

Effect of Intake Length on Flow Interactions in a Coupled Compact Intake-fan in Crosswind

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More compact and short intakes can be a key enabler for the design of Ultra-High Bypass Ratio (UHBR) large civil aero engines. Under key design conditions such as crosswind significant flow distortion at the fan face can adversely affect the performance and engine compatibility. Shorter intakes may result in stronger intake-fan aerodynamic coupling, and the resulting unsteady interactions currently remain insufficiently understood. This study investigates how the intake length and crosswind direction can affect the intake-fan unsteady aerodynamics and distortion. Two computational models are used: a steady Reynolds-Averaged Navier-Stokes method with an Immersed Boundary Method with Smeared Geometry (RANS-IBMSG), and a time resolved fully coupled model (URANS-TRF). Swirl distortion is quantified in the relative frame of reference using a blade tracking method based on blade incidence angle. For the combination of research fan and intake analysed, the findings show that the fan proximity can reduce the onset of gross separation for shorter intake designs. This effect enables a reduction of intake length by about 25% while still meeting a crosswind operating condition requirement. In general, the RANS-IBMSG method predicts the main characteristics of the onset of gross intake separation and is in good agreement with the unsteady URANS-TRF simulations. Based on the unsteady simulations, a gross separation on the intake surface occurred at a lower crosswind velocity for the co-rotating configuration compared to the counter-rotating case for the research fan and intake studied. The RANS-IBMSG method does not capture some of the aerodynamic features responsible for differences between counter- and co-rotating configurations. Overall, while low-order fan models are useful for early-stage intake design evaluations, coupled unsteady simulations are required to fully capture the effects of crosswind direction and intake-fan interactions.

I. Nomenclature

L_{int}	=	intake length
D_{fan}	=	fan diameter
H	=	intake-ground plane clearance
D_{hi}	=	highlight diameter
ω_{fan}	=	fan rotational speed
θ	=	azimuthal coordinate
f_{bp}	=	blade passing frequency
f_s	=	sampling frequency
f_{res}	=	resolution frequency
α	=	absolute swirl angle

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β	=	relative swirl angle
V_θ	=	absolute tangential velocity
V_x	=	axial velocity
U	=	peripheral velocity
W_θ	=	relative tangential velocity
r	=	radial coordinate
i	=	blade incidence angle
β_m	=	blade metal angle
i_{nom}	=	nominal blade incidence angle
Δi	=	variation of blade incidence angle with reference to nominal conditions
t_j	=	time instant
t_0	=	initial time for the swirl distortion event
t_e	=	time duration of the swirl distortion event
Δi_{peak}	=	intensity of the peak swirl distortion event
$\sigma(i)$	=	standard deviation of incidence
t_{peak}	=	time duration of peak swirl distortion event
ϕ	=	azimuthal exposure to the peak swirl distortion event
R_{norm}	=	normalised radial location
M_{rel}	=	relative Mach number
r_{hub}, r_{fan}	=	r_{hub} radius at the hub, r_{fan} radius at the tip of the fan
V_{cw}	=	crosswind velocity
M_{ise}	=	isentropic Mach number
PR	=	total pressure ratio with reference to the freestream value
τ_{wx}	=	component of the wall shear stress in the axial direction
GV	=	ground vortex
ρV_x	=	mass flux
GV	=	ground vortex
$\rho, \rho V_x$	=	ρ density, ρV_x mass flux,
TV	=	trailing vortex
p	=	static pressure
x	=	axial coordinate

II. Introduction

Ultra-High Bypass Ratio (UHBR) engines are a key enabler to improve the propulsion efficiency and offer reduction in cruise fuel burn. However, the increased fan diameter and nacelle size associated with UHBR architectures can result in higher overall propulsion system mass and drag. To counteract these potential penalties, modern propulsion systems may adopt more compact or shorter nacelle configurations [1], [2], [3], [4]. The design of aero-engine intakes for such configurations can play a significant role to ensure engine operability and aerodynamic performance. One of the key aerodynamic challenges in this context is the performance and stability of engine intakes under off-design conditions. Under these conditions, the intake flow separation can occur in the presence of shock boundary layer interaction (SBLI) or subsonic diffusion [5]. In crosswind, the intake aerodynamics is also notably influenced by interactions with both the ground plane and the downstream fan [6]-[11].

Recently, Benjamin et al. [12] used a Design of Experiments (DoE) approach to investigate three-dimensional isolated intake nacelle geometries across several off-design conditions, including crosswind, low-speed high-incidence, and static start. This work showed that crosswind was the most critical condition for the total pressure distortion. However, the intake-fan interactions were not considered as a pressure boundary was used at the fan-face. The interaction between intake geometry and fan proximity needs to be considered as a key area of research. Cao et al. [13] highlighted the ability of the fan to suppress separation in short intakes at high incidence due to local acceleration near the fan tip. Gunn et al. [8] furthermore examined the effect of intake length at high incidence conditions using a fully coupled computational model. Greater levels of total pressure and swirl distortion were identified at lower angles of attack for the shorter intake design relative to the conventional intake length.

The importance of unsteady fan-intake interactions in crosswind conditions was investigated by Boscagli et al. [6], [14]. It was noted that upstream-propagating pressure waves can potentially trigger boundary layer separation under crosswind conditions. The work also showed that the crosswind direction and the direction of the ground vortex can affect the onset of the limit crosswind distortion condition [14]. In other studies, the direction of crosswind

combined with angle of attack created asymmetries in distortion for coupled intake-fan systems [15]. Castillo-Pardo et al.[9] explored the intake-fan interactions for a short and conventional intake length in crosswind and found that while the extent of separation can be reduced for the shorter intake, it can also result in increased swirl variation, particularly in counter-rotating configurations. However, the assessment was limited to one crosswind velocity. Recent work also demonstrated that a large variation of ground clearance can notably affect the unsteady intake separation and swirl distortion in crosswind [16].

Despite these extensive investigations, a gap remains in how intake length, geometry, and fan proximity jointly influence intake aerodynamics and flow distortion under crosswind, especially if intake-fan coupling, ground effects, and crosswind orientation are considered. Building on previous investigations into the effects of intake length and crosswind direction on the fan operability and performance [9], this work examines the intake flow separation characteristics in crosswind, and the influence of the intake-fan interaction. This is achieved with a variation of cylindrical duct upstream of the fan-face to isolate of the effect of fan proximity while maintaining the same intake lip and diffuser geometries. The intake performance is investigated varying the crosswind velocity (V_{cw}) to identify the condition of gross separation. For the first time, the effect of crosswind direction on the peak unsteady swirl distortion events is assessed for both a short and a conventional intake length in a fully coupled intake-fan configuration.

III. Methodology

A. Intake design and crosswind configuration

A set of intake designs with different intake lengths (L_{int}) were generated (Figure 1 a) by varying the length of a cylindrical section upstream of the fan face. Starting from a conventional intake with $L_{int}/D_{fan}=0.50$ (D_{fan} is fan diameter) the intake length is progressively reduced ($L_{int}/D_{fan}=0.45, 0.40$) to the shortest configuration with $L_{int}/D_{fan}=0.37$ and no cylindrical extension. The intake geometries were designed using the in-house Tool for Intake Design (TIDE)[17], [18] method. A parametric approach based on intuitive class shape transformation (iCST) curves was used to create 3D non-axisymmetric intake geometries. The designs are assessed at full scale and at a fixed ground clearance of $H/D_{hi}=0.25$, where H (Figure 1b) denotes the height of the bottom lip above the ground and D_{hi} is the highlight diameter (Figure 1 a). Fully structured 3D meshes consisting of about 3×10^7 cells were used for the RANS-IBMSG models and with about 6×10^7 cells for the URANS-TRF computations. The wall boundary layer was resolved with a $y^+=1$. Static pressure far-field boundary conditions are applied at the freestream, while the intake, fan cowl, spinner, and ground plane are modelled as no-slip walls (based on [6]). Two crosswind directions are investigated so that the resulting ground vortex (GV) is counter (Figure 1b) and co-rotating (Figure 1c) relative to the fan rotation (ω_{fan}) for wind coming from $\theta=90^\circ$ and 270° respectively. The magnitude of the crosswind velocities is varied to find the critical condition that is associated with a gross separation within the intakes.

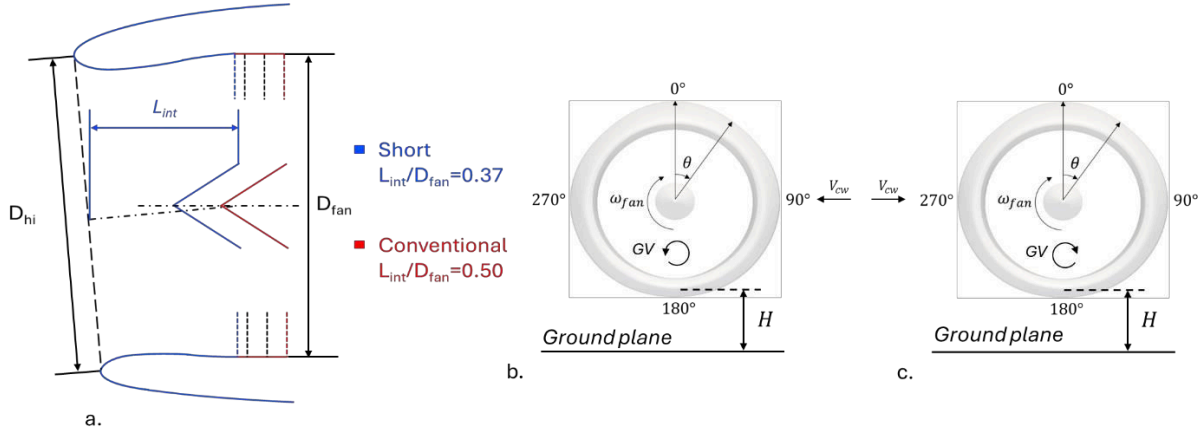


Figure 1 a. Schematic representation of intake designs with $L_{int}/D_{fan}=0.50, 0.45, 0.4, 0.37$, b. counter-rotating configuration, c. co-rotating configuration.

