

EFFECT OF A FAN ON THE UNSTEADY DISTORTION OF S-DUCT INTAKES

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ABSTRACT

A key requirement for the integration of the propulsion and air induction systems is the assessment of the response of the fan to incoming flow distortion. This is especially crucial for the development of novel aircraft configurations with highly embedded engines. The recent advances in non-intrusive laser-based flow diagnostics increased the experimental capability to measure unsteady flows in convoluted intakes with high resolution in time and space. In the pathway to full-scale intake-engine tests, this work introduces the capability to successfully acquire non-intrusive high resolution flow distortion measurements in close proximity to a high-speed rotating fan. This also quantifies the impact of the fan on the inherent flow distortion of S-duct intakes. The measurements demonstrate that although the effect of the fan on the flow distortion is limited, the rotating blades can cause a local increase of the maximum levels swirl intensity at the blade tip region. Further development work on the ducted fan simulator is needed to operate the fan in the representative range of transonic rotors.

1. INTRODUCTION

In the last decade there has been a notable focus on the development of new aircraft designs such as Blended-Wing-Body (BWB) and Boundary Layer Ingesting (BLI) aircraft which could help address the need for fuel burn reduction [1–3]. However, the use of convoluted intakes for integrated propulsion systems generate unsteady inlet flow distortion [4]. This can affect the propulsion system performance [5] and its aerodynamic and mechanical stability [6,7]. A key consideration to de-risk the development of these novel architectures is to have the capability to assess the unsteady flow distortion and to evaluate the interactions with the propulsion system. Researchers have previously simulated engine effects with a windmilling fan in civil intakes and demonstrated that the presence of the fan can suppress the inlet flow distortion caused by inlet lip separation on high angles of

attack and by the ingestion of the vortices [8–10]. However, these investigations were carried out without a powered fan and with steady-state total pressure measurements. In more recent work, it has been shown that time-resolved stereo-PIV (TR-SPIV) can provide non-intrusive, high resolution, and synchronous measurements to characterize the unsteady flow distortion [11–14]. This has opened the route to novel methods to evaluate the magnitude and the extent of the unsteady distortion events. For example, the flow distortion has been evaluated with TR-SPIV measurement in an envisaged nominal relative frame of reference [15]. This provided a first estimate of the levels of distortion at which the blades can be exposed during the rotation. It was acknowledged that the interactions between the fan and inlet distortion were not included in the assessment as this would require the presence of rotating blades in the distorted domain. The development of a TR-SPIV approach to measure the unsteady distortion ahead of the fan is the main focus of the work. In addition, the assessment of the effects of the rotating blades on the unsteady S-duct distortion is also of interest. This is achieved by introducing a closely-coupled fan downstream of S-duct diffuser.

2. EXPERIMENTAL AND DATA PROCESSING METHODS

The experiments are conducted in the Cranfield Complex Intake Test Facility (CCITF, Figure 1). A detailed description and operating controls are reported by Migliorini et al. [16]. For the coupled intake-fan tests, the S-duct diffuser is coupled with an Electric Ducted Fan (EDF) Vasyfan VF-160 with a fan diameter of 158 mm, maximum operating speed of 25,000 rpm and a maximum tip Mach number of 0.6. This fan is used as prime mover for the CCITF and the operating Mach number range is $M_{ref} = 0.07 - 0.36$ measured 1.45 inlet diameters upstream the S-duct inlet plane (Figure 2).

