

A STUDY ON THE DEVELOPMENT OF THE FLOW DISTORTION DOWNSTREAM OF AN S-DUCT INTAKE

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Abstract

The use of complex intakes (S-ducts) can enable a closer integration between the airframe and the propulsion system to target a reduction of aircraft fuel consumption, noise, drag, and emissions. However, these advantages may be offset by the increased unsteady flow distortion that arises which can adversely affect the aero-engine. This is also of interest where non-uniform conditions are present at the inlet, for example in Boundary Layer Ingestion (BLI) aircraft. The flow distortion may result in a reduction of the operability range of the engine and in a risk for the development of new propulsion systems. Recently, high-bandwidth Particle Image Velocimetry (PIV) and the statistical modelling of extreme events have been used to assess the S-duct flow distortion. In this work, these methods are used to assess the development of the flow distortion characteristics downstream of the S-duct outlet plane. Non-uniform conditions at the inlet of the S-duct intake produced a sharp growth of the peak distortion levels which is attributed to the increase of local flow unsteadiness that could be linked to the secondary S-duct separation. These peak distortion levels were identified through the modelling of extreme events where the growth of the peak distortion levels was projected beyond the experimental observations. Overall, this work highlights the importance of statistical modelling of the unsteady distortion and shows the development of the unsteady swirl distortion levels downstream of the S-duct outlet plane.

Keywords: Intake, Flow distortion, Aero-engine, Unsteady, Swirl

1. General Introduction

In the last decade there has been a notable focus on the development of new aircraft designs which could cut emissions and reduce noise and fuel consumption. Several proposed novel configurations explore a closer integration of the aero-engine with the fuselage [1]. The development of Blended-Wing-Body (BWB) and Boundary Layer Ingestion (BLI) aircraft may offer several benefits including a reduction of the fuel burn and increase in propulsive efficiency [2]. However, these configurations with more embedded propulsion systems sometimes require more complex intakes. These intakes typically generate unsteady flow distortion [3] which can affect the propulsion system performance [4] as well as the aerodynamic and mechanical stability [5,6].

Recently, high-bandwidth stereo-particle image velocimetry (S-PIV) enabled the assessment of the unsteady swirl distortion at the S-duct aerodynamic interface plane (AIP) [7,8]. It was demonstrated that the ingestion of relatively thick boundary layers could greatly increase the swirl intensity of unsteady bulk swirl distortion events [9]. A novel methodology was introduced to exploit the high temporal and spatial resolution of high-bandwidth PIV measurements. This enabled the assessment of the temporal-spatial variations and the flow distortion in the envisaged relative frame of reference of a compressor rotor [10]. The analysis showed that the presence of non-uniform inlet conditions can increase the exposure time of the rotors to large fluctuations in the nominal incidence. Moreover, it highlighted that some fluctuations of incidence are non-uniform across the blade span and that these generate an uneven blade loading which are potentially linked with the generation of stall cells [10]. These findings highlight the potential risk for the development of future aircraft configurations with integrated propulsion systems, and, in more general, for the operation of the propulsion system with non-uniform inlet conditions.

In previous work, the embedded propulsion systems demanded a new design of the fan so that it could tolerate the high levels of flow distortion [11,12]. However, further effort is also needed to establish the tolerance of the fan for a range of different operating conditions. In addition to the intake arrangement, the integration of the propulsion system with the airframe depends on several aspects including the integration with other systems and architectural requirements [2]. Although from a compactness point of view there may be benefits in having a close coupling between the intake and the propulsion AIP this may not always be possible. In certain circumstances the AIP may be located downstream of the complex intake. Within this context, the aim of this paper is to quantify the development of the flow distortion characteristics downstream of the S-duct outlet plane.

2. Methodology

2.1 Experimental Facility

This work was carried out on the S-duct intake facility at Cranfield University. The diffusing S-duct was previously investigated by Zachos et al. [7] and a brief description is provided here (Figure 1). Upstream of the intake, a honeycomb circular screen with variable porosity can be optionally placed at station 1 (Figure 1) to reproduce boundary layer-type total pressure profiles. In addition to the configuration with the reference rig boundary layer thickness ($\delta/D_{in} = 0.04$), this study included also total pressure profile with $\delta/D_{in} = 0.332$ (Profile A). This could represent typical boundary layer thickness presented to a rear-mounted aero-engine on a BLI aircraft [13,14]. This inlet profile was also oriented by $\psi = 90^\circ$ to represent asymmetric inlet conditions that may occur in some operation of the intake under angles of side slip [9,15,16]. The operating point of the rig is controlled via the measured centreline average Mach number at the reference inlet plane, which was 0.27 ± 0.005 (Plane R, Figure 1).

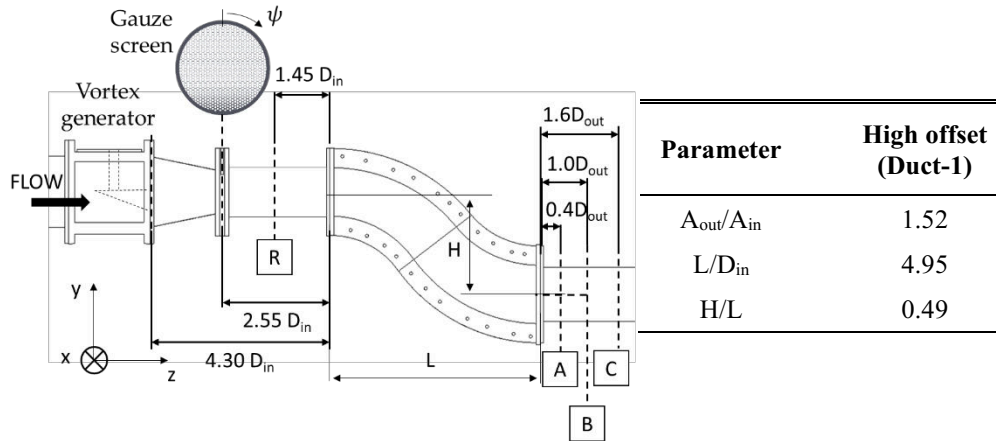


Figure 1: Experimental facility for complex intakes with key dimensions.

