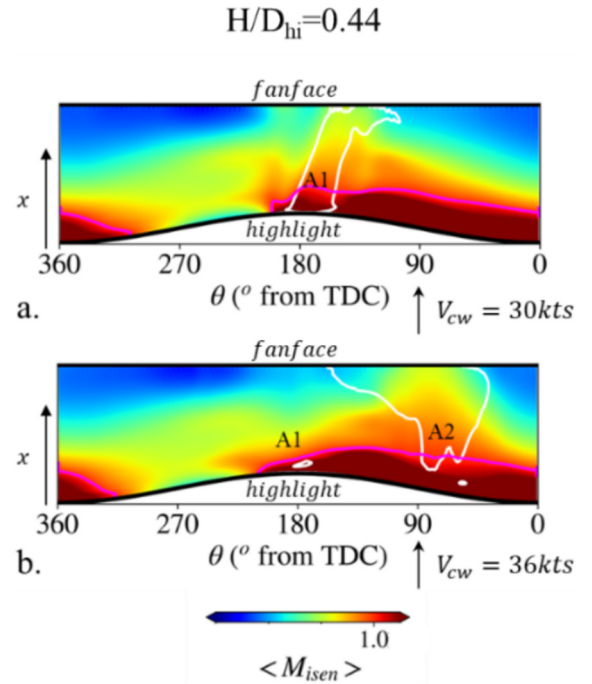


Fig. 17. Time averaged M_{isen} on the unwrapped intake surface with isoline of $\langle M_{isen} \rangle = 1$ (magenta), and axial wall shear stresses $\langle \tau_{wx} \rangle = 0$ (white) for $H/D_{hi}=0.44$ at (a.) $V_{cw}=30kts$, (b.) $V_{cw}=36kts$.

that the dominant unsteady content associated with the gross separation is at relatively low frequencies, below the blade-passing frequency and comparable with the frequencies associated with the frequency of one engine revolution (Lobuono et al., 2024). These low-frequency features can generate fluctuations in total pressure and blade incidence angle at the fan inlet, and this can affect both the fan performance (Castillo Pardo et al., 2025; Zhang and Vahdati, 2019; Migliorini et al., 2022) and aero-mechanical response (Vahdati et al., 2020; Berthelon et al., 2019; Tambe et al., 2020).

In addition to the main aerodynamic effects on critical crosswind velocity and intake mass flow, the proximity of the intake to the ground influences the formation and strength of the ground vortex (Murphy and MacManus, 2011; Mishra et al., 2012; Nichols et al., 2022; Dupuy, 2022; Courtine et al., 2022; Zhang et al., 2024; Rao et al., 2022; Zantopp et al., 2010). For example, an increase in ground clearance from $H/D_{hi}=0.25$ to 0.44 reduces the strength of the ground vortex and causes a reduction in local total-pressure loss associated with the GV (Fig. 14, Fig. 15). This reduction in total pressure loss is consistent with the reduction in strength observed by Murphy et al. for an increase in ground clearance from 0.25 to 0.4 (Murphy and MacManus, 2011). There is also a small change in the position of the ground vortex which moves to the leeward side of the intake for $H/D_{hi}=0.44$ (Fig. 14; Fig. 15). This can be associated with the different mass flow distribution. As more flow is redirected towards the lower region of the intake, the ground vortex migrates to the leeward side. The detailed formation and characteristics of the ground vortex have been studied in the literature (Murphy and MacManus, 2011; Mishra et al., 2012; Nichols et al., 2022; Dupuy, 2022; Courtine et al., 2022; Zhang et al., 2024; Rao et al., 2022; Zantopp et al., 2010) where the relative importance of ground clearance, MFCR, approaching boundary layer, rolling take off, and freestream flow angle were assessed for aspirated intake configurations. Because the present work focuses on the characteristics of the separation and resulting distortion, the analysis of GV formation is outside the scope of this study.

Overall, these results demonstrate that the ground clearance can significantly affect the location of the gross flow separation within the intake. A higher ground clearance is not always beneficial as gross

separation occurs at 6kts lower V_{cw} compared to the $H/D_{hi}=0.25$ configuration for a specific intake design. However, the total pressure loss associated with the ground vortex and the onset of windward separation are improved because of the lower ground vortex strength and mass flow distribution. For $H/D_{hi}=0.44$, the main separation on the windward side occurs at 6kts higher V_{cw} , but this is more distorted than the equivalent critical condition for $H/D_{hi}=0.25$ ($V_{cw}=30$ kts).