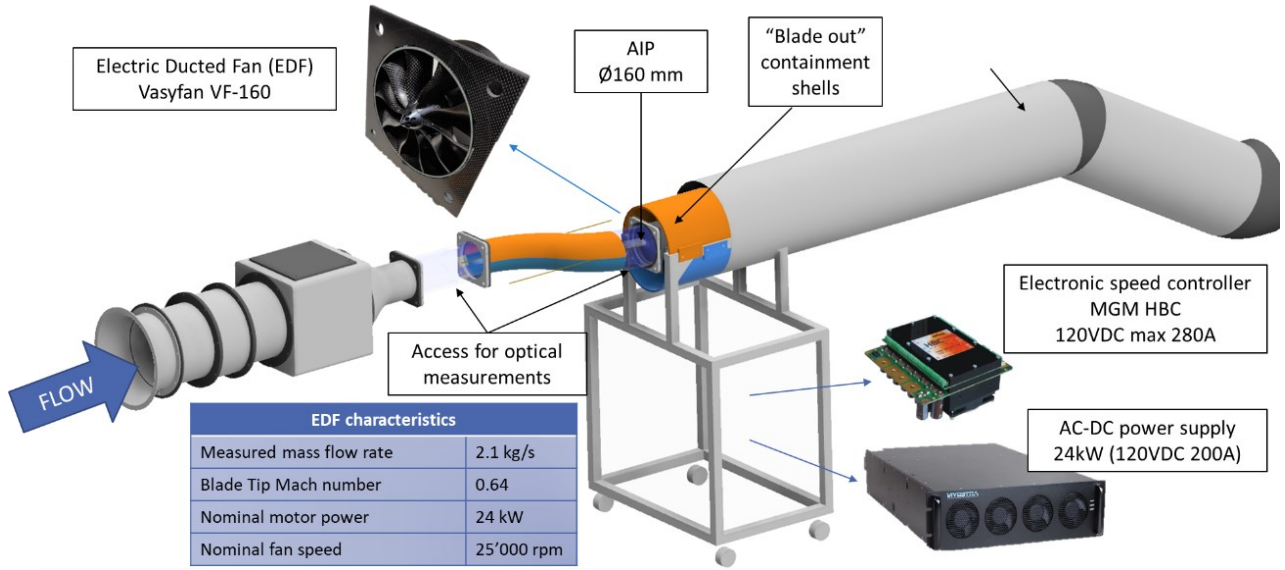


Figure 1: 3D rendering of the Cranfield Complex Intake Test Facility (CCITF) with an Electric Ducted Fan (EDF) as prime mover for coupled intake-fan tests.

The fan is driven using a 24 kW AC-DC rectifier to provide up to 200A at 120VDC to the Electronic Speed Controller (ESC) (Figure 1) with a brushless DC motor which powers the fan blades. This configuration enables continuous operation for the experiments.

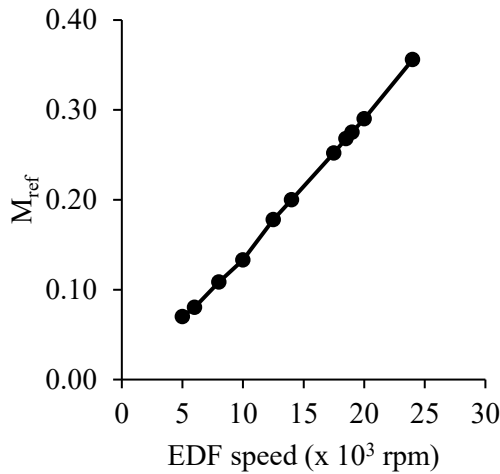


Figure 2: Measured inlet Mach number during operation of the CCITF operated with EDF.

The S-duct diffuser can also be coupled with a suction fan for the operation between inlet Mach number $M_{ref} = 0.05 - 0.60$ (Figure 3). The rig can be re-configured via the modular support structure mounted on caster wheels by disconnecting the ducting at the S-duct diffuser exit plane. The relative positioning of the instrumentation and the structural rigidity of the structure is maintained with a set of optical rails which support the test diffuser, the cameras, the laser and section upstream the S-duct

diffuser (Figure 3). This enables the use of the upstream section as a standalone unit whose measurement system can be calibrated when the unit is de-coupled from the prime movers and to maintain comparable measurement uncertainty on the two configurations, as this largely depends on the optical configuration.