B. Computational modelling

The simulations are conducted using a proprietary Navier Stokes code, which is an unstructured finite volume

solver [19], [20]. The computations are performed with an implicit solver and the steady and unsteady interactions are investigated using two different computational models. A steady Reynolds Averaged Navier-Stokes with Immersed Boundary Method with Smeared Geometry (RANS-IBMSG Figure 2a) is used as a low order fan model to assess the steady interactions and results within a design context [6], [13], [21]. A time-resolved Reynolds-averaged Navier-Stokes computational approach, referred to as URANS-Time Resolved Fan (URANS-TRF), is used to calculate the unsteady flow field for a fully coupled unsteady intake-fan configuration (Figure 2b) [6], [16], [22]. This comprises a research fan stage with a full annulus rotating fan, a single passage outlet guide vane (OGV) and a single passage engine sector stator (ESS) (Figure 2b) [6], [7], [16], [22]. A sliding plane boundary condition is used at the interface between the full annulus fan and intake, while a mixing-plane boundary condition is applied between the fan-OGV and fan-ESS regions. The main elements of the computational methodology for turbomachinery applications were validated by Boscagli et al. [6] through simulations of a standalone research fan stage. Both computational models assume a fixed downstream mass flow and use the $k-\omega$ SST turbulence model. The URANS-TRF simulations are conducted with a computational frequency corresponding to 60 times the blade passing frequency (f_{bp}). Data sampling occurs every 12 timesteps, yielding a sampling frequency ratio of $f_s/f_{bp}=5$. A resolution frequency of $f_{res}/f_{bp} \sim 0.01$ is achieved [16], [22].

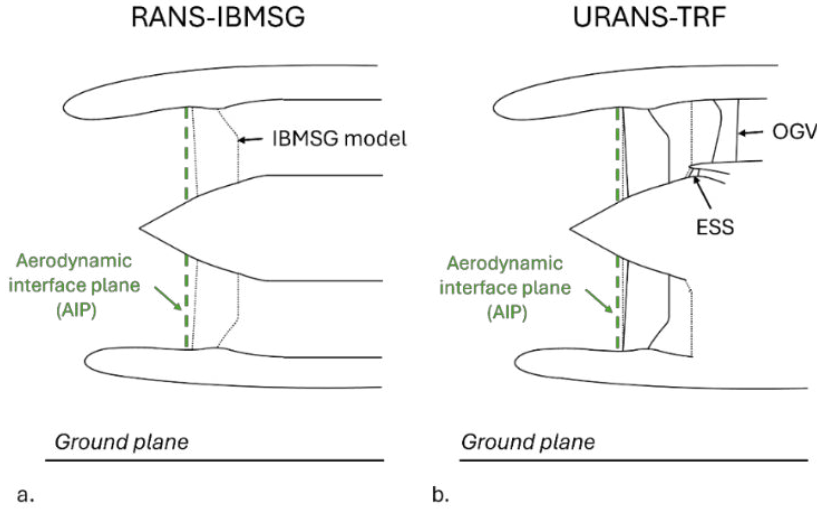


Figure 2 Schematic representation of the intake-fan computational models. a. Reynolds-averaged Navier-Stokes with Immersed Boundary Method with Smeared Geometry (RANS-IBMSG), b. Unsteady RANS with time resolved fan (URANS-TRF)

C. Unsteady post-processing

The swirl (α) and relative swirl (β) angles are calculated using Eq. (1) and (2), where V_θ and V_x represent the tangential and axial components of the absolute velocity. The blade speed, U , is defined by Eq. (3), and the difference $V_\theta - U = W_\theta$ gives the relative tangential velocity. Both V_θ and W_θ are considered positive in the same direction as U ; α , β and are considered positive in the clockwise direction, which is the same as the fan rotational speed ω_{fan} [rad/s].

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

$$\beta = \tan^{-1}((V_\theta - U)/V_x) \quad (2)$$

$$U = \omega_{fan} r \quad (3)$$

Based on this sign convention for β , the blade incidence angle i is determined using Eq. (4), where β_m denotes the blade metal angle. The change of blade incidence angle, Δi , is calculated with Eq. (5) with respect to the nominal incidence angle i_{nom} . This is obtained from a circumferential average of i in a steady single passage fan simulation.

$$i = \beta_m - \beta \quad (4)$$

$$\Delta i = i - i_{nom} \quad (5)$$

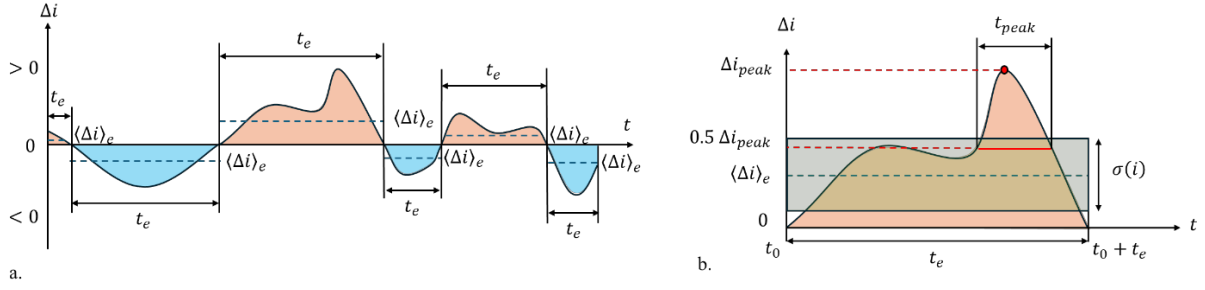


Figure 3 a. Time variation of change in incidence (Δi) and blade distortion events; b. peak distortion event (based on [23][16]).

The variation of blade incidence, Δi , is tracked for each blade and across the radial span at the aerodynamic interface plane (AIP, Figure 2 a-b). The method was described by Migliorini et al. [23] and defines a swirl distortion event as any time interval where $\Delta i(t)$ remains strictly positive or strictly negative (Figure 3a). Each distortion event is characterised by its duration t_e and the average value $\langle \Delta i \rangle_e$. Within each event, the peak Δi_{peak} is identified. An event is classified as a peak distortion event if it satisfies the criterion specified in Eq. (6) (Figure 3b). The standard deviation of blade incidence is represented by $\sigma(i)$.

$$\exists t_j \in [t_0, t_0 + t_e] \mid |\Delta i(t_j)| > |\langle \Delta i \rangle_e| + \frac{\sigma(i)}{2} \quad (6)$$

For each peak event, the maximum value Δi_{peak} denotes the peak intensity, while the duration of the peak event t_{peak} corresponds to the time interval during which $|\Delta i| \geq 0.5 |\Delta i_{peak}|$. This duration is further expressed in terms of azimuthal exposure, ϕ , as defined by Eq. (7). Also, for each peak swirl distortion event, the normalised radial location (R_{norm} , Eq. (8)) and the relative Mach number (M_{rel}) are evaluated.

$$\phi[^\circ] = \omega t_{peak} \times \frac{180^\circ}{\pi} \quad (7)$$

$$R_{norm} = \frac{r - r_{hub}}{r_{fan} - r_{hub}} \quad (8)$$

IV. Results

A. Steady separation characteristics and fan-intake interactions with RANS-IBMSG model

Based on the IBMSG calculations, for the counter rotating configuration (Figure 4a) and intake lengths of $L_{int}/D_{fan}=0.50$ and $L_{int}/D_{fan}=0.45$, the intake flow is considered attached up to $V_{cw}=24$ kts (Figure 4 b, f). At $V_{cw}=26$ kts (Figure 4c, g) a notable region of total pressure loss arises on the upper right quadrant of the AIP. For the shorter intake designs with $L_{int}/D_{fan}=0.4$ and $L_{int}/D_{fan}=0.37$ the total pressure loss arises for $V_{cw}=28$ knots (Figure 4l) and 30 knots (Figure 4q), respectively. For all the designs, two shock induced separations (Figure 5a-f) arise on the intake lip at $20^\circ < \theta < 120^\circ$ and $\theta \sim 150^\circ$. The one on the sideline ($20^\circ < \theta < 120^\circ$) is ultimately the main driving mechanism for the region of reverse mass flow that extends from the lip towards the diffuser (Figure 4a, f, l, q). The critical condition is defined as the crosswind velocity at which this gross separation arises. For the longest intake designs ($L_{int}/D_{fan}=0.5$ and $L_{int}/D_{fan}=0.45$), the onset of gross separation at a lower crosswind velocity is related to the merging of the shock driven separation with local separated regions within the intake diffuser. For example, for $L_{int}/D_{fan}=0.50$ these diffuser separations arise at $V_{cw}=24$ knots ($\theta=55^\circ$ and $\theta=140^\circ$ in Figure 5a) and merge with the lip separation at $V_{cw}=26$ knots (Figure 5b); this interaction results in the gross separation evident at the AIP (Figure 4c). The proximity of the fan improves the diffuser flow for the shorter designs $L_{int}/D_{fan}=0.4$ and $L_{int}/D_{fan}=0.37$ by alleviating the adverse pressure gradients. For $V_{cw}=24$ kts, the isentropic Mach number (M_{ise}) on both the intake lip and the diffuser for the $\theta=90^\circ$ aero line (Figure 6) are progressively reduced as the length of the cylindrical section is increased. This results in the absence of notable diffuser separations at $V_{cw}=24$ and 26 knots for $L_{int}/D_{fan}=0.37$ (Figure 5d, e).