3.2. Swirl distortion characteristics

The variation of incidence (Δi) is mainly attributed to the change of two aerodynamic quantities, the swirl angle α and the axial velocity V_{ax} . Taking as a reference an ideal condition with uniform axial velocity $V_{ax}=V_{ax}^{id}$ (axial velocity in isentropic conditions) and $\alpha=0^\circ$, a positive Δi is generally due to either negative swirl angles (tangential velocity opposite to the fan rotation) or low or even negative values of V_{ax} . In contrast, positive swirl (tangential velocity in the same direction of the fan rotation) and higher axial velocity can reduce incidence ($\Delta i < 0$).

According to Castillo Pardo et al. (Pardo et al., 2024) three main types of secondary flows can be responsible for counter and co-swirl regions at the AIP. These effects are generated within coupled intakes-fan in crosswind because of the intake droop, flow turning of the captured stream tube, and the flow separation.

In the bottom-left part of the intake the co-swirl effects due to the crosswind direction (Fig. 18) generates a region of positive swirl and $\Delta i < 0$ (Fig. 19 a). This is amplified at the hub. The counter-swirl effect on the top-right part of the intake (Fig. 19 a) is not as evident as the co-swirl effect in the bottom-left region. The counter-swirl due to the crosswind direction is probably counter-balanced by the co-swirl that directs the flow towards the separation (Fig. 18). The increase in axial velocity is much greater in the region adjacent to the separation and that results in $\Delta i < 0$ on the windward side (Fig. 19 a).

The greatest variation of blade incidence is observed in the separated flow regions and the ground vortex. For example, for the $H/D_{hi}=0.25$ configuration (Fig. 19a) a counter-rotating ground vortex generates a positive variation of incidence at the tip and negative variation in the inner side. The velocity triangles for the GV (Fig. 19b-c) are characterised by $V_{ax} > V_{ax}^{id}$, and Δi is dominated by $\alpha > 0$ ($\Delta i < 0$, Fig. 19b) and $\alpha < 0$ ($\Delta i > 0$, Fig. 19 c) induced by the ground vortex. The flow in the separated region and in its immediate proximity is characterised by high magnitude of α (positive and negative); however, $\Delta i > 0$ is mainly associated with either small and positive V_{ax} (Fig. 19 d) or $V_{ax} < 0$.

An additional trailing vortex can also originate on the leeward side. This vortex rotates in the direction opposite to the ground vortex (co-rotating for counter-rotating GV); it is usually considerably weaker than the ground vortex and does not result in significant changes in incidence on the leeward side (Fig. 19 a).

The flow features within the intake are observed for the three configurations $H/D_{hi}=0.25$, $V_{cw}=30$ kts (Fig. 20 a), $H/D_{hi}=0.44$ and $V_{cw}=30$ kts (Fig. 20b), $H/D_{hi}=0.44$ and $V_{cw}=36$ kts (Fig. 20 c). In all the three cases, the windward lip flow separation generates the maximum variation of incidence at the AIP. The windward separation of H/

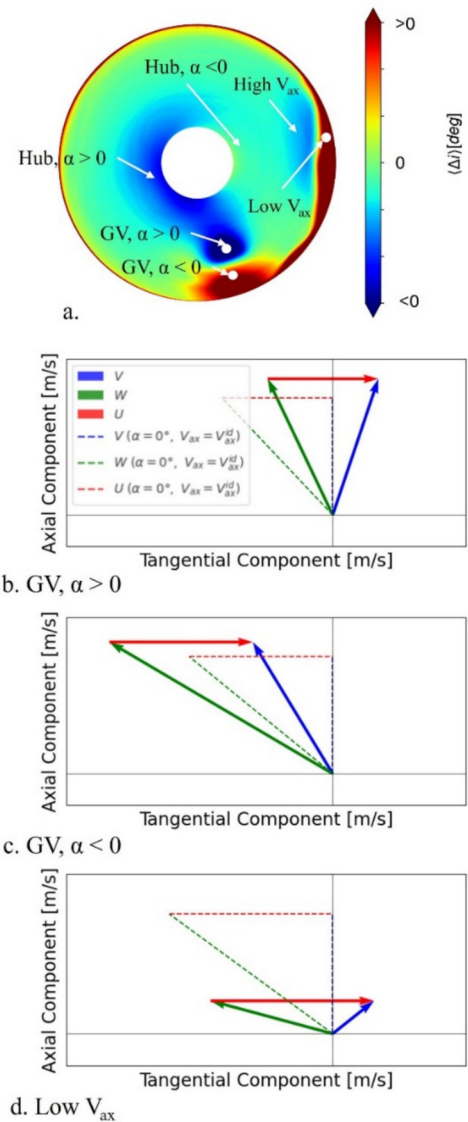


Fig. 19. (a.) Time-averaged distribution of Δi for $H/D_{hi}=0.25$ and $V_{cw}=30$ kts, time-averaged velocity triangles: (b.) for the region of the GV with $\alpha > 0$, (c.) for the region of the GV with $\alpha < 0$, (d.) for the region at the tip with low V_{ax} . $V_{cw}=36$ kts.