3. DATA ACQUISITION AND POST-PROCESSING METHODS

Time-Resolved Stereo-Particle Image Velocimetry (TR-SPIV) has been used as the measurement system to characterize the unsteady flow distortion at the fan face. A pair of CMOS cameras with a resolution of 1280 x 800 px was used for imaging 1 μ m DEHS seeding particles at the exact exit plane of the S-duct diffuser. A light sheet generated by a pulsed Nd:YAG laser was installed at this location. A dataset comprising 20,000 velocity flow-fields was captured at 8 kHz. The S-PIV measurements yielded a spatial resolution at 2.3 x 2.3 mm on a 160 mm diameter Aerodynamic Interface Plane (AIP), which resulted in approximately 3,000 3D velocity vectors. To mitigate errors stemming from alignment discrepancies between the calibration plate and laser light, a disparity correction technique was employed. This reduced errors to sub-pixel scale. The data has been processed with the commercial software LaVision Davis ver. 10.2.1. After processing, a region that covered 90% of the AIP radius were considered to avoid spurious velocity vectors induced by laser light reflections. The uncertainty associated with the velocity components was determined to be 3.3% of the area-averaged, time-averaged streamwise velocity at the AIP, following the methodology proposed by Raffel et al. [17].

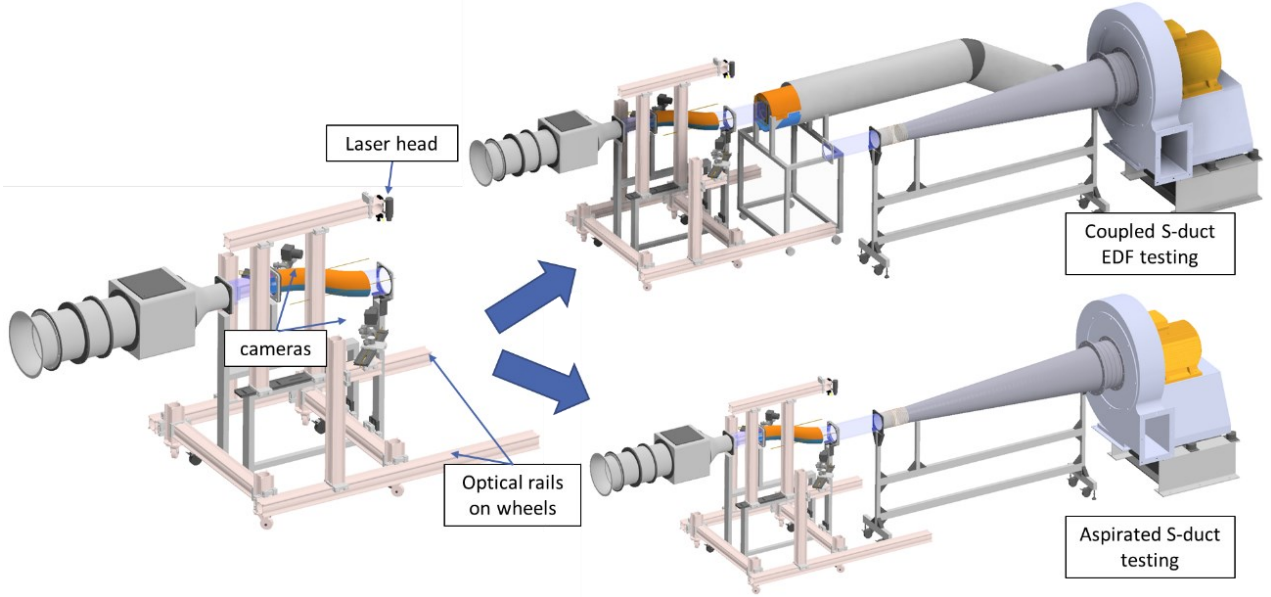


Figure 3: 3D rendering of the Cranfield Complex Intake Test Facility (CCITF) with an Electric Ducted Fan (EDF) as prime mover for coupled intake-fan tests.

Cameras were arranged in a stereo configuration on an optical bench (Figure 3). A preliminary study of the optical access was carried out by assessing the line of sight of two PIV cameras of the exit portion of S-duct intake with the intent to optimize the axial length of the transparent walls of the S-duct intake upstream the fan face (z_{TR} , Figure 4). A shorter axial length of the transparent portion would benefit its optical properties as the shorter tool required for machining the optical duct would induce less vibrations and thus less optical distortion. On the other hand, a shorter length of the transparent domain would reduce the optical access for the non-intrusive measurements and would impose larger stereo half-angles, which in turn increase the PIV measurement uncertainty.