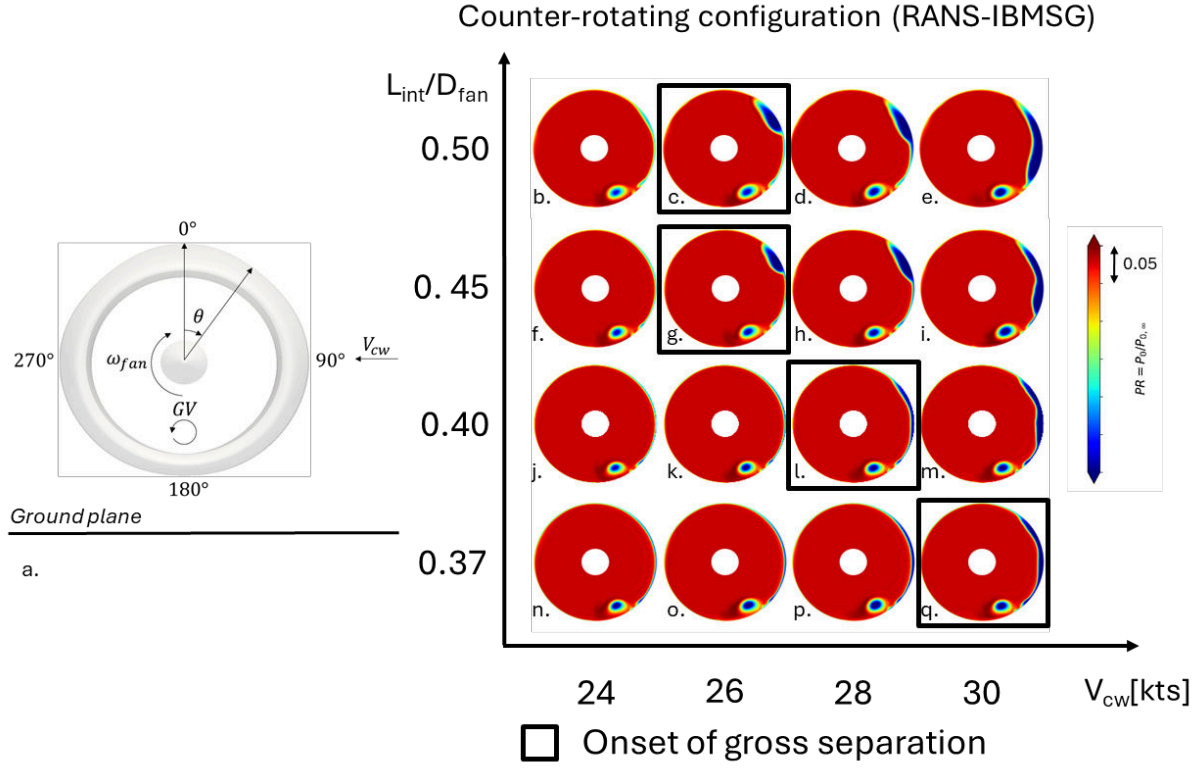


Figure 4 a. Counter-rotating configuration; total pressure ratio ($PR=P_0/P_{0,\infty}$) at the AIP with RANS-IBMSG for counter rotating configuration b.-e. $L_{int}/D_{fan}=0.50$, f.-i. $L_{int}/D_{fan}=0.45$, j.-m. $L_{int}/D_{fan}=0.4$, n.-q. $L_{int}/D_{fan}=0.37$ at $V_{cw}=24-30$ kts.

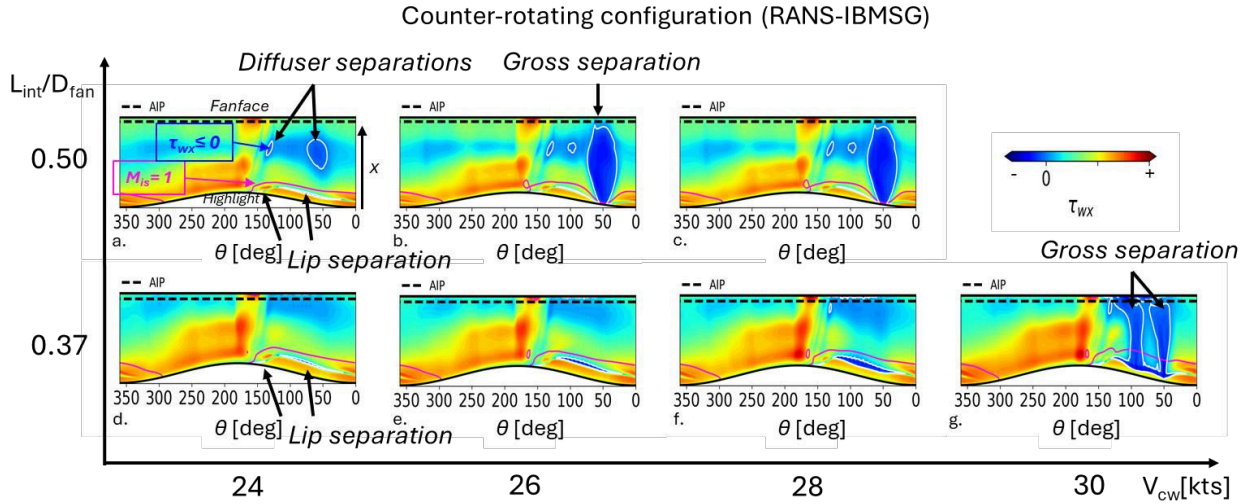


Figure 5 Axial component of wall shear stress vector (τ_{wx}) on the unwrapped intake surface with RANS-IBMSG model for the counter-rotating configuration a.-c. $L_{int}/D_{fan}=0.50$ at $V_{cw}=24-28$ kts and d.-g. $L_{int}/D_{fan}=0.37$ at $V_{cw}=24-30$ kts.

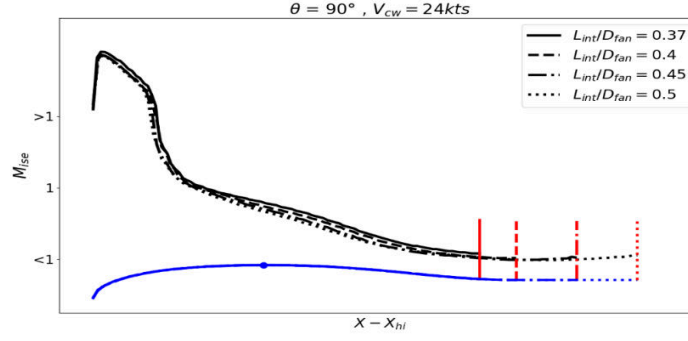


Figure 6 Distribution of isentropic Mach number (M_{ise}) over the intake surface (black), intake geometry (blue), and fan face location (red) for the $\theta=90^\circ$ aeroline for $L_{int}/D_{fan}=0.37, 0.4, 0.45$ and 0.5 and counter-rotating configuration with RANS-IBMSG model at $V_{cw}=24$ kts.

For the co-rotating configuration (Figure 7a), the gross separation arises at 26 knots for $L_{int}/D_{fan}=0.50$ (Figure 7c) and 0.45 (Figure 7g), 28 knots for $L_{int}/D_{fan}=0.4$ (Figure 7l) and 30 knots for $L_{int}/D_{fan}=0.37$ (Figure 7q). Similar to the counter-rotating configuration (Figure 4, Figure 5, Figure 6), the diffuser flow benefits from the proximity of the fan for the shorter designs. In both counter- ($\theta=130^\circ$ in Figure 5a-f) and co-rotating ($\theta=230^\circ$ in Figure 8a-f) configurations, a small pocket of diffuser separation is located on the windward side in the proximity of the ground vortex. This separation is slightly larger for the co-rotating configuration ($\theta=230^\circ$ in Figure 8a-f) and may be associated with a different interaction between the ground vortex and the boundary layer in the diffuser.

Overall, based on the IBMSG calculations, the short intake has up to approximately +4kts improvement for the onset of gross separation in both the counter- (Figure 4, Figure 5) and co-rotating (Figure 7, Figure 8) configurations. Also, the main aerodynamic mechanisms that lead to gross separation are similar for both configurations. However, it is expected that the direction of the ground vortex has an impact on the unsteady interaction between the flow features, and this is investigated using the unsteady URANS-TRF models.