$D_{hi}=0.25$ and $V_{cw}=30$ kts (Fig. 20 a.) is associated with a larger extent of very high Δi regions compared to the bottom separation of $H/D_{hi}=0.44$ and $V_{cw}=30$ kts (Fig. 20 b). However, as the crosswind velocity is increased to $V_{cw}=36$ kts the windward separation arises for the large ground clearance (Fig. 20 c), and it extends for a larger azimuthal extent compared $H/D_{hi}=0.25$ and $V_{cw}=30$ kts (Fig. 20 a). The fan is likely to be exposed to regions with very high incidence at the tip and this can be detrimental for its operation (Awes et al., 2020). Also, for $H/D_{hi}=0.25$ (Fig. 20 a), the swirl associated with the ground vortex generates a greater variation of incidence. This is due to the increased strength of the GV. For $H/D_{hi}=0.44$ and $V_{cw}=36$ kts (Fig. 20 c), the ground vortex moves to the leeward side and towards the intake surface. That limits the radial extent of the negative and positive swirl regions associated with the GV, but the azimuthal extent of the distorted region is increased.

3.3. Unsteady swirl distortion

The unsteady features of swirl distortion can potentially have notable impact on the fan operation, as the temporal and spatial

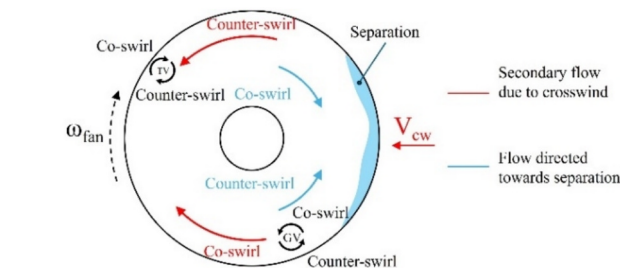


Fig. 18. Secondary flows and vortices for an intake in crosswind for a counter-rotating configuration. Partially based on (Pardo et al., 2024).

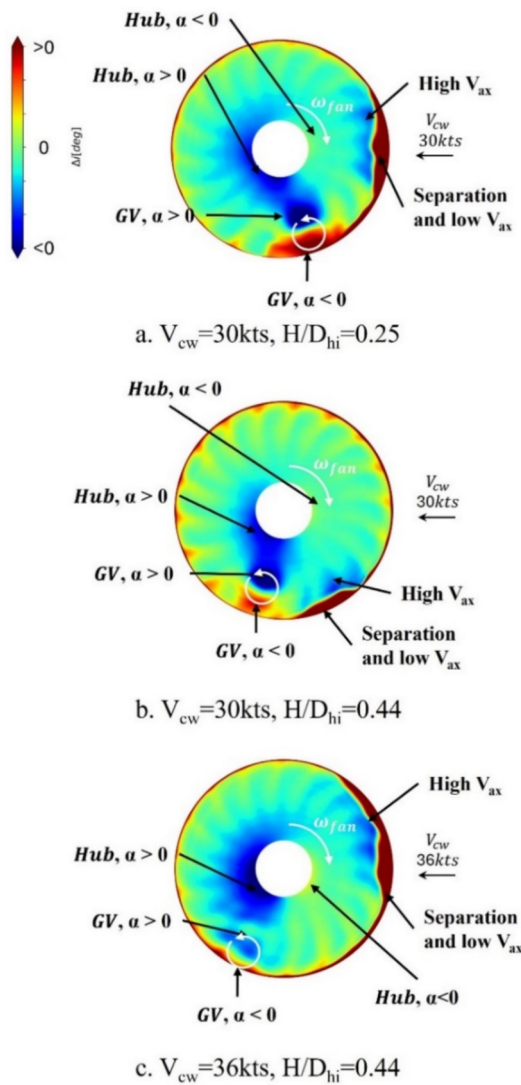


Fig. 20. Snapshot of Δi for (a.) $H/D_{hi}=0.25$, $V_{cw}=30\text{kts}$, (b.) $H/D_{hi}=0.44$, $V_{cw}=30\text{kts}$, (c.) $H/D_{hi}=0.44$, $V_{cw}=36\text{kts}$.