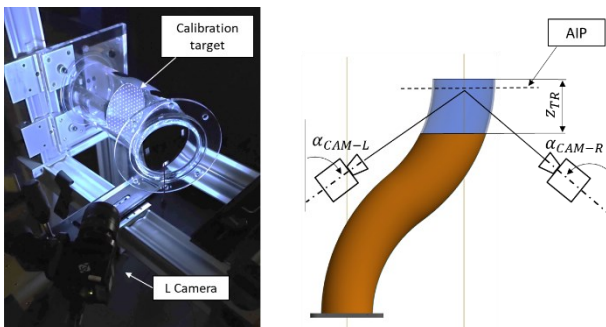


Figure 4: Line of sight assessment for the optical access for PIV measurements at the S-duct exit plane.

It was chosen to limit the stereo half angle to $\alpha_{CAM} \leq 55^\circ$. The AIP was positioned so that the plane would correspond to the tip of the EDF spinner, approximately 0.16 S-duct outlet diameters upstream the EDF fan face. This in turn set the length of the transparent portion

upstream the fan face of $z_{TR} = 0.84$ times the S-duct outlet diameter. Nevertheless, during the preparation of the full experimental setup, the camera on the port side has been lowered relative to the S-duct centreline to compensate for the reduced space available near the first S-duct bend (camera in the bottom of the picture, Figure 5a). This enabled a reduction of the $\alpha_{CAM} \cong 50^\circ$.

The presence of the spinner imposed additional challenges on the PIV acquisition at the fan face. High-intensity and unsteady laser light reflections were diffused in the region around the spinner worsening the signal to noise ratio locally. Additionally, the spinner generates blockage in the line of sight as the camera cannot see the areas immediately behind the spinner. This generates areas of the AIP which are seen by only one of the two PIV cameras and for which the 3D vector calculation through image cross-correlation is not possible. This data loss in regions of the AIP unavoidable in a two-camera setup, but can be substantially reduced with multi-view camera systems [16,18], however these were not available for the current setup. Due to the current camera configuration (Figure 5a), these areas are not symmetric with respect to the spinner and can be evaluated with the distribution of the time-averaged streamwise velocity uncertainty provided by the software and calculated with Wieneke's method [19] (Figure 5b). The area with high uncertainty has been approximated with an ellipse with centre in $X = 0.1 \, r_{AIP}$ and $Y = 0.1 \, r_{AIP}$ and with main axis $a_x = 0.35 \, r_{AIP}$ and $b_y = 0.25 \, r_{AIP}$. The data within this ellipse has been excluded from the analysis. The additional areas with high velocity uncertainty in the lower right corner (Figure 5b) are attributed to a combination of laser light reflections due to the AIP curvature and optical distortion caused by the

bends in the S-duct walls, which could not be avoided. The laser light also created additional reflections in the left side of the domain boundary as visible in Figure 5b.

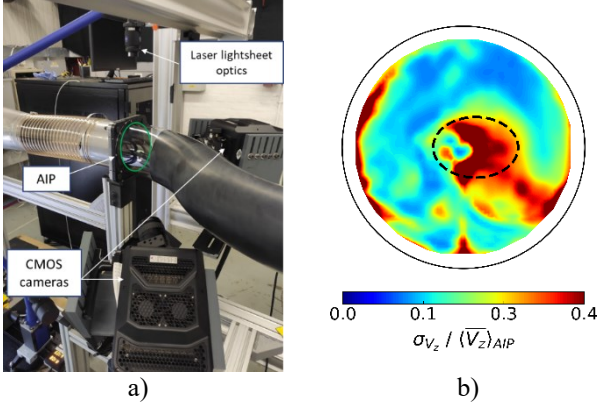


Figure 5: a) experimental configuration port camera lowered with reference to the AIP centreline, and b) uncertainty of the streamwise velocity component due to laser light reflections and spinner shadows.