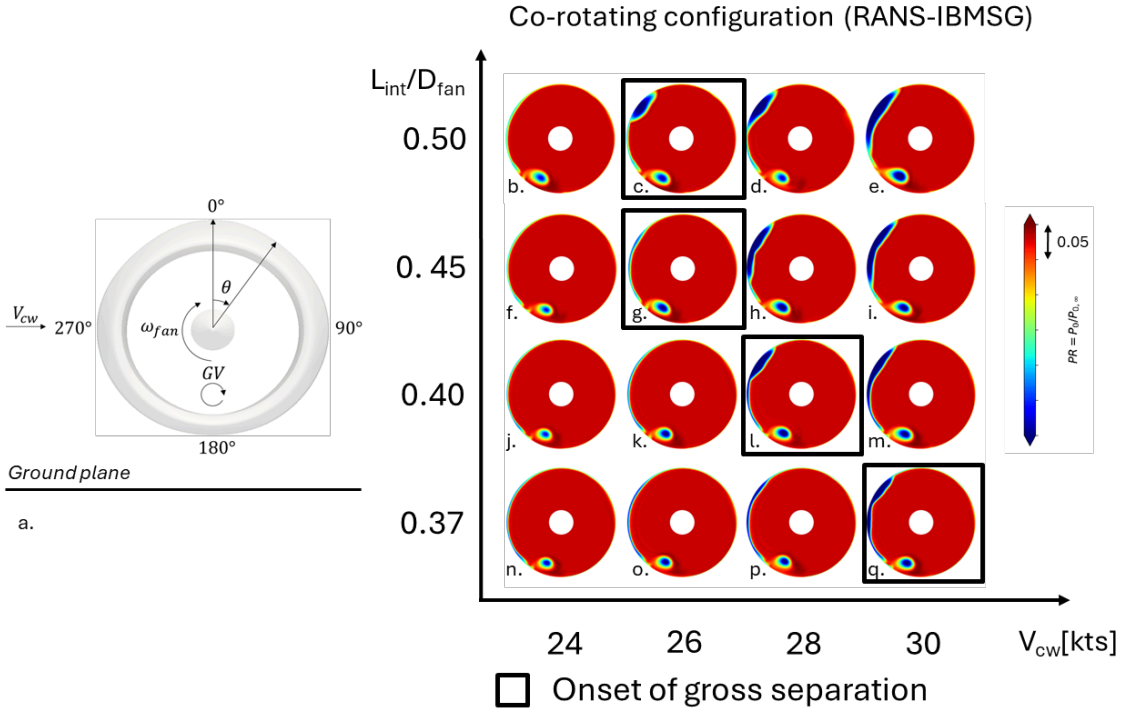


Figure 7 Co-rotating configuration; total pressure ratio ($PR=P_0/P_{0,\infty}$) at the AIP with RANS-IBMSG model for co-rotating configuration b.-e. $L_{int}/D_{fan}=0.50$, f.-i. $L_{int}/D_{fan}=0.45$, j.-m. $L_{int}/D_{fan}=0.4$, n.-q. $L_{int}/D_{fan}=0.37$ at $V_{cw}=24-30$ kts.

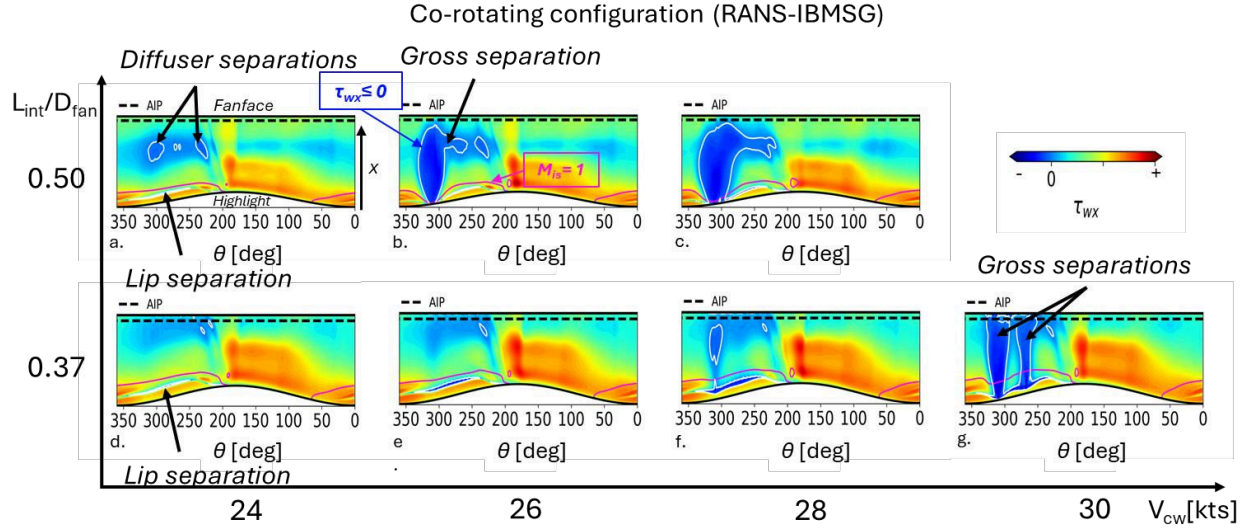


Figure 8 Axial component of the wall shear stress vector (τ_{wx}) on the unwrapped intake surface with RANS-IBMSG model for co-rotating configuration for a.-c. $L_{int}/D_{fan}=0.50$ at $V_{cw}=24-28$ kts and d.-g. $L_{int}/D_{fan}=0.37$ at $V_{cw}=24-30$ kts.

B. Unsteady separation characteristics with URANS-TRF model

Based on URANS-TRF calculations, for the counter rotating configuration (Figure 1b) and intake length of $L_{int}/D_{fan}=0.50$, the intake flow is considered attached up to $V_{cw}=28$ knots (Figure 9 a. and Figure 10 a). A large total pressure loss due to a gross separated region arises on the windward side of the AIP at $V_{cw}=30$ kts (Figure 9 b). Similarly to the RANS-IBMSG results (Figure 5 a-b), this separation is associated with the merging of the shock induced separation on the lip and the separation in the diffuser (Figure 10 a-b). Although this gross separation causes an extensive total pressure loss at the AIP (Figure 9 a-b), it reattaches just upstream of the fan and there is almost no reverse mass flow at the AIP. For the short intake design $L_{int}/D_{fan}=0.37$, the intake flow is attached up to $V_{cw}=30$ kts (Figure 8 c-d, Figure 9 c-d), while an intermittent gross separation arises on the windward side at $V_{cw}=32$ kts (Figure 9 e, Figure 10 e). This gross separation with reverse flow intermittently reaches the AIP. For this particular research fan and intake configurations, the fan has an unsteady effect on the separation characteristics in the diffuser. In comparison with the RANS-IBMSG results (Figure 5 d-g) for the same configuration and conditions ($V_{cw}=28$ knots, $L_{int}/D_{fan}=0.37$, counter-rotating), additional local pockets of diffuser separations arise on the intake surface and are phase-locked with the fan blades (Figure 10 c-e). The rotating shocks at the tip of the blades locally increase the static pressure and contribute to the small diffuser separations together with the adverse pressure gradient in the diffuser and the status of the boundary layer downstream of the lip shock [16], [22]. These rotating separations are different compared to the diffusion separation for $L_{int}/D_{fan}=0.50$ at $V_{cw}=28$ kts (Figure 10 a) where the region with the highest rate of diffusion is further upstream and the influence of the fan is weaker. Consequently, the diffusion separation is not phase-locked with the fan pressure pulses and extends for a larger region. Overall, although the pressure pulses generate pockets of separation which are phase locked with the fan blades, the fan proximity has a beneficial effect and limits the size of the diffusion separations for $L_{int}/D_{fan}=0.37$ (Figure 10 c-e). Compared to the longer intake of $L_{int}/D_{fan}=0.50$ (Figure 10 b), this results in a +2kts improvement of the onset of gross separation for the shorter $L_{int}/D_{fan}=0.37$ (Figure 10 e) configuration under counter-rotating conditions for this research fan and intake combination.

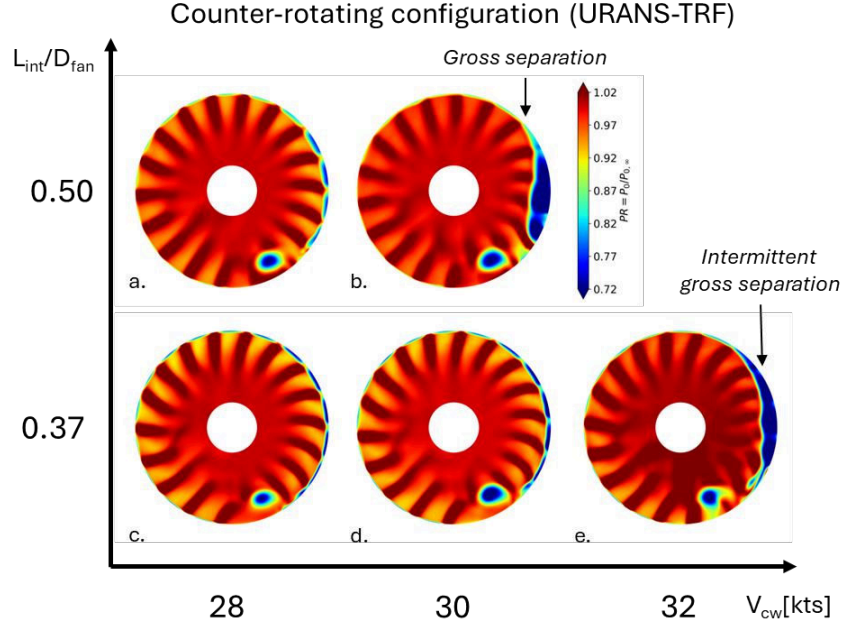


Figure 9 Snapshots of total pressure ratio ($PR=P_0/P_{0,\infty}$) at the AIP with URANS-TRF model for counter-rotating configuration a.-b. $L_{int}/D_{fan}=0.50$ at $V_{cw}=28-30$ kts, c.-e. $L_{int}/D_{fan}=0.37$ at $V_{cw}=28-32$ kts.