fluctuations of incidence can trigger fan stall (Zhang and Vahdati, 2019; Awes et al., 2020; Zhang, 2019). In this section the temporal variation of incidence is evaluated for the dominant shock driven separation with time zero defined after an initial transient of 4 fan revolutions (Fig. 21 a-c). The variation of incidence is evaluated according to the frame of reference in Fig. 8 and the observation locations are shown in Fig. 21 d.

For $H/D_{hi}=0.25$ and $V_{cw}=30\text{kts}$, the time variation of Δi (Fig. 21 a) is characterised by notable high incidence in the separated region at $\theta=90^\circ$ and $r/r_{fan}=0.98$ (Fig. 18 d). This variation is significantly unsteady with a standard deviation of $\sigma=5.2^\circ$. As the ground clearance is increased to $H/D_{hi}=0.44$ and for the same crosswind velocity of $V_{cw}=30\text{kts}$ (Fig. 21 b), the separated region in the lower quadrant of the intake ($\theta=160^\circ$ and $r/r_{fan}=0.98$, Fig. 21 d) is associated with a similar mean value of Δi . For this configuration, the signal is also relatively periodic, and the standard deviation is reduced with $\sigma=3.9^\circ$. For $H/D_{hi}=0.44$ and $V_{cw}=36\text{kts}$ (Fig. 21 c) the intake is grossly separated and there is an extended transient period. After a total transient equivalent to 8 revolutions, the level of unsteadiness related to the separation is comparable to the fluctuations for $H/D_{hi}=0.25$ and $V_{cw}=30\text{kts}$ with a standard deviation of $\sigma=5.3^\circ$. Also, the average value of Δi after the transient is similar to the one observed $H/D_{hi}=0.25$ and $V_{cw}=30\text{kts}$. Overall, the level of unsteadiness and average effect of the separation is similar when the gross separation occurs on the windward side for the two configurations.

The time variation of Δi includes both low and high frequency content (Lobuono et al., 2024). While the high frequency oscillations are related to the blade passing (f_{bp}), the low frequency signatures are mainly associated with the gross separations in the lower and windward regions. The high-frequency signatures originate from the fan itself; therefore, these fluctuations are not distortion peaks in the fan relative frame of reference. Conversely, the low frequency fluctuations are of interest because are comparable with the frequencies associated with one engine revolution (Lobuono et al., 2024), and can affect both the fan performance (Castillo Pardo et al., 2025; Zhang and Vahdati, 2019; Migliorini et al., 2022) and aero-mechanical response (Vahdati et al., 2020; Berthelon et al., 2019; Tambe et al., 2020), as mentioned in section 3.1.

Overall, the two types of gross separations (windward and lower quadrant) produce similar mean Δi at $r/r_{fan}=0.98$, but the unsteady signature for these separations are significantly different. This difference is linked to the magnitude and dynamics of the separated region. The separation in the bottom quadrant for $H/D_{hi}=0.44$ with $V_{cw}=30\text{kts}$ is smaller and exhibits a periodic motion in the counter-clockwise direction from $\theta=180^\circ$ to 150° (Fig. 16 c), and from the highlight toward the fan face. As it approaches the AIP, the separated region decreases in size, and the associated $\Delta i > 0$ is primarily due to reduced axial velocity and small fluctuations of α rather than consistent reverse flow. This mechanism leads to a more regular and periodic temporal variation of Δi compared with the windward separation. Conversely, the windward separation for $H/D_{hi}=0.25$ with $V_{cw}=30\text{kts}$, and for $H/D_{hi}=0.44$ with $V_{cw}=36\text{kts}$, is dominated by a strong shock-boundary-layer interaction (SBLI). The SBLI generates a larger, irregular, and non-periodic separated region that propagates toward the AIP with significantly negative V_{ax} . This mechanism leads to large-amplitude variations of V_{ax} and α with a change of polarity of both V_{ax} and α . As a result, the time variation of Δi for the windward separation is characterised by irregular fluctuations.

The results show that the temporal variation of Δi within the separated region alone does not provide sufficient evidence to draw conclusions about the influence of ground clearance and crosswind velocity on swirl distortion. A method that accounts for both spatial and temporal unsteadiness is required. This aspect is addressed in the next section.