2.2 PIV measurements

The flow distortion was assessed at cross-flow planes at $z/D_{out} = 0.4, 1.0$, and 1.6 downstream the S-duct outlet plane (planes A, B, C, respectively, Figure 1). The characteristics of the high-bandwidth particle image velocimetry system are described in detail by Gil-Prieto et al. [17]. The processing strategy resulted in a vector resolution of approximately $0.0153 D_{out}$ (2.3 mm) in both directions across the AIP to provide a total of approximately 2,000 velocity vectors across the measurement plane. The temporal resolution of the PIV velocity fields was 8 kHz, which is 20 times the highest dominant flow frequency for the selected S-duct intake ($St = 1.06$) [18].

2.3 Unsteady distortion analysis methods

The swirl distortion was assessed with the use of swirl descriptors from the SAE industry standards, which quantify the intensity, the directivity and the number of the vortical structures at the AIP (SI, SD, and SP, respectively) [19]. Joint-Probability density function maps (j-PDF) were introduced by Gil-Prieto et al. [20] to assess the distribution of unsteady swirl patterns and their relative probability. It was revealed that the intensity of snapshots of the swirl angle distortion can be twice the measured

mean distortion levels [8]. Even higher distortion levels can appear beyond the experimental testing times due to the unsteady nature of these complex flows [21]. Peak fluctuations are of interest for the engine stability since these could trigger spike-stall inception mechanisms [22]. Thus, the analysis of the maximum distortion levels is complemented with a statistical model for the projection of the highest distortion levels. In this work, the Extreme Value Theory in the Peak-Over-Threshold formulation is adopted for the prediction of the upper-bounds of the unsteady swirl intensity distribution. A more detailed description of this theory is included in previous works by Coles, Gil-Prieto et al., and Tanguy et al. [23–25].

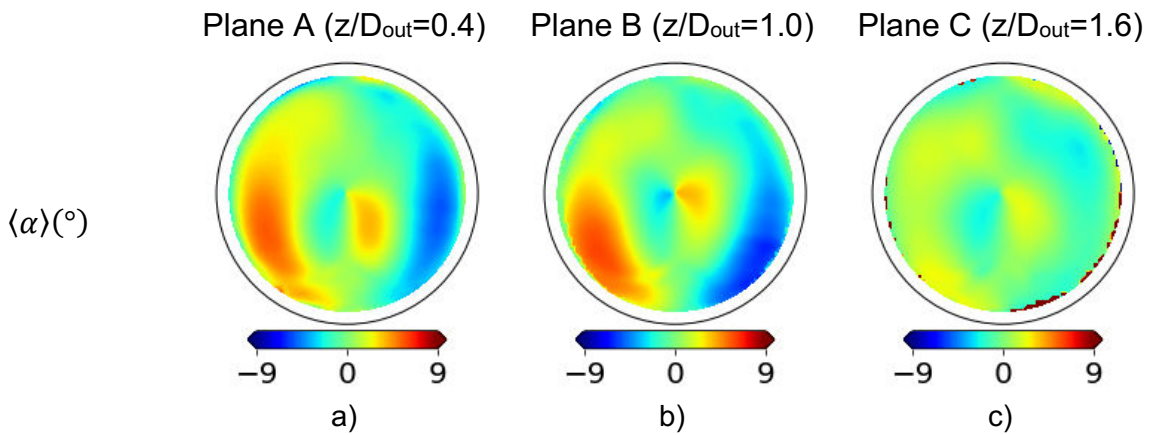
3. Results

3.1 Flow distortion development with uniform inlet conditions

3.1.1 Time-averaged and unsteady distortion analysis

The aerodynamics of the high-offset S-duct geometry included in this study was thoroughly investigated in previous work, including experimental and computational studies [26,18] evaluations of steady and unsteady total pressure distortion [25], swirl distortion [17], sensitivity to inlet Mach number [7], as well as the effectiveness of passive and active flow control methods [27]. However, most of the investigations on the flow distortion were conducted close to the S-duct exit plane at $z/D_{out} = 0.4$ (Plane A, Figure 1). In this study, the downstream development of the flow distortion at $z/D_{out} = 1.0$, 1.6 (planes B, C, Figure 1) were investigated. Overall, for the time-averaged flow field, the typical twin vortical pattern was observed at all the measurement planes but the magnitude of the swirl distortion decays with increasing distance from the S-duct outlet plane. For uniform inlet conditions ($\delta/D_{in}=0.04$) the range of the time-averaged swirl angle distribution is approximately $\langle\alpha\rangle = \pm 10^\circ$ at $z/D_{out} = 0.4$ (plane A) and $z/D_{out} = 1.0$ (plane B) while it decays to $\langle\alpha\rangle = 6^\circ$ at $z/D_{out} = 1.6$ (Plane C) (Figure 2a, b, c). The swirl angle unsteadiness $std(\alpha)$ reduces monotonically from $std(\alpha) = 16^\circ$ to $std(\alpha) = 12^\circ$ and $std(\alpha) = 7^\circ$ for $z/D_{out} = 0.4$, 1.0 and 1.6 , respectively (Figure 2d, e, f).