To enable a more comprehensive comparative assessment between the aspirated and intake-fan coupled configurations, swirl distortion metrics have been also introduced in the analysis. The key swirl distortion metrics SI, SP, SD characterize the intensity (SI), number of pairs (SP) and directivity (SD) of the swirl distortion structures, respectively and are the industrial standard for the integration of the air induction and the propulsion system. For brevity, the reader is referred to the Aerospace Information Report AIR 5686 by SAE International for the complete formulation [20]. These descriptors are calculated on data interpolated on 5 equal-area rings corresponding to typical 5x8 probe arrangement according to the Aerospace Recommended Practice ARP1420 [21]. These descriptors are analysed in pairs with joint-probability density function maps to assess the unsteadiness of swirling structures in time [13,22]. Spectral analysis on the swirl angle fluctuations has also been introduced in the analysis. This analysis is conducted with an averaged periodogram method [23] in which the PIV dataset has been divided into 20 parts and a Hann window has been introduced to reduce frequency leakage.

4. RESULTS

The effects of the flow distortion generated by an S-duct intake has been evaluated in the two experimental configurations: aspirated and close-coupled with EDF. Three operating points at inlet $M_{ref} = 0.18, 0.27$ and 0.36 have been chosen across the operating range of the rig when coupled with the EDF. The analysis of the flow distortion characteristics showed that the effects of the fan were broadly the same independently from the operating speed. This was expected, as previous work demonstrated that the inherent flow distortion

characteristics of S-duct intakes is insensitive to Mach number [11], and the EDF is a subsonic fan. Thus, the analysis focused mainly on the operating point at $M_{ref} = 0.36$. Results are presented from the perspective of incoming flow direction with horizontal axis positive towards the right, for which the fan is rotating clockwise. (Figure 6). The velocity distributions have been normalized against the area-averaged, time-averaged streamwise velocity component (V_z) of the aspirated S-duct configuration to enable the magnitude comparison.

The distribution of the streamwise velocity component V_z shows an area of high momentum on the right-hand side of the domain, which corresponds to the outward wall of the first S-duct bend (Figure 6a). In this region, the streamwise velocity is approximately constant (Figure 6a), which indicates this is insensitive to the presence of the fan. The low momentum region on the left-hand side of the domain linked with the typical S-duct secondary flows is instead affected by the presence of the fan (Figure 6a). This promotes the uniformity of the flow by redistributing radially the flow. An increase of the radial velocity V_r towards positive values is observed across the full AIP plane (Figure 6c). It is envisaged this is due to the combined presence of a spinner and EDF motor casing, which deflect the flow radially towards the duct boundaries. This is consistent with previous investigations on the effect of a centrebody on the S-duct intake flow distortion [24].

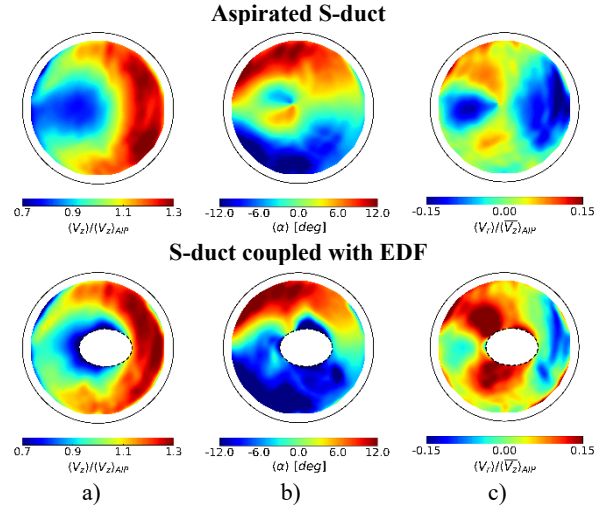


Figure 6: Distribution of time-averaged a) streamwise velocity component V_z , b) swirl angle α , and c) radial velocity V_r at the AIP for aspirated and close-coupled S-duct intake configurations at $M_{ref} = 0.36$.

On the other hand, the tangential redistribution of the flow is secondary. In the region between the two main vortical structures, the fan biases the flow towards negative angles, whereas for the aspirated intake configuration the swirl angle remained close to zero (Figure 6c). However, overall, the swirl angle

distributions and the maximum values remain approximately the same in the two configurations. This indicates that the effect of the fan on the incoming flow distortion is relatively mild.