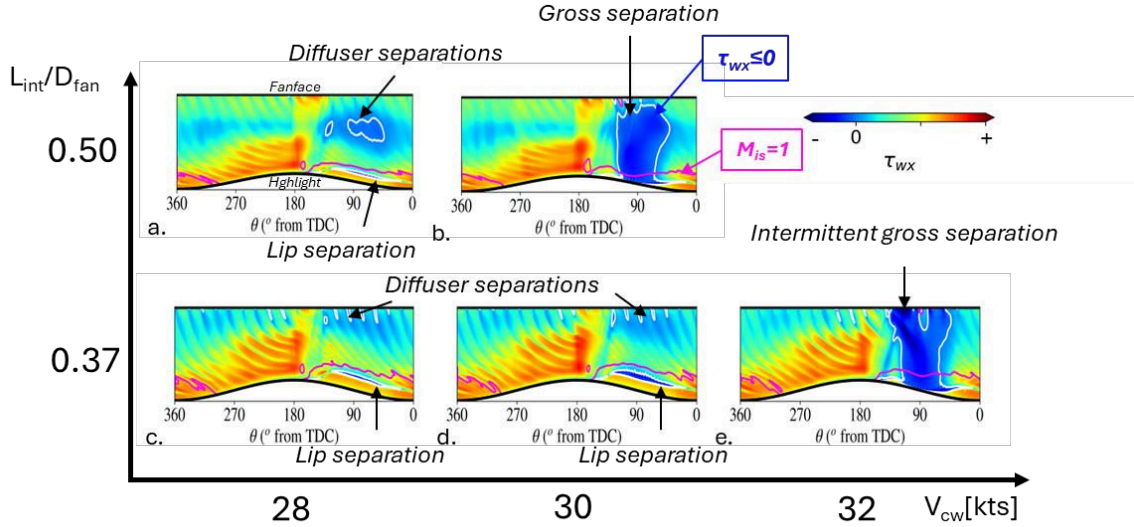


Figure 10 Snapshots of the axial component of the wall shear stress vector (τ_{wx}) on the unwrapped intake surface with URANS-TRF model for counter-rotating configuration a.-b. $L_{int}/D_{fan}=0.50$ at $V_{cw}=28-30$ kts, c.-e. $L_{int}/D_{fan}=0.37$ at $V_{cw}=28-32$ kts.

For the co-rotating configuration (Figure 11, Figure 12), the onset of gross separation is at $V_{cw}=28$ kts for $L_{int}/D_{fan}=0.50$ (Figure 11 b, Figure 12 b) and at $V_{cw}=30$ kts for $L_{int}/D_{fan}=0.37$ (Figure 11 d, Figure 12 d). Similarly to the counter-rotating configuration (Figure 9, Figure 10), the earlier onset of gross separation for $L_{int}/D_{fan}=0.50$ relative to $L_{int}/D_{fan}=0.37$ is due to the merging of the shock driven separation on the lip with a large separation in the diffuser. For $L_{int}/D_{fan}=0.50$, the gross separation intermittently reaches the fan face (Figure 11 b, Figure 12 b). For $L_{int}/D_{fan}=0.37$ and a co-rotating configuration, the pockets of separation rotate with the fan blades on the windward side of the diffuser ($210^\circ \leq \theta \leq 310^\circ$) at $V_{cw}=28$ kts (Figure 11 c, Figure 12 c). Overall, although the separations in the diffuser at pre-critical conditions are similar for the co- (Figure 11 a,c, Figure 12 a,c) and counter-rotating configurations (Figure 9 a,c-d, Figure 10 a,c-d), those for the co-rotating are larger and arise at a lower crosswind velocity (~ 2 kts) for

$L_{int}/D_{fan}=0.50$ and $L_{int}/D_{fan}=0.37$ for the combination of research fan and intake. In contrast, for the RANS-IBMSG model, the onset of gross separation is at the same crosswind velocity for counter- (Figure 4, Figure 5) and co-rotating configurations (Figure 7, Figure 8).

For both counter- and co- configurations, the radial extension of the gross separation is larger for the long intake design (Figure 13 a-b). However, the fan enables the flow reattachment (intermittent for co-rotating) in the long intake (Figure 13 a-b), in the short intake the reversed flow reaches the AIP (Figure 13 c-d). Both effects were also observed by Castillo-Pardo et al.[9], who compared a conventional intake $L_{int}/D_{fan}=0.54$ to a short design with $L_{int}/D_{fan}=0.34$ at a single value of V_{cw} .

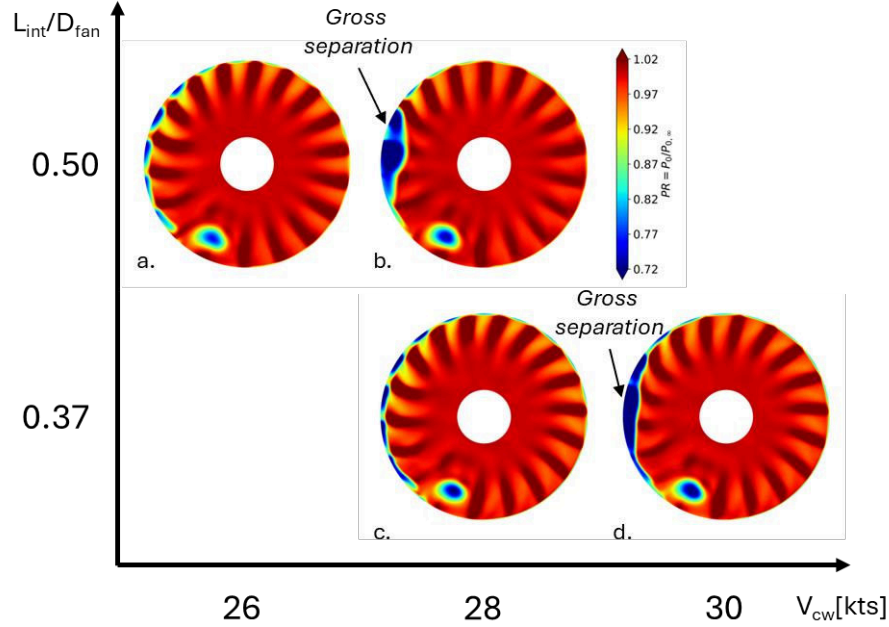


Figure 11 Snapshots of total pressure ratio ($PR=P_0/P_{0,\infty}$) at the AIP with URANS-TRF model for co-rotating configuration a.-b. $L_{int}/D_{fan}=0.50$ at $V_{cw}=28-30$ kts, c.-d. $L_{int}/D_{fan}=0.37$ at $V_{cw}=30-32$ kts.

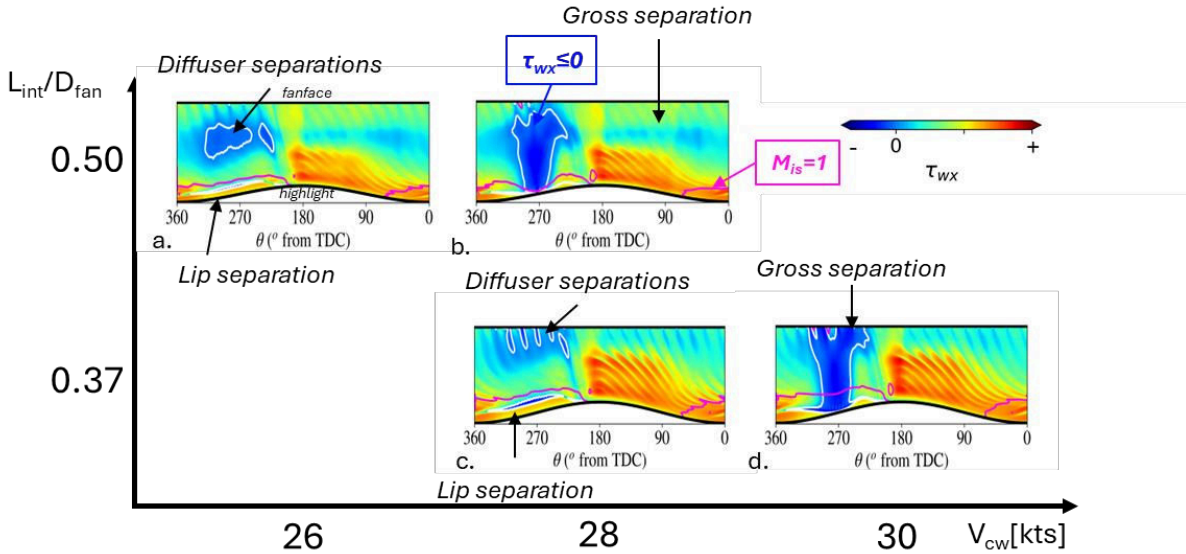


Figure 12 Snapshots of the axial component of the wall shear stress vector (τ_{wx}) on the unwrapped intake surface with URANS-TRF model for co-rotating configuration a.-b. $L_{int}/D_{fan}=0.50$ at $V_{cw}=26-28$ kts, c.-d. $L_{int}/D_{fan}=0.37$ at $V_{cw}=28-30$ kts.