The decay of the swirl intensity was observed also through the analysis of the unsteady swirl distortion descriptors. The j-PDF maps highlight the importance of considering the unsteady swirl characteristics instead of the time-averaged swirl levels as the peak swirl intensity values can be as much as twice the time-average values. As these events are believed to trigger spike-stall inception mechanisms [22], it is vital to assess the intensity of these unsteady events for the various configurations. Within this context, the maximum values of area-averaged swirl intensity $\overline{SI}$ decreased from 14.7° to 13.2° and 11.8° at $z/D_{out} = 0.4$, 1.0 , and 1.6 from the S-duct outlet (Planes A, C, and D respectively, Figure 3a, b, c).



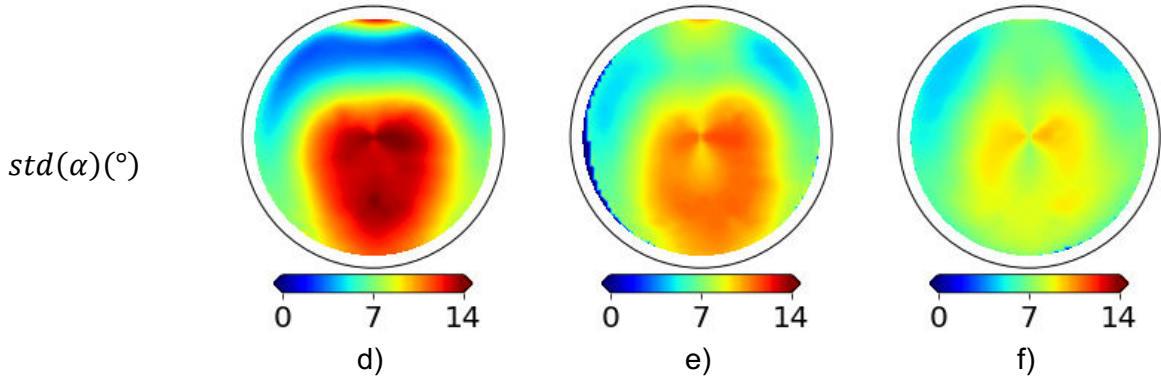


Figure 2: Time-averaged swirl angle and unsteadiness for baseline inlet conditions ($\delta/D_{in} = 0.04$) at locations downstream the S-duct outlet plane.

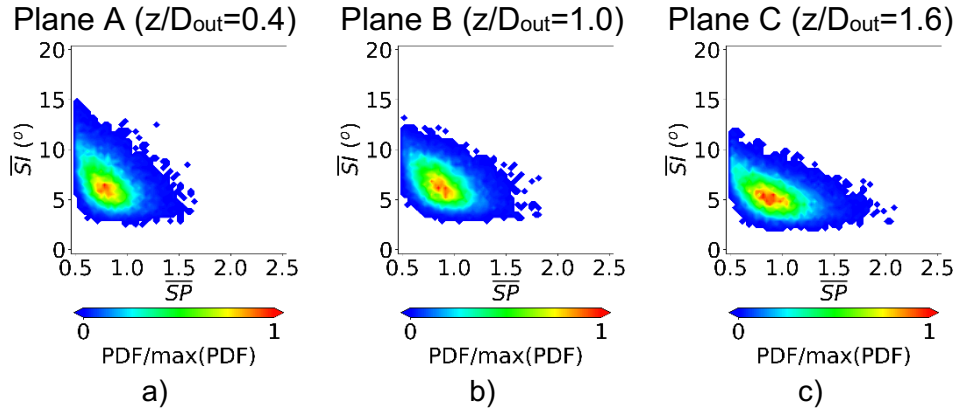


Figure 3: Area-averaged SI-SP j-PDF maps at the AIP for baseline inlet conditions ($\delta/D_{in} = 0.04$) at locations downstream the S-duct outlet plane.

3.1.2 Extreme swirl distortion projections for uniform inlet conditions

For aero-engine propulsion systems, it is known that peak distortion events generate instabilities which can trigger spike-stall inception [22]. Thus, the compatibility between the intake and propulsion system is affected by the peak distortion levels that the aero-engine can tolerate without stalling [28]. Although experimental testing indicates levels of the peak distortion, often the experiment sampling time is not sufficient to capture the real peak distortion due to the unsteady random nature of the peak distortion events. Indeed, peak distortion and severe instabilities may occur after several minutes of testing time [29]. It was also demonstrated that the peak distortion levels increase with the data acquisition time and that statistical modelling with Extreme Value Theory (EVT) was needed to predict the peak distortion for a return time beyond the experimental observations [21]. In this work, EVT has been applied to the area-averaged swirl intensity $\overline{SI}$ snapshots to evaluate the evolution of the peak distortion downstream the S-duct intake. The aim is to evaluate likely peak distortion characteristics downstream of the S-duct.