The effects of the fan on the S-duct flow distortion have also been assessed with the SAE swirl distortion descriptors. Unsteady full-plane swirl angle distributions enabled the combined assessment of the swirl angle magnitude (SI) and the associated topology (SP, SD). Particular attention should be given to instantaneous individuals with high swirl intensity, as these potentially change the local blade loading and could cause excessive mechanical forcing on the fan blades. The analysis focused on two radial positions at $r/R = 0.84$ (Figure 7) and $r/R = 0.71$ (Figure 8), depicted as typically representative of the tip area of the blades and the region with the peak blade loading, respectively. Regions closer to the spinner have been excluded from the analysis to avoid eventual leakage of spurious vectors due to residual reflections described in Figure 5b. The EDF caused an increase of the maximum SI by approximately 3.5° at the blade tip ($r/R = 0.84$, Figure 7) while it increased by 1.5° at the peak blade loading point ($r/R = 0.71$, Figure 8). This is envisaged to be a worsening operating condition for the fan rotor, as it is linked with higher incidence angles which could favour the development of stall cells [25,26].

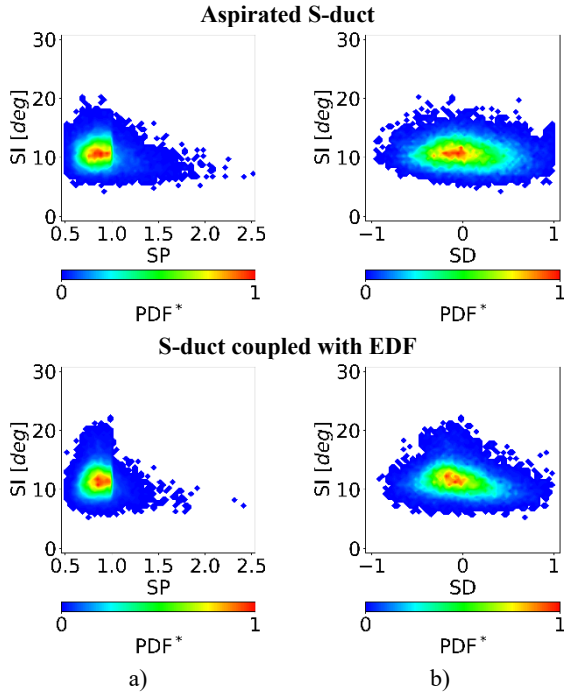


Figure 7: j-PDF distribution of Swirl Intensity (SI), Swirl Pairs (SP) and Swirl Directivity (SD) measured at $r/R = 0.84$ for aspirated and close-coupled S-duct intake configurations at $M_{ref} = 0.36$.

On the other end, another effect of the fan is to reduce the number of single bulk swirl patterns ($SD = \pm 1$), in favour of more events with twin-paired swirl distributions. This is visible by comparing the peak swirl events in the SI-SD maps (Figure 7b and Figure 8b). In a previous study by Mehdi [27], it was found that bulk swirl events can have a higher impact on the reduction of the compressor surge margin compared to the other flow topology. Hence, it is notable that the presence of the fan has an impact of the characteristics of the swirl distortion.

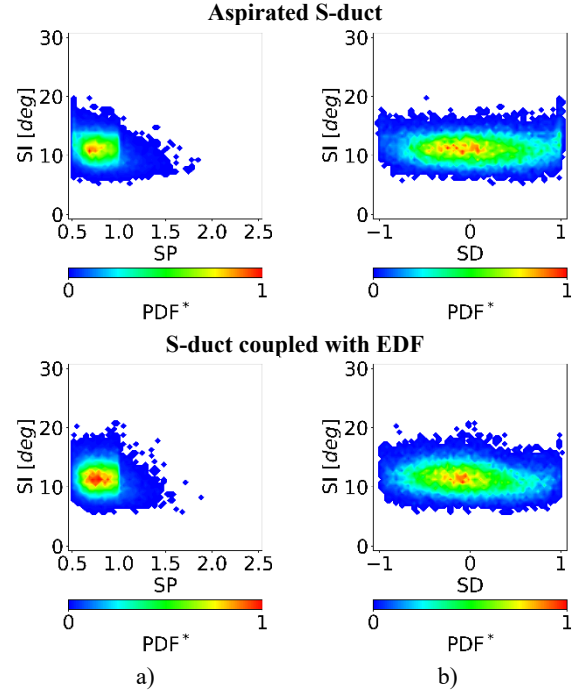


Figure 8: j-PDF distribution of Swirl Intensity (SI), Swirl Pairs (SP) and Swirl Directivity (SD) measured at $r/R = 0.71$ for aspirated and close-coupled S-duct intake configurations at $M_{ref} = 0.36$.