3.4. Peak swirl distortion events in the relative frame of reference

The blade incidence angle varies both over time and across different spatial locations. Therefore, it is necessary to analyse the full unsteady aspect. To accurately capture these variations, the peak fluctuations of Δi should be assessed in the blade rotating frame of reference. It is also considered to be beneficial if the swirl distortion events are sufficiently distant in the azimuthal direction to allow the fan to recover (Awes et al., 2020). The intensity and the exposure ϕ to peak swirl event can be assessed to evaluate the compatibility of an intake design and configuration with a fan. In this section the flow features that are responsible for the variation in Δi and the associated peak events are investigated. This is achieved by tracking the peak distortion events for all the blades (Fig. 22 a-b, Fig. 23 a-b, Fig. 24 a-b) together with the relative Mach number M_{rel} and the radial location R_{norm} associated with the flow distortion (Eq. (12)).

$$R_{norm} = \frac{r - r_{hub}}{r_{fan} - r_{hub}} \quad (12)$$

For $H/D_{hi}=0.25$, $V_{cw}=30\text{kts}$ (Fig. 22 a-b), the peak events with the highest azimuthal exposure are the ones associated with the swirl variation at the hub (hub, $\alpha < 0$ and hub, $\alpha > 0$). However, the resulting peak intensity (Fig. 22 a-b) is modest ($|\Delta i_{peak}| \sim 10^\circ$). Conversely, the peak distortion events with the highest positive intensity are mainly related to the separation and low V_{ax} on the windward side. At the tip (Fig. 22 a-b), some peak events reach an intensity about 4.5 times