During the experiment, snapshots of the area-averaged swirl intensity $\overline{SI}$ were considered and the maximum measured swirl intensity was recorded ($\overline{SI}_{peak,exp}$). The EVT model was used to project the peak swirl intensity beyond the experimental observations. Typically, this statistical model estimates the extreme values for a number of observations 100 times greater than the experimental dataset [21] (Figure 4). Since the experimental dataset comprised 2×10^4 unsteady snapshots, the peak swirl intensity at $m = 10^6$ observations was considered ($\overline{SI}_{m=10^6,EVT}$) (Figure 4). This prediction is associated

with a confidence interval (CI) which is typically in the order of $\pm 1.0^\circ$ and the tendency is described with the upper bound asymptote $U_{b,EVT}$ (diamond marker, Figure 4). At plane A ($z/D_{out}=0.4$), the measured peak swirl intensity ($\bar{S}I_{peak,exp}$) was 14.7° while the EVT model predicted extreme events $\bar{S}I_{m=10^6,EVT} = 16.2 \pm 1.0^\circ$ for 10^6 observations and a projected upper bound $U_{b,EVT} = 18.0 \pm 0.1^\circ$ (Figure 4). Therefore, the EVT predicts that for $m = 10^6$ observations, the $\bar{S}I_{m=10^6,EVT}$ could be up to 2.5° greater than the experimental observations. To put these values into a context, previous work showed that the increase of SI of 5° could produce a 5% loss in compressor pressure ratio [30] and that it could reduce the surge margin of a transonic axial compressor by up to 5% [31].

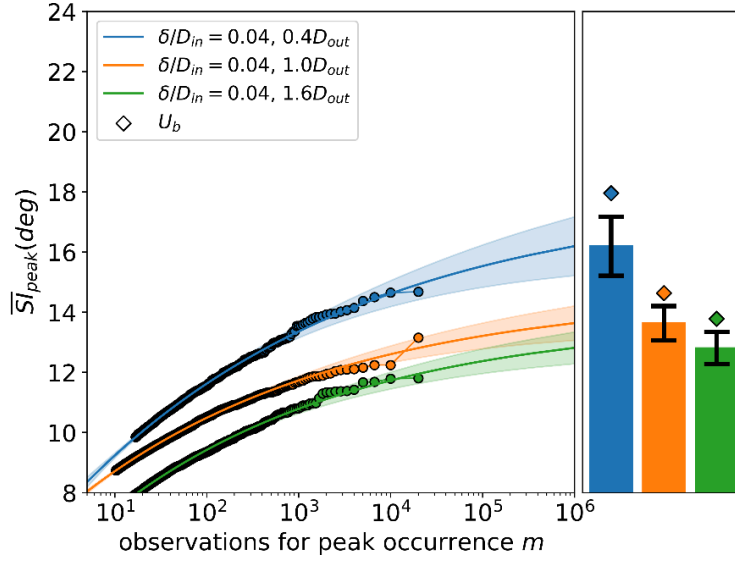


Figure 4: EVT models of the area-averaged Swirl Intensity at location planes A, B, C downstream of the S-duct intake.

Baseline inlet conditions ($\delta/D_{in} = 0.04$)			
	Plane A $z/D_{out} = 0.4$	Plane B $z/D_{out} = 1.0$	Plane C $z/D_{out} = 1.6$
$\bar{S}I_{m=10^6,EVT} (^\circ)$	16.2 ± 1.0	13.6 ± 0.6	12.8 ± 0.5
$U_{b,EVT} (^\circ)$	18.0	14.6	13.8
$\bar{S}I_{peak,exp} (^\circ)$	14.7	13.2	11.8

Table 1: EVT prediction of the peak swirl intensity for 10^6 observations ($\bar{S}I_{m=10^6,EVT}$), projected upper bound ($U_{b,EVT}$), and experimental peak swirl intensity ($\bar{S}I_{peak,exp}$) for baseline inlet conditions ($\delta/D_{in} = 0.04$) at measurements planes A, C and D.

For the baseline inlet conditions ($\delta/D_{in} = 0.04$), both the EVT model ($\bar{S}I_{m=10^6,EVT}$ and $U_{b,EVT}$) and experimental observations ($\bar{S}I_{peak,exp}$) showed a decay of the peak values when z/D_{out} increased from 0.4 to 1.0 and 1.6 (from Plane A to Plane B and Plane C, Figure 5) However, by normalizing the values of swirl intensity against the values at $z/D_{out} = 0.4$, the EVT projections exhibited quadratic decay of $\bar{S}I_{m=10^6,EVT}$ and $U_{b,EVT}$, whereas the experimental observations ($\bar{S}I_{peak,exp}$) exhibited a linear decay as function of z/D_{out} (Figure 5 and Table 2). Thus, the upper bound of the extreme events ($U_{b,EVT}$) show a much more pronounced initial decay from 16.2 ± 1.0 to 13.6 ± 0.6 and 12.8 ± 0.5 at planes A, B and C, respectively relative to the decay of measured peak values ($\bar{S}I_{peak,exp}$).

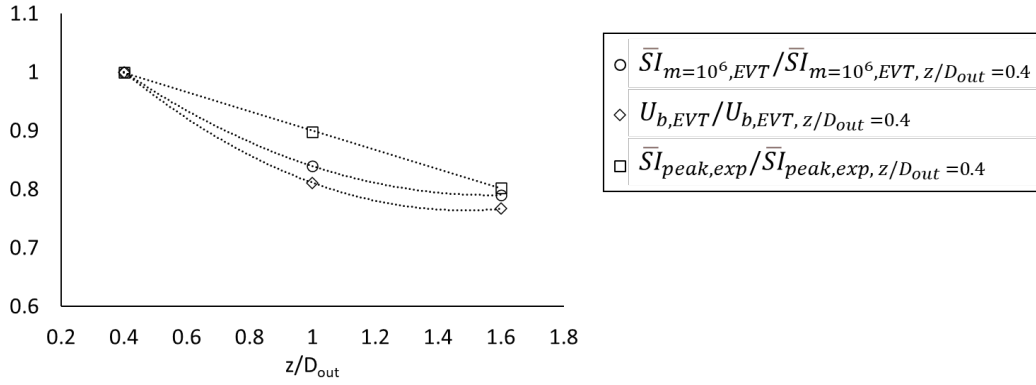


Figure 5: Decay of the peak swirl intensity for 10^6 observations ($\bar{S}I_{m=10^6,EVT}$), projected upper bound (U_b), and experimental peak swirl intensity ($\bar{S}I_{peak,exp}$) for baseline inlet conditions ($\delta/D_{in} = 0.04$) at measurements planes A, B and C.