For the operating point $M_{ref} = 0.27$, where at $r/R = 0.84$ and at $r/R = 0.71$ the SI increased by approximately 3° in the presence of the EDF compared with the aspirated S-duct configuration (Figure 9). At $M_{ref} = 0.18$, the maximum SI remained approximately constant at r/R between the aspirated and the EDF configuration, while it decreased slightly by 1.5° at $r/R = 0.71$. This indicates that the levels of peak swirl distortion across the range of operating conditions is increasing mainly at the blade tip. Nevertheless, this also indicates that the fan rotor does not have a suppression effect on the peak swirl distortion but instead is likely increasing the maximum swirl intensity, especially at the blade tip.

The spectral signature of the swirl angle fluctuations has also been considered to investigate the rotating fan effects. The frequency bands are defined on the Strouhal number $St = f D_{AIP} / \langle V_z \rangle$ where f is the frequency of the

fluctuations, D_{AIP} the diameter of the AIP, and $\langle \bar{V}_z \rangle$ the time-averaged, area-averaged streamwise velocity at the AIP.

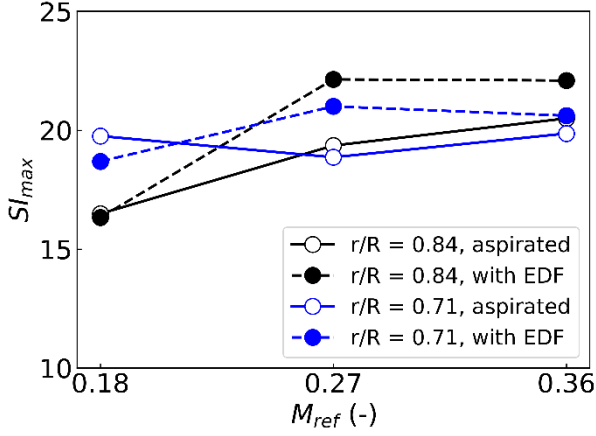


Figure 9: Comparison of the time-averaged Swirl Intensity (SI) at ring locations $r/R = 0.71$ and 0.84 for aspirated and close-coupled S-duct intake configurations at different operating points.

Each contribution is normalized by the overall area-averaged value of the variance across each frequency band in the aspirated S-duct configuration, which allows comparisons on the relative magnitude of the spectra in the two configurations (Figure 10). Based on the Nyquist criterion, frequencies up to about $St = 8$ can be determined for an acquisition frequency of 8 kHz. This is

far greater than typical swirl angle fluctuations of this S-duct intake, which are typically in a range between $St = [0.2, 1.2]$ for uniform inlet flow conditions [22]. The strongest contribution is noted in a band between $St = [0.4, 0.6]$ (Figure 10), which consists in the swirl switching mode and corresponds to the alternation of positive and negative bulk swirl and twin-paired swirl patterns [13]. With the introduction of the fan, the contribution of this switching mode at $St = [0.4, 0.6]$ still prevails on the other spectral bands (Figure 10). This was partially expected as the analysis of the swirl distortion through the descriptors highlighted a population of swirl patterns spanning between negative bulk ($SD = -1$), twin swirl ($SD = 0$), and positive bulk swirl ($SD = 1$) (Figure 7b and Figure 8b). The spectral analysis confirms that the swirl switching mode still occurs at the reference frequency. Overall, a slight decrease of the magnitude of the swirl fluctuations is observed across all the frequency bands for the close-coupled S-duct relative to the aspirated S-duct configuration (Figure 10). The variance reduced especially in the left area of the AIP where the main vortical structures of the flow reside. This is attributed to the reduction of the bulk swirl pattern individuals ($SD = \pm 1$, Figure 7b and Figure 8b). It is envisaged that the fan limits the most extreme swirl angle fluctuations which would bias the flow to rotate only towards one direction. This is considered a stabilizing effect which reduces the magnitude of the swirl angle fluctuations overall.