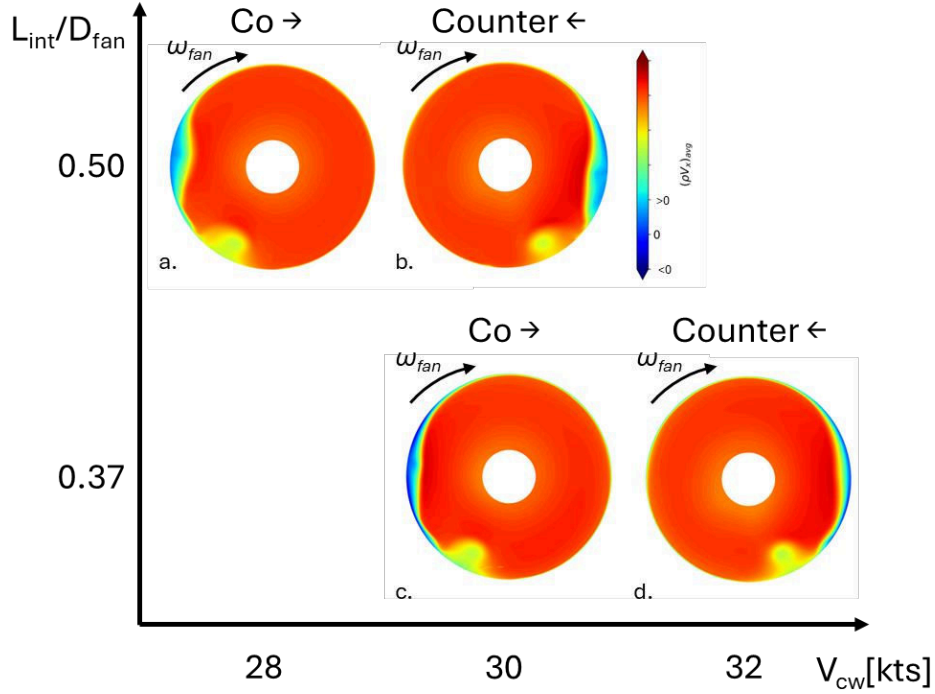


Figure 13 Time averaged mass flux (ρV_x) at the AIP for the onset of gross separation a. $L_{int}/D_{fan}=0.5$ at $V_{cw}=28$ kts co-rotating configuration, b. $L_{int}/D_{fan}=0.5$ at $V_{cw}=30$ kts counter-rotating configuration, c. $L_{int}/D_{fan}=0.37$ at $V_{cw}=30$ kts co-rotating configuration, d. $L_{int}/D_{fan}=0.37$ at $V_{cw}=30$ kts counter-rotating configuration.

C. Effect of crosswind direction on the unsteady intake-fan interactions

Relative to the counter-rotating configuration, the co-rotating case has a small penalty of -2kts for the onset of gross separation for both $L_{int}/D_{fan}=0.37$ and $L_{int}/D_{fan}=0.50$. As observed by Boscgli et al. [14], this may be associated with the different interactions of the pressure pulses from the fan leading edge with the shock over the intake lip. Local augmentations of the pressure pulses originate in the proximity of the ground and trailing vortices (Figure 14 a-b). The regions of the vortices that are characterised by negative swirl (Figure 14 a-b) can locally increase the relative Mach number and blade incidence, and, consequently, the amplitude of the pressure pulses associated with the blade tip shocks (Figure 15 a-b). For the counter-rotating configuration (Figure 14 b, Figure 15 a), starting from $\theta=0^\circ$ in the clockwise direction, the blades encounter first the windward region and then the ground and trailing vortices. The region of the ground vortex at the tip has $\alpha < 0^\circ$ (Figure 14 b) and high M_{rel} of up to 1.4. Pressure pulses from the fan are generated in this region, propagate upstream and, ultimately, interact with the lip shock in the top dead centre region ($300^\circ < \theta < 30^\circ$). As a result, the pressure pulses do not directly interact with the lip shock on the windward side. Therefore, the onset of gross separation may not be influenced by the interaction of these pressure pulses with the shock.

For the co-rotating configuration, the sequence of the unsteady interactions is different. In this case (Figure 14 a, Figure 15 a), the blades encounter in sequence the trailing vortex and bulk up-wash swirl ($\alpha < 0^\circ$) on the leeward side, the ground vortex and finally the windward side flow distortion. For the blade tip, the region of negative swirl of the trailing vortex and bulk up-wash swirl ($\alpha < 0^\circ$) increase the amplitude of the pressure pulses on the leeward side ($70^\circ < \theta < 190^\circ$ in Figure 15 a). Other pressure pulses are originated in the region of negative swirl of the ground vortex and propagate upstream and towards the windward lip ($200^\circ < \theta < 290^\circ$ in Figure 15a). Although the amplitude of the pulses that originate on the leeward side and the ground vortex decays towards the lip, the perturbations can still interact with the shock region and trigger the gross separation from the lip. This may be the reason for the reduced margin for the gross separation for the co-rotating configuration (Figure 15 a) relative to the counter-rotating one (Figure 15 b). Previous studies also demonstrated that the post-shock region is sensitive to the adverse pressure gradients and can trigger separation at a lower crosswind velocity [7]. Other interactions of the pulses with the shock arise at the top-line for the co-rotating case ($300^\circ < \theta < 30^\circ$ in Figure 15 a), but, similar to the counter-rotating case ($300^\circ < \theta < 30^\circ$ in Figure 15 b), may not affect the gross separation because the region is distant from the loaded sideline.

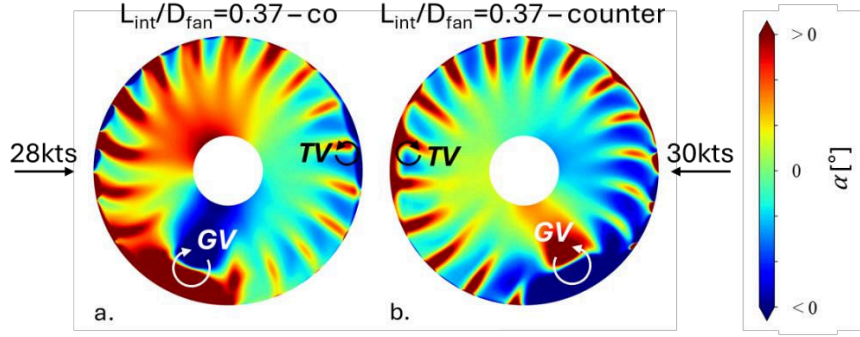


Figure 14 Snapshots of absolute swirl angle (α) at the AIP with URANS-TRF model for $L_{int}/D_{fan}=0.37$ a. co-rotating configuration at $V_{cw}=28$ kts, b. counter-rotating configuration at $V_{cw}=30$ kts.

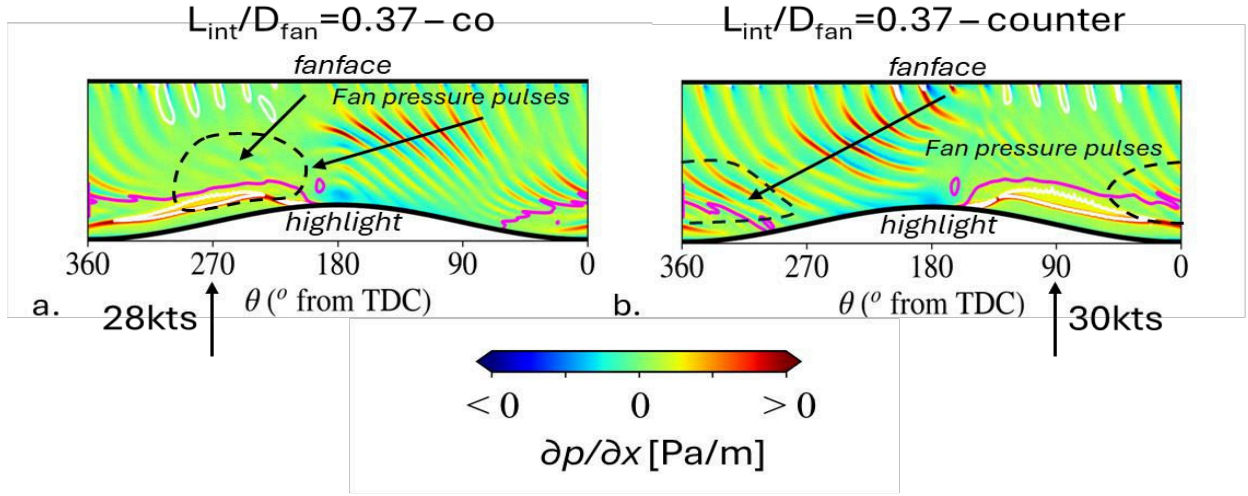


Figure 15 Snapshots of static pressure gradient in the axial direction ($\partial p/\partial x$) at the AIP with URANS-TRF model for $L_{int}/D_{fan}=0.37$ a. co-rotating configuration at $V_{cw}=28$ kts, b. counter-rotating configuration at $V_{cw}=30$ kts

For the counter-rotating configuration, compared to the RANS-IBMSG results (Figure 9, Figure 10), the unsteady URANS-TRF simulations (Figure 4, Figure 5) indicate the intake gross separation arises with an increase in V_{cw} of +4kts and +2kts for the $L_{int}/D_{fan}=0.50$ and $L_{int}/D_{fan}=0.37$ designs respectively. For the co-rotating configuration, the onset of gross separation is the same for URANS-TRF and RANS-IBMSG models for $L_{int}/D_{fan}=0.37$ (Figure 7 q, Figure 9 d), while there is an improvement of +2kts for the $L_{int}/D_{fan}=0.50$ intake design (Figure 7 c, Figure 9 b). These differences are in contrast with previous results [14] which reported reductions of critical crosswind velocity of -12 kts for the counter-rotating configurations and -22kts for the co-rotating configuration [14]. This difference may be associated with the different intake design, but also with the criterion used to identify the critical condition. In the previous work [14], the threshold for the critical crosswind velocity was based on a strict reversed mass flow criterion at the AIP (negative mass flow greater than 0.001% of nominal condition). In this study the critical crosswind condition is considered as the onset of gross separation, where the separation extends from the lip towards the diffuser. Small pockets of separation rotating with the fan blades can occur at crosswind velocities that are lower than the critical one (Figure 10 c-d Figure 12 c), but these do not cause extensive regions of reverse mass flow and do not necessarily consist of a gross intake separation. Therefore, the reverse flow criterion is likely to be overly restrictive.