$Y = a(z/D_{out})^2 + b(z/D_{out}) + c$				
Y	a	b	c	R ²
$\bar{S}I_{m=10^6,EVT}$ (°)	0.154	-0.484	1.169	1.000
$U_{b,EVT}$ (°)	0.201	0.596	1.206	1.000
$\bar{S}I_{peak,exp}$ (°)	0	-0.164	1.064	0.999

Table 2: Fitting coefficients and R-squared values for the decay for peak swirl intensity for 10^6 observations ($\bar{S}I_{m=10^6,EVT}$), projected upper bound (U_b), and experimental peak swirl intensity ($\bar{S}I_{peak,exp}$) for baseline inlet conditions ($\delta/D_{in} = 0.04$) at measurements planes A, B and C.

3.2 Flow distortion development with inlet total pressure profiles

3.2.1 Time-averaged and unsteady distortion analysis

In a recent study, the presence of thick inlet total pressure profiles ($\delta/D_{in} = 0.332$) at the S-duct inlet plane provoked a notable increase of the measured peak swirl intensity ($\bar{S}I_{peak,exp}$) and the level of flow unsteadiness ($std(\alpha)$) at the AIP [9]. Thus, it is of interest to quantify the development of the flow distortion downstream the S-duct outlet plane under this condition where the intake ingests a relatively thick inlet boundary layer. In this configuration (Profile A, $\delta/D_{in} = 0.332$, at $\psi = 0^\circ$) the peak $\bar{S}I$ measured at plane A ($z/D_{out} = 0.4$) was $\bar{S}I_{peak,exp} = 18.1^\circ$, which is substantially higher than the peak $\bar{S}I$ measured with uniform inlet conditions ($\delta/D_{in} = 0.04$) where $\bar{S}I_{peak,exp} = 14.7^\circ$. For profile A ($\delta/D_{in} = 0.332$) at $\psi = 0^\circ$ and relative to plane A ($z/D_{out} = 0.4$), the measured peak $\bar{S}I$ reduces down to 16.1° and 13.3° at $z/D_{out} = 1.0$ and 1.6 respectively (Planes B and C, Figure 6). Similar to the case in which the S-duct inlet was uniform ($\delta/D_{in} = 0.04$), the measured swirl intensity ($\bar{S}I_{peak,exp}$) decays at increasing distance from the S-duct outlet plane.

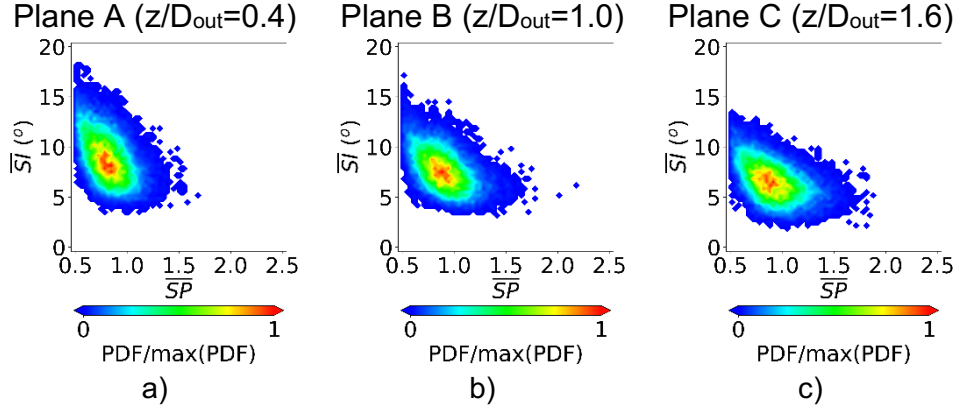


Figure 6: Area-averaged SI-SP j-PDF maps at the AIP for inlet Profile A ($\delta/D_{in} = 0.332$) at $\psi = 0^\circ$ at locations downstream the S-duct outlet plane.

3.2.2 Extreme swirl distortion projections for inlet total pressure profiles configurations

The application of EVT with the baseline inlet conditions ($\delta/D_{in} = 0.04$) showed a monotonic decay of the peak swirl intensity ($\bar{S}I_{m=10^6,EVT}$) as a function of z/D_{out} (Figure 4). Indeed, for the baseline inlet configuration ($\delta/D_{in} = 0.04$), the EVT model predicts a monotonic decay of the swirl intensity upper bound ($U_{b,EVT}$) which reduces as the distance from the S-duct exit planes increases from $z/D_{out} = 0.4$ to 1.6. This is aligned with the measured $\bar{S}I_{peak,exp}$ (Figure 7). Initially, the distortion was also expected to decay for the configuration with the thicker inlet Profile A ($\delta/D_{in} = 0.332$, $\psi = 0^\circ$). Indeed, a decay of the measured peak swirl intensity ($\bar{S}I_{peak,exp}$) was observed and this reduced linearly from 18.1° to 16.1° and 13.3° for the measurement planes at $z/D_{out} = 0.4$, 1.0, and 1.6 respectively (Planes A, B and C, Figure 7). However, a comparison between the maximum levels of measured distortion measured ($\bar{S}I_{peak,exp}$) with the upper bounds predicted by the EVT model ($U_{b,EVT}$) showed that the decay is non-monotonic for Profile A ($\delta/D_{in} = 0.332$, $\psi = 0^\circ$) (Figure 7). The upper bound of the EVT projections $U_{b,EVT}$ increases notably from 21.4° to 29.1° ($z/D_{out} = 0.4$ and 1.0 respectively) and then decays further downstream to 15.0° at $z/D_{out} = 1.6$ (Figure 7).