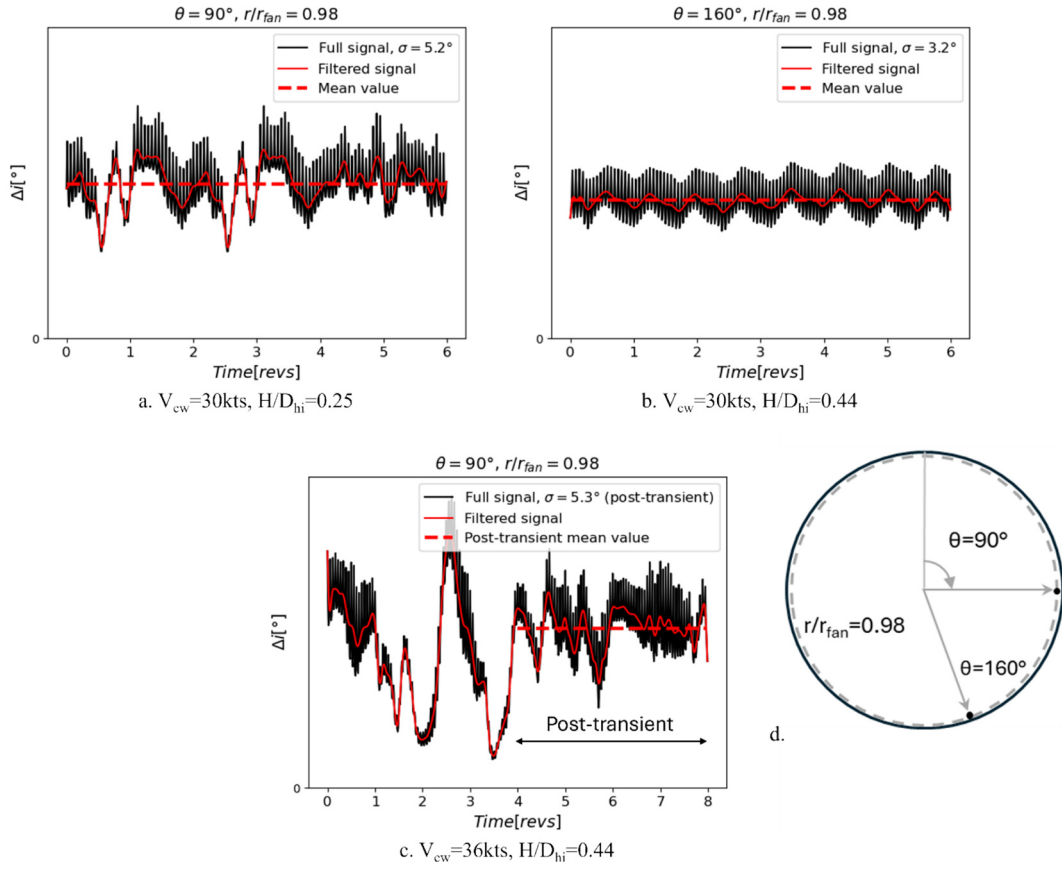


Fig. 21. Time variation of Δi at $r/r_{fan} = 0.98$ for (a.) $H/D_{hi} = 0.25$, $V_{cw} = 30kts$ ($\theta = 90^\circ$), (b.) $H/D_{hi} = 0.44$, $V_{cw} = 30kts$, ($\theta = 160^\circ$) (c.) $H/D_{hi} = 0.44$, $V_{cw} = 36kts$ ($\theta = 90^\circ$), (d.) indication of radial and azimuthal location of probes.

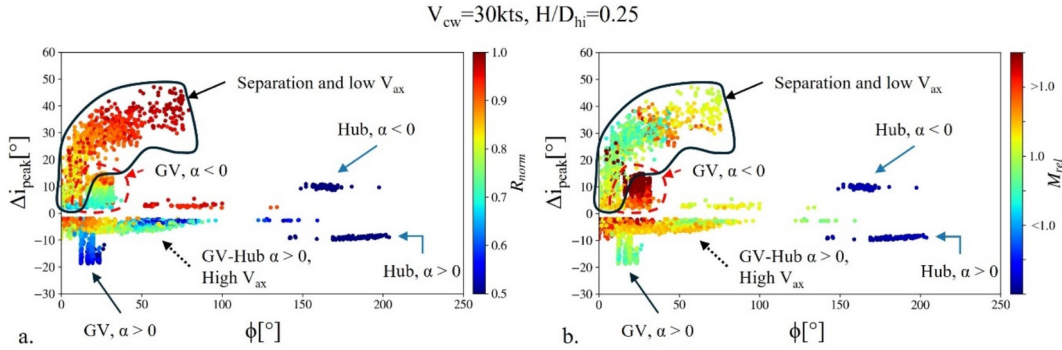


Fig. 22. Peak swirl distortion events tracked for the fan blades for $H/D_{hi} = 0.25$, $V_{cw} = 30kts$, coloured by (a.) R_{norm} and (b.) M_{rel} .

greater than those at the hub ($\Delta i_{peak} \sim 45^\circ$) and an exposure up to $\phi = 80^\circ$. Also, the ground vortex generates positive peak distortion events (Δi_{peak} between 0° and 15°). These are associated with $M_{rel} > 1.0$ (Fig. 22 b), and $R_{norm} \sim 0.85 - 0.9$ (Fig. 22 a). The peak events associated with the positive swirl at the hub-GV, and the high V_{ax} region have negative values of Δi (Fig. 22 a-b, Fig. 20 a). Although the peak intensity is modest ($0^\circ < \Delta i_{peak} < 10^\circ$), the exposure extends from $\phi = 0^\circ$ up to 100° . While the high V_{ax} is related to $M_{rel} > 1.0$ (Fig. 22 b) and high values of $R_{norm} \sim 0.85 - 0.9$ (Fig. 22 a), the positive swirl at the hub-GV is associated with $M_{rel} < 1.0$ (Fig. 22 b) and $R_{norm} \sim 0.6 - 0.75$ (Fig. 22 a). The GV is also related to highly negative Δi peak events (Δi_{peak} between -20° and -10°) at the tip ($R_{norm} = 0.75 - 0.92$, Fig. 22 a) due to $\alpha < 0^\circ$ with an exposure within $\phi = 15 - 30^\circ$. Overall, for $H/D_{hi} = 0.25$, the peak events characterised by the highest intensity are the ones associated with the

windward separation and low V_{ax} . However, the GV generates peak distortion events that are characterised by $M_{rel} > 1.0$ at the tip (Fig. 22 b).

For the same $V_{cw} = 30kts$, when the ground clearance is increased to $H/D_{hi} = 0.44$ (Fig. 23 a-b), there is an asymmetry for the positive and negative Δi peak events regions at the hub. While the region with $\Delta i > 0$ (hub, $\alpha < 0$) has an exposure of $\phi = 190 - 220^\circ$, for the one with $\Delta i < 0$ (Hub, $\alpha > 0$), the exposure is $\phi = 90 - 140^\circ$. At the higher ground clearance, the ground vortex strength has decreased, along with the associated peak intensity of the $\Delta i > 0$ ($0^\circ < \Delta i_{peak} < 10^\circ$ for GV, $\alpha < 0$) and $\Delta i < 0$ ($-15^\circ < \Delta i_{peak} < 0^\circ$ for GV, $\alpha > 0$) events. The intensity and the exposure associated with the separation have also reduced, as the separation in the lower quadrant has a smaller azimuthal extent compared to the separation on the windward side for $H/D_{hi} = 0.25$, $V_{cw} = 30kts$ (Fig. 22 a).