Overall, for this research fan and intake combination, there is generally good agreement between the two computational models. Both models predict that the driving mechanism for the gross separation is the shock induced separation on the lip and the interaction with separations in the diffuser can move the onset of gross separation to lower V_{cw} for the longer intake designs. However, the RANS-IBMSG is pessimistic in terms of critical V_{cw} compared to the URANS-TRF model. Also, the unsteady pressure pulses from the fan can cause local increases of static pressure

in the diffuser, but the proximity of the fan can still be beneficial for shorter intake designs and limits the extent of the main separations in the diffuser.

D. Swirl distortion in the fan relative frame of reference

The unsteady characteristics of swirl distortion can significantly affect fan performance, as temporal and spatial variations in blade incidence may lead to fan stall [24], [25], [26]. The variation of incidence (Δi) is primarily influenced by the changes of two aerodynamic parameters: the swirl angle (α) and the axial velocity (V_{ax}) [16]. Using an ideal condition with uniform axial velocity $V_x = V_x^{id}$ (axial velocity in isentropic conditions) and $\alpha = 0^\circ$ as a reference, a positive Δi typically results from either a negative swirl angle $\alpha < 0^\circ$ (tangential velocity opposite to the fan rotation) or reduced, even negative, axial velocity. Conversely, a positive swirl (tangential velocity aligned with the fan rotation) or higher axial velocity tend to decrease the incidence. According to previous work [16], the largest variation of $\Delta i > 0^\circ$ is observed in the presence of gross intake separation and the ground vortex, while supersonic values of M_{rel} typically arise in the region of the ground vortex with the tangential velocity opposite to the fan rotation ($\alpha < 0^\circ$).

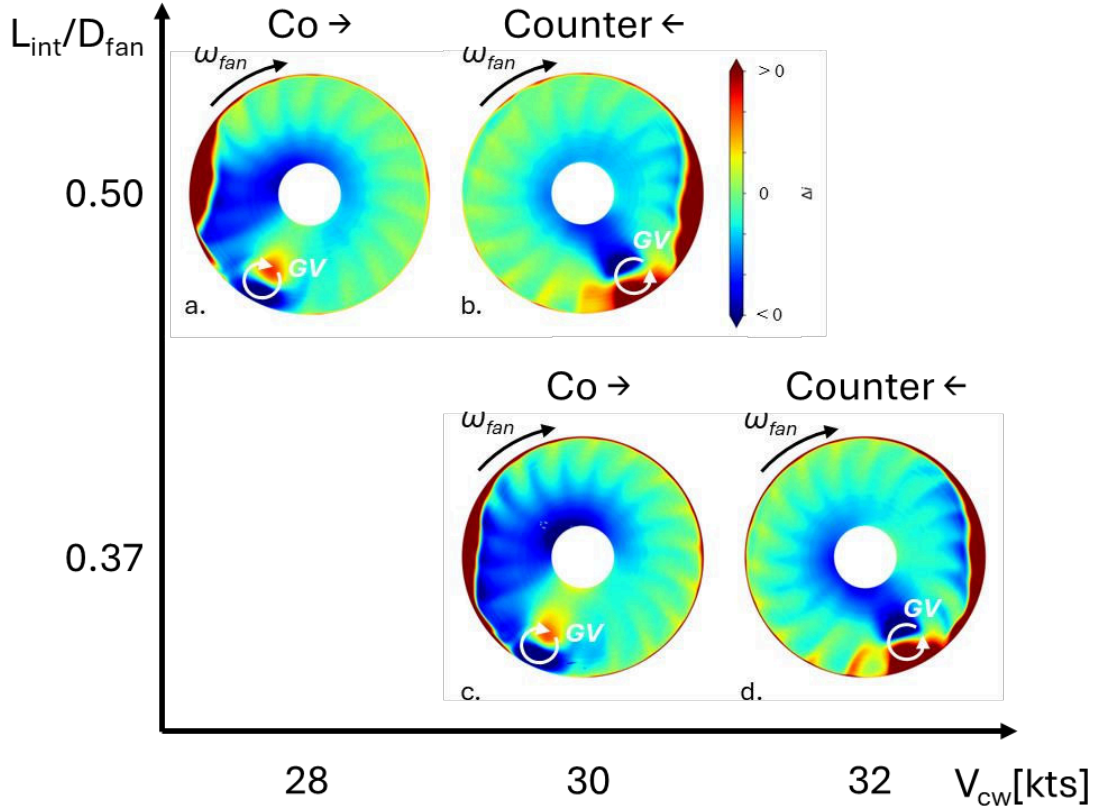


Figure 16 Snapshots of variation of incidence (Δi) at the AIP for the onset of gross separation a. $L_{int}/D_{fan}=0.5$ at $V_{cw}=28$ kts co-rotating configuration, b. $L_{int}/D_{fan}=0.5$ at $V_{cw}=30$ kts counter-rotating configuration, c. $L_{int}/D_{fan}=0.37$ at $V_{cw}=30$ kts co-rotating configuration, d. $L_{int}/D_{fan}=0.37$ at $V_{cw}=30$ kts counter-rotating configuration.

The variation of incidence (Δi) is assessed at the AIP for the two intake lengths and crosswind directions at the critical V_{cw} . For both co- (Figure 16 a, Figure 16 c) and counter-rotating (Figure 16 b and Figure 16 d) configurations the highest values of positive incidence are in the region of the gross windward separation. Depending on the crosswind configuration, the part of the ground vortex at the tip can be associated with either positive (counter) or negative (co) Δi . In the counter-rotating configuration (Figure 16 b and Figure 16 d) the ground vortex rotates in the direction opposite to that of the fan. Therefore, a region of positive swirl $\alpha > 0^\circ$ forms near the hub; that leads to a decrease of incidence ($\Delta i < 0^\circ$). Conversely, near the tip, the swirl angle is negative ($\alpha < 0^\circ$), which leads to an increase in the relative tangential velocity and $\Delta i > 0^\circ$. The opposite trend is observed in the co-rotating configuration (Figure 16 a, Figure 16 c): $\Delta i < 0^\circ$ near the tip and $\Delta i > 0^\circ$ closer to the hub.

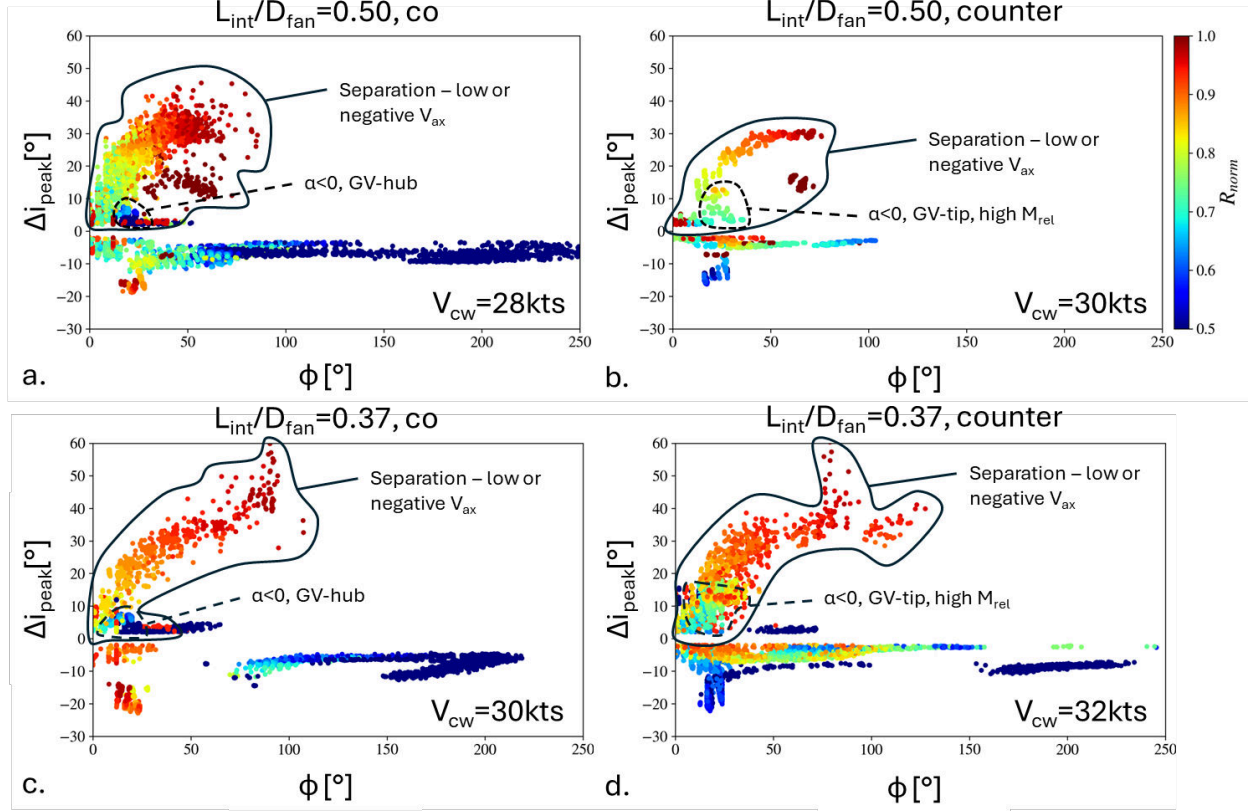


Figure 17 Intensity (Δi_{peak}) and exposure (ϕ) of the peak swirl distortion events coloured by normalised radial location (R_{norm}) for the onset of gross separation a. $L_{int}/D_{fan}=0.5$, co-rotating configuration and $V_{cw}=28$ kts, b. $L_{int}/D_{fan}=0.5$, counter-rotating configuration and $V_{cw}=30$ kts, c. $L_{int}/D_{fan}=0.37$, co-rotating configuration and $V_{cw}=30$ kts, d. $L_{int}/D_{fan}=0.37$, counter-rotating configuration and $V_{cw}=32$ kts.