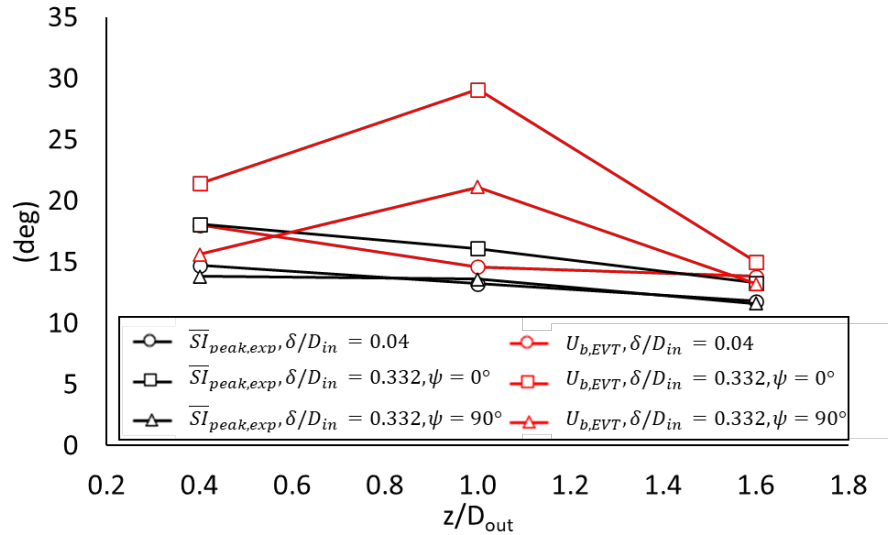


Figure 7: Comparison between maximum levels of distortion of the experimental measurements and EVT predictions for various configurations and locations downstream the S-duct outlet plane.

The growth of the projected peak swirl intensity values ($\bar{S}I_{m=10^6,EVT}$ and $U_{b,EVT}$) at $z/D_{out} = 1.0$ is highlighted also in the EVT models. The growth rate of the peak swirl intensity ($\bar{S}I_{m=10^6,EVT}$) at plane B ($z/D_{out} = 1.0$) for an increasing number of observations (Figure 8) is much higher than the one at plane A ($z/D_{out} = 0.4$) and consequently, the projected upper bound U_b increases notably from 21.4° to 29.1° ($z/D_{out} = 0.4$ and 1.0 respectively, Table 3).

In another test configuration, the inlet total pressure profile ($\delta/D_{in} = 0.332$) was oriented at $\psi = 90^\circ$ to represent the operation of the intake under angles of side slip. The characteristic growth of $\bar{S}I_{m=10^6,EVT}$ at $z/D_{out} = 1.0$ relative to $z/D_{out} = 1.0$ noticed for Profile A ($\delta/D_{in} = 0.332$) oriented at $\psi = 0^\circ$ was observed also for Profile A ($\delta/D_{in} = 0.332$) oriented at $\psi = 90^\circ$. In the latter, the experimental peak swirl angle ($\bar{S}I_{peak,exp}$) decreased monotonically from 13.8° , to 13.6° and 11.6° as function of $z/D_{out} = 0.4$, 1.0 and 1.6 , respectively (Figure 7). However, the EVT predictions showed that the peak swirl intensity ($\bar{S}I_{m=10^6,EVT}$) increased from $14.8 \pm 0.5^\circ$ to $15.2 \pm 1.2^\circ$ from of $z/D_{out} = 0.4$ (Plane A) to 1.0 (plane B) respectively, whereas it decayed to $12.4 \pm 0.5^\circ$ further downstream at $z/D_{out} = 1.6$ (Plane C, Figure 9 and Table 3). Thus, in summary, for the configurations with inlet total pressure Profile A ($\delta/D_{in} = 0.332$) oriented at either $\psi = 0^\circ$ and 90° , the EVT model predicts an increase of up to 8° in $U_{b,EVT}$ between plane A and plane B ($z/D_{out} = 0.4$ and 1.0 respectively, Figure 7) which is not captured with the assessment of the experimental values ($\bar{S}I_{peak,exp}$), which instead reduce monotonically from $z/D_{out} = 0.4$ to 1.0 .