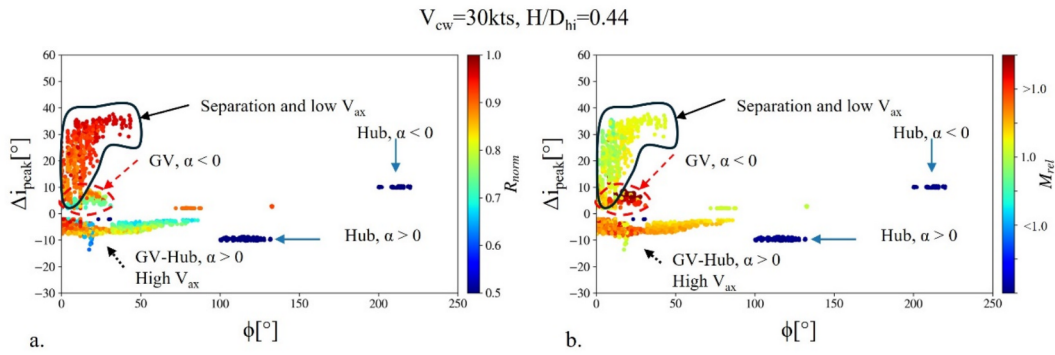


Fig. 23. Peak swirl distortion events tracked for the fan blades for $H/D_{hi}=0.44$, $V_{cw}=30$ kts, coloured by (a.) R_{norm} and (b.) M_{rel} .

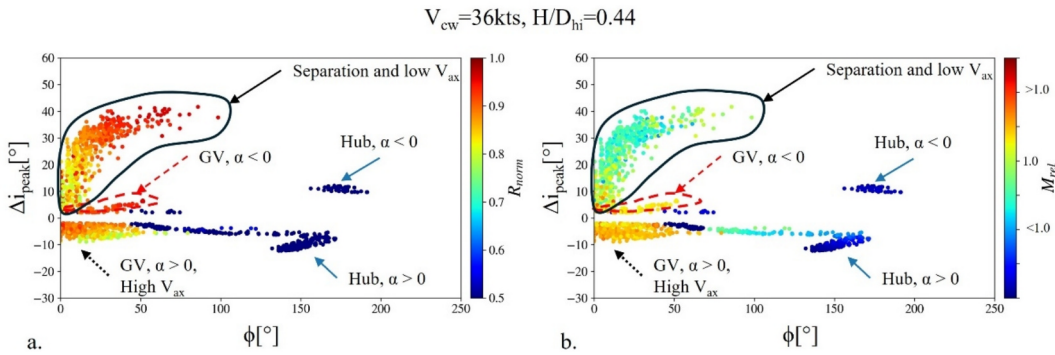


Fig. 24. Peak swirl distortion events tracked for the fan blades for $H/D_{hi}=0.44$, $V_{cw}=36$ kts, coloured by (a.) R_{norm} and (b.) M_{rel} .

Overall, for $H/D_{hi}=0.44$ the effects of the separation in the lower quadrant results in lower intensity and exposure of the peak events compared with the windward separation of $H/D_{hi}=0.25$. At the tip, the intensity of the positive peak events and the M_{rel} associated with the GV is also reduced when H/D_{hi} is increased.

For the large ground clearance $H/D_{hi}=0.44$ and $V_{cw}=36$ kts (Fig. 24 a-b), the analysis of the peak events was restricted to the last four fan revolutions in order to minimize the influence of transient effects (Section 3.3, Fig. 21 c). Compared to the other two configurations (Fig. 22 b, Fig. 23 a-b) the intensity of the peak events related to the GV has reduced as the GV has moved towards the intake surface ($0^\circ < |\Delta i_{peak}| < 10^\circ$). However, the exposure has increased substantially up to $\phi=60^\circ$. The peak events at the hub also have greater intensity ($|\Delta i_{peak}| \sim 10-15^\circ$) than for $H/D_{hi}=0.44$, $V_{cw}=30$ kts (Fig. 23 a-b) and $H/D_{hi}=0.25$, $V_{cw}=30$ kts (Fig. 22 a-b). Compared to $V_{cw}=30$ kts, $H/D_{hi}=0.25$ (Fig. 22 a-b), the maximum exposure associated with the windward separation and low V_{ax} have increased up to $\phi=100^\circ$ for $H/D_{hi}=0.44$ and $V_{cw}=36$ kts (Fig. 24 a-b). This variation can be due to a larger separation on the windward side, which originates at the lip due to the shock-boundary layer interaction at a higher crosswind velocity. However, compared to $V_{cw}=30$ kts, $H/D_{hi}=0.25$ (Fig. 22 a-b), the peak intensity has reduced from $\Delta i_{peak} \sim 45^\circ$ to $\Delta i_{peak} \sim 40^\circ$.