The variation of incidence (Δi) is tracked in the relative frame of reference (Section III C) and the peak swirl distortion events are identified for the four combinations of crosswind directions and intake lengths at the associated critical V_{cw} (Figure 17, Figure 18). The peak events are assessed in terms of intensity (Δi_{peak}), exposure (ϕ), normalised radial location (R_{norm} , Figure 17) and relative Mach number (M_{rel} , Figure 18) to identify the flow features and quantify the distortion associated with the peak swirl distortion events.

For the co-rotating configuration and $L_{int}/D_{fan}=0.50$ (Figure 17 a, Figure 18), the separation and the associated deficit in axial velocity generate peaks of positive swirl distortion events with Δi_{peak} up to 45° and a maximum exposure of $\phi = 85^\circ$. As the intake length is reduced to $L_{int}/D_{fan}=0.37$ (Figure 17 d, Figure 18 d), both the peak intensity and exposure associated with the separation are increased. The maximum peak intensity is $\Delta i_{peak} \sim 60^\circ$ (Figure 17 c) while the maximum exposure is $\phi \sim 110^\circ$. This difference is associated with the higher critical V_{cw} and notable reverse flow at the AIP of the shorter intake (Figure 13 c). Also, for both intake lengths (Figure 17 a, Figure 17 c), the ground vortex generates positive peak events ($\Delta i > 0^\circ$) with M_{rel} just above the sonic condition.

For the counter-rotating configuration with $L_{int}/D_{fan}=0.50$ (Figure 17 b, Figure 18 b), the peak events associated with the separation have a maximum intensity of $\Delta i_{peak} \sim 30^\circ$ and the exposure up to $\phi \sim 75^\circ$. Relative to the co-rotating configuration and the same $L_{int}/D_{fan}=0.50$ (Figure 17 a, Figure 18 a), both the intensity and exposure are reduced. This difference is due to the separation reattachment of the counter-rotating configuration, while the reversed flow intermittently reaches the AIP in the co-rotating case. Also, in the counter-rotating configuration, the part of the ground vortex with a negative swirl ($\alpha < 0^\circ$) is positioned near the tip, where the blade speed is highest, and there is a reduction of axial velocity in the boundary layer. This results in a greater relative Mach number up to $M_{rel} \sim 1.4$ (Figure 18 Figure 18b) for the counter-rotating configuration relative to the co-rotating one (Figure 18 a). As the intake length is reduced from $L_{int}/D_{fan}=0.50$ (Figure 17 b, Figure 18 b) to $L_{int}/D_{fan}=0.37$ (Figure 17 d, Figure 18 d), the intensity and exposure of the peak events associated with the separation reach maximum values of $\Delta i_{peak} \sim 60^\circ$ and $\phi \sim 130^\circ$ for the counter-rotating configuration. This difference between the two intake lengths is mainly due to the significant reversed

mass flow at the AIP (Figure 13 d) and the 2 kts higher critical crosswind velocity for the short intake configuration. Similar to $L_{int}/D_{fan}=0.50$ (Figure 18 a), the peak events associated with the ground vortex reach $M_{rel} \sim 1.4$ for $L_{int}/D_{fan}=0.37$ (d).

Overall, there is a higher level of distortion at the fan tip for the shorter intake relative to the long intake design in both co- and counter-rotating configurations. However, this comparison was made at the critical crosswind velocity, which was 2 kts higher for the shorter intake in both configurations. Also, the peak events associated with the ground vortex have a relative Mach number that is higher for the counter-rotating configuration.

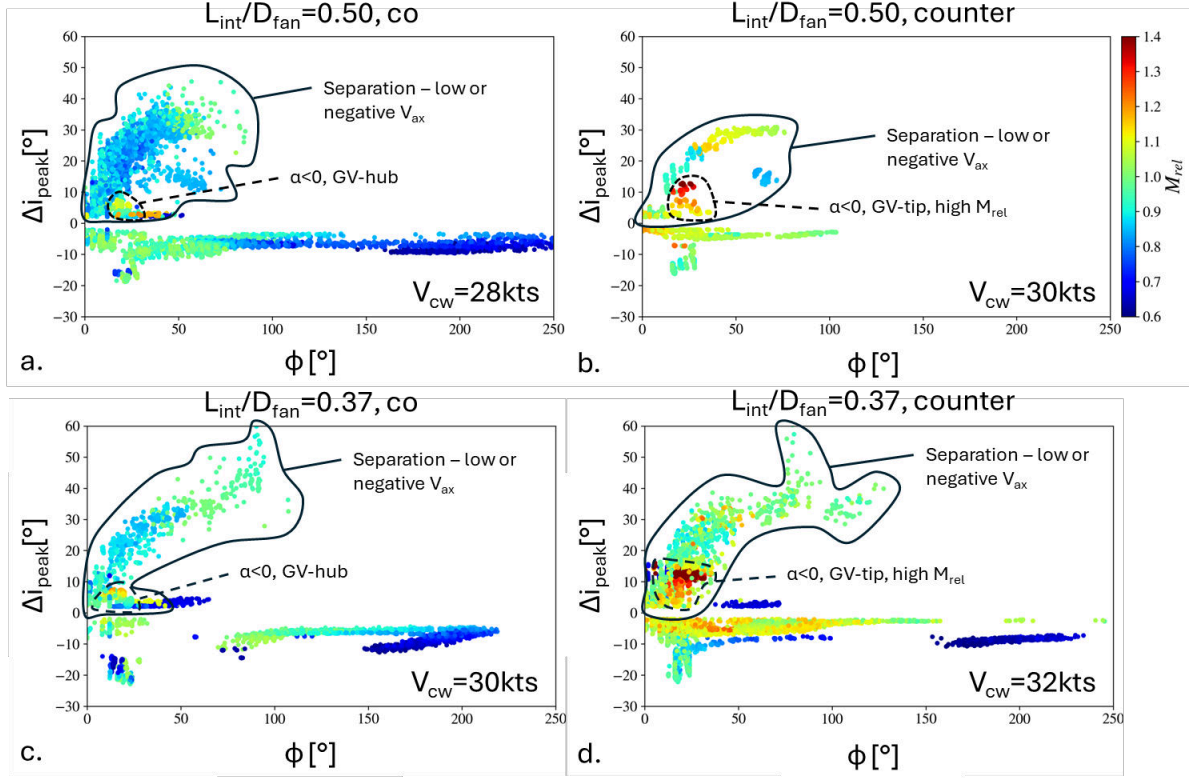


Figure 18 Intensity (Δi_{peak}) and exposure (ϕ) of the peak swirl distortion events coloured by relative Mach number (M_{rel}) for the onset of gross separation a. $L_{int}/D_{fan}=0.5$, co-rotating configuration and $V_{cw}=28$ kts, b. $L_{int}/D_{fan}=0.5$, counter-rotating configuration and $V_{cw}=30$ kts, c. $L_{int}/D_{fan}=0.37$, co-rotating configuration and $V_{cw}=30$ kts, d. $L_{int}/D_{fan}=0.37$, counter-rotating configuration and $V_{cw}=32$ kts.

V. Conclusion

This study investigated the effect of intake length and crosswind direction on the intake-fan flow separation characteristics and swirl distortion in a fully coupled intake-fan system. For the first time, the unsteady influence of the fan is assessed using designs with the same lip and diffuser geometries, while the intake length is changed by varying the length of a cylindrical duct upstream of the fan face. The primary contribution of this work lies in the identification of distinct separation mechanisms due to intake-fan interactions. Additionally, the peak swirl distortion events associated with the flow separation and ground vortex are quantified for the first time for two different intake lengths and two crosswind directions. Based on a comparative analysis of RANS-IBMSG and URANS-TRF flow fields, the following conclusions can be drawn for this research fan and intake combination:

- Based on URANS-TRF computations for both co- and counter-rotating configurations, the overall effect of the fan is beneficial for the diffuser flow for the specific geometries analysed in this work. This enables the successful operation of the short intakes ($L_{int}/D_{fan}=0.37$ compared with $L_{int}/D_{fan}=0.50$) with an additional improvement of +2kts in crosswind velocity before the onset of gross separation.

- The crosswind direction and the direction of the ground vortex can affect the interaction of the pressure perturbations originating at the fan tip leading edge and the shock on the lip. This has a penalising effect and reduces the onset of gross separation by 2 kts for the co-rotating configuration relative to the counter-rotating one for both $L_{int}/D_{fan}=0.5$ and $L_{int}/D_{fan}=0.37$.
- Steady, low-order fan models can be used for preliminary intake design assessments. However, fully coupled unsteady models are essential to fully capture the impact of crosswind direction and intake-fan interactions.
- It is shown that new distortion metrics that consider the relative frame of reference are needed to characterise the complexity of the distortion of coupled intake-fan systems.

In an industrial context, a comprehensive understanding of the interaction between the intake geometry, fan proximity, separation mechanisms, and distortion is essential to optimize intake performance and ensure robust design choices under crosswind conditions.

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Effect of intake length on flow interactions in a coupled compact intake-fan in crosswind

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