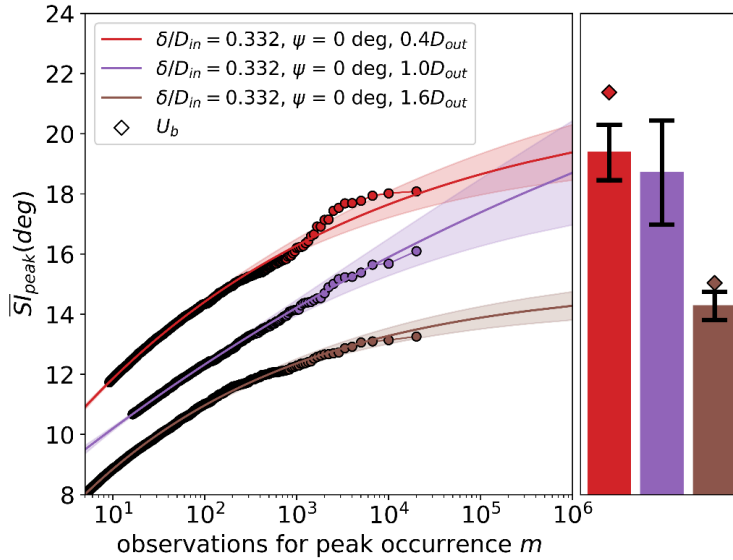


Figure 8: EVT models of the area-averaged swirl intensity ($\bar{S}I_{m=10^6,EVT}$) at location planes A, B, C downstream of the S-duct intake for inlet Profile A ($\delta/D_{in} = 0.332$, $\psi = 0^\circ$).

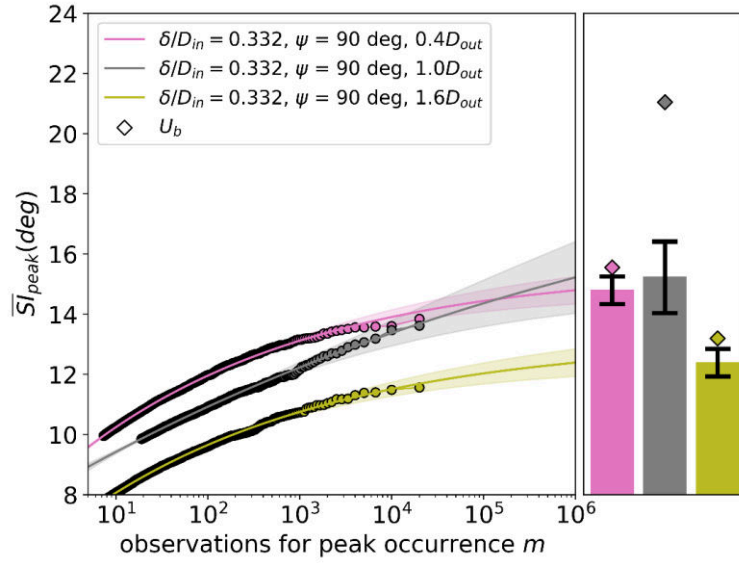


Figure 9: EVT models of the area-averaged Swirl Intensity at location planes A, B, C downstream of the S-duct intake for inlet Profile A ($\delta/D_{in} = 0.332$, $\psi = 90^\circ$).

	Inlet Profile A $\delta/D_{in} = 0.332$, $\psi = 0^\circ$			Inlet Profile A $\delta/D_{in} = 0.332$, $\psi = 90^\circ$		
	Plane A $z/D_{out} = 0.4$	Plane B $z/D_{out} = 1.0$	Plane C $z/D_{out} = 1.6$	Plane A $z/D_{out} = 0.4$	Plane B $z/D_{out} = 1.0$	Plane C $z/D_{out} = 1.6$
$\bar{S}I_{m=10^6,EVT} (^\circ)$	19.4 ± 0.9	18.7 ± 1.7	14.3 ± 0.5	14.8 ± 0.5	15.2 ± 1.2	12.4 ± 0.5
$U_{b,EVT} (^\circ)$	21.4	29.1	15.0	15.6	21.1	13.2
$\bar{S}I_{peak,exp} (^\circ)$	18.1	16.1	13.3	13.8	13.6	11.6

Table 3: EVT prediction of the $\bar{S}I_{peak,exp}$, projected upper bound $U_{b,EVT}$, and experimental $\bar{S}I_{peak,exp}$ for inlet Profile A ($\delta/D_{in} = 0.332$) at $\psi = 0^\circ$ and 90° at measurements planes A, B, and C.

The development of the peak swirl intensity ($\bar{S}I_{m=10^6,EVT}$) and upper bounds ($U_{b,EVT}$) for the Profile A ($\delta/D_{in} = 0.332$, $\psi = 0$ and 90°) configuration is believed to be associated with changes in the characteristics of S-duct bend flow separation and associated local levels of flow unsteadiness. While for the baseline inlet configuration ($\delta/D_{in} = 0.04$) the unsteadiness associated with the streamwise velocity stays approximately constant from $z/D_{out} = 0.4$ to 1.0 (Figure 10a, b), for the Profile A ($\delta/D_{in} = 0.332$) configuration the streamwise unsteadiness increases (Figure 10a, b). This is notable especially in the region of the high-momentum flow, and near the top boundary of the duct section (Figure 10b). Therefore, for the relatively thick inlet total pressure profile (Profile A, $\delta/D_{in} = 0.332$), it is postulated that the separation of the second S-duct bend results in an increase in the local levels of unsteadiness and therefore an increase in the projected $\bar{S}I_{m=10^6,EVT}$ and $U_{b,EVT}$. The levels of unsteadiness then subsequently reduce again at $z/D_{out} = 1.6$ and overall, the EVT signatures have an associated non-monotonic distribution of $\bar{S}I_{m=10^6,EVT}$ and $U_{b,EVT}$ as a function of z/D_{out} .