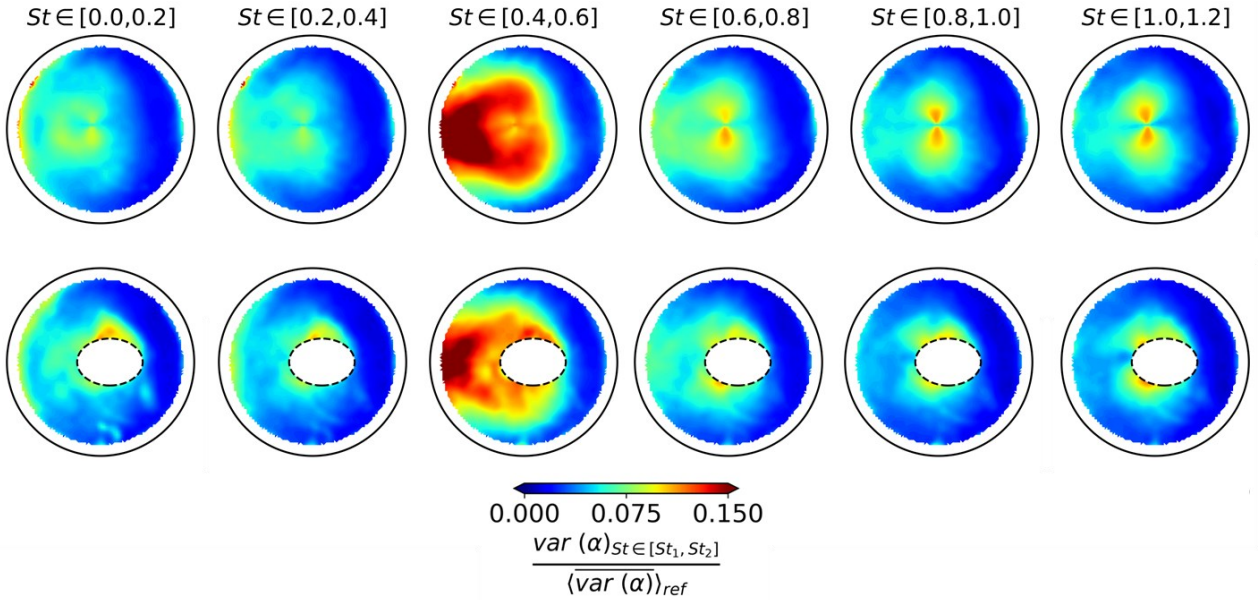


Figure 10: Spectral signature of swirl angle α fluctuations arranged in bands of Strouhal number $\Delta St = 0.2$ for aspirated and close-coupled S-duct intake configurations at $M_{ref} = 0.36$.

5. CONCLUSIONS

This work demonstrates TR-SPIV measurements for non-intrusive, synchronous unsteady flow distortion measurements in convoluted diffusers, at the face of a rotating fan. To the authors' knowledge, this has never been reported previously in the open literature and represents a significant step forward in the experimental capability for intake-engine integration assessments. The availability of non-intrusive, time-resolved 3D velocity vectors across the full fan face enabled the quantification of the impact of rotating blades on the unsteady swirl topology and magnitude, and on the spectral signature of the swirl fluctuations. The advanced measurement methodology enabled to identify critical increase of peak swirl intensity at specific blade span locations which would not be possible to capture with measurements from neither time-averaged multi-hole probes nor high-frequency single point measurement methods. Overall, a mild effect of the fan was observed on the inherent S-duct flow distortion. However, this is expected to be more prominent for transonic fans, hence the natural step forward in the research is the further development of this propulsion system to operate the fan transonic speeds. This would simulate the operation of typical transonic fan embedded with convoluted intakes. It is envisaged that the impact of this work is to highlight the need of novel laser diagnostic techniques on industrial settings and to embed this measurement method in the de-risking of integrated propulsion systems across the development phases.

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