Overall, significant differences in the unsteady intensity and exposure of the peak Δi events were identified. Both the exposure and the intensity are greater for the separation on the windward region (Fig. 22 a-b, Fig. 24 a-b) in comparison with the separation in the lower quadrant (Fig. 23 a-b). Although the gross windward separation occurs at higher V_{cw} for $H/D_{hi}=0.44$ (Fig. 24 a-b), the maximum azimuthal exposure associated with the separation on the windward side is greater compared to $V_{cw}=30$ kts for $H/D_{hi}=0.25$ (Fig. 22 a-b). While a larger ground clearance can be considered beneficial to improve the margin for the windward separation, once this occurs ($V_{cw}=36$ kts), the associated azimuthal exposure to swirl distortion could be greater ($+20^\circ$ for ϕ) relative to $H/D_{hi}=0.25$, $V_{cw}=30$ kts. These effects should be evaluated in

the fan relative frame of reference when both the spatial and unsteady effects are taken into account.

While prior studies examined intake-fan interactions at a single crosswind condition (Castillo Pardo et al., 2025; Pardo et al., 2024); this work shows that the characteristics of the separation and the resulting peak levels and azimuthal extent of swirl distortion can vary significantly with the crosswind velocity and the ground clearance. Therefore, it is recommended to investigate multiple crosswind configurations to identify the onset of the gross separation and characterise the influence on swirl distortion.

4. Conclusions

A large variation of intake ground clearance is investigated for the first time with an unsteady fully coupled model of the intake/fan. The key contribution of this study is the identification of distinct characteristics of shock-driven separation due to significant changes in ground clearance. These findings challenge the common assumption that increased ground clearance is usually beneficial. It is demonstrated that gross separation can occur at lower crosswind velocities (-6 kts compared with $H/D_{hi}=0.25$) and at the lower region of the intake rather than along the windward sideline. This behaviour is attributed to a mass flow redistribution, which directs more airflow toward the bottom lip. Conversely, the onset of the gross windward separation is improved for the larger ground clearance ($+6$ kts with reference to $H/D_{hi}=0.25$) due to the off-loading of the sideline.

A further novelty of this study is in the assessment of unsteady swirl distortion and peak events in a relative frame of reference for a compact intake-fan system at full scale. The results indicate that for the larger ground clearance, the flow separation on the bottom-lip exhibits lower peak intensity and reduced exposure compared to windward separation across both $H/D_{hi}=0.25$ and 0.44 configurations. However, when windward separation occurs for the $H/D_{hi}=0.44$ configuration ($V_{cw}=36$ kts), it leads to greater maximum azimuthal exposure to swirl

distortion than the equivalent critical condition for $H/D_{hi}=0.25$ ($V_{cw}=30\text{kts}$).

Within an industrial context these findings highlight the necessity of evaluating intake designs at the expected ground clearance. Understanding the relationship between ground clearance, separation mechanisms, and swirl distortion is essential to assess intake aerodynamics and ensure robust design choices under crosswind conditions.

CRedit authorship contribution statement

L. Lobuono: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. MacManus:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **J. Hueso-Rebassa:** Visualization, Software, Methodology. **R. Christie:** Supervision, Project administration, Methodology, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Luca Lobuono reports financial support was provided by Rolls-Royce plc. Luca Lobuono reports financial support was provided by Engineering and Physical Sciences Research Council. David MacManus reports financial support was provided by Innovate UK. Robert Christie reports financial support was provided by Innovate UK. Robert Christie reports a relationship with Rolls-Royce plc that includes: funding grants. David MacManus reports a relationship with Rolls-Royce plc that includes: consulting or advisory and funding grants. Josep Hueso-Rebassa reports a relationship with Rolls-Royce plc that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Due to commercial confidentiality agreements the supporting data is not available.

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