In summary, this work outlines two important considerations. Firstly, that the identification of the greatest level of flow distortion cannot rely exclusively on the assessment of the maximum value of measured distortion. Although a longer experimental testing time is needed to verify the predictions of the statistical model, the EVT method projected sharp growth rates of the peak distortion levels beyond the experimental observations for configurations in which the measured peak distortion was relatively modest. The maximum levels of EVT predicted distortion depends on the growth rate of the peak distortion events and thus this demonstrates the importance of including a statistical analysis method to also evaluate the growth of the extreme events in addition to the measured peak distortion. Secondly, the development of the flow distortion downstream of the S-duct intake clearly depends on

the inherent aerodynamics of the S-duct intake but it is also very sensitive to the inlet conditions. The configurations with non-uniform inlets showed increased flow unsteadiness at the location of the second S-duct separation which are believed to cause a sharper growth of the extreme distortion values and thus these are likely be most challenging operating conditions for the coupled engine. In these cases, and perhaps contrary to initial expectations, the EVT predicted levels of peak distortion do not decay monotonically with distance downstream of the S-duct exit.

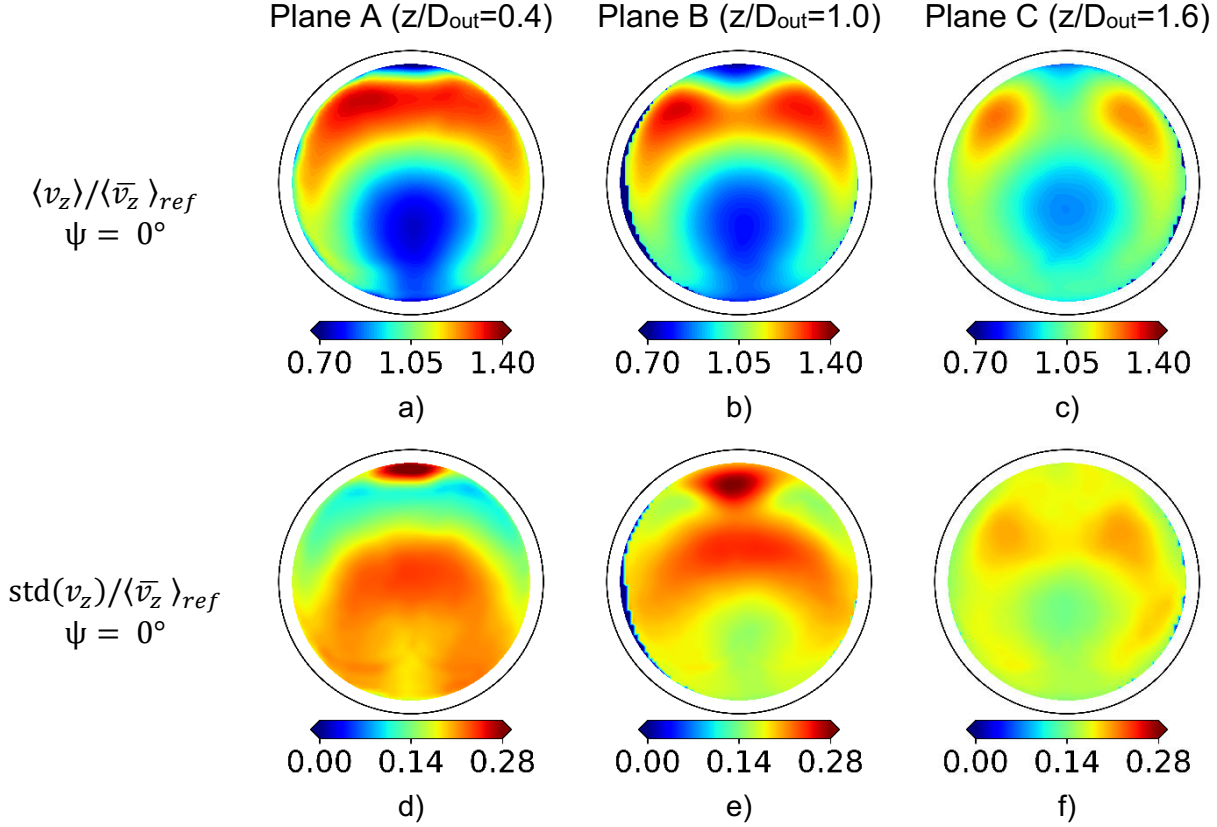


Figure 10: Time-averaged streamwise velocity and streamwise velocity unsteadiness for inlet Profile A ($\delta/D_{in} = 0.332$) at $\psi = 0^\circ$ at locations downstream the S-duct outlet plane.

4. Conclusions

Previous work by McLelland et al. [9] and Migliorini et al. [10] showed that non-uniform inlet conditions substantially alter the inherent flow distortion of S-duct intakes. This work evaluated the development of the flow distortion downstream of the S-duct outlet plane with non-uniform inlet conditions. Although a decay of the flow distortion was observed downstream of the S-duct outlet plane under uniform inlet conditions, the presence of non-uniform conditions at the S-duct inlet plane modified the inherent distortion characteristics and generates more severe unsteady flow distortion at the Aerodynamic Interface Plane (AIP). It is demonstrated that in some cases the streamwise decay of the flow distortion is not monotonic downstream of the S-duct but instead it may be linked with the local increase of unsteadiness levels caused by the second S-duct separation. The modelling of extreme events showed that the growth rate of the extreme distortion events was relatively pronounced in some locations downstream the S-duct outlet plane and in some cases, under non-uniform inlet conditions, these peak distortion levels were higher relative to the levels of distortion recorded in the proximity of the S-duct outlet plane. Thus, this highlights the importance of using a statistical method to assess the extreme distortion levels for the intake-engine integration.

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A study on the development of the flow distortion downstream of an s-duct intake

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