

# Characterization of unsteady distortion events for S-duct intakes under non-uniform inlet conditions

Matteo Migliorini<sup>1</sup>, Pavlos K. Zachos<sup>2</sup>, and David G. MacManus<sup>3</sup>  
*Cranfield University, Centre for Propulsion and Thermal Power Engineering, Cranfield,  
Bedfordshire, MK43 0AL, UK*

The use of convoluted intakes is expected to grow in novel aircraft configurations as designers seek to integrate more closely the propulsion system with the airframe. Previous research highlighted considerable unsteady flow distortions for S-duct configurations. However, most of the work was limited to the types of flow distortion inherently generated within the duct which reflects a relatively narrow range of aerodynamic conditions. In addition, the conditions of the flow distortion approaching the propulsion system is still not well understood due to the lack of experimental data and methods for unsteady distortion analysis. Recently, a novel analysis method was developed to consider the unsteady flow distortion from the perspective of an envisaged rotor blade through the exploitation of measurements with high-bandwidth Particle Image Velocimetry. In this study, and with this method, the aim is to provide a more advanced classification of unsteady distortion events based on the distribution of incidence on the envisaged rotor blades. This work can provide guidelines for methods to evaluate peak distortion levels under different inlet configurations for intake-engine integration assessments.

## I. Nomenclature

|           |                                    |
|-----------|------------------------------------|
| AIP       | = aerodynamic interface plane      |
| $c$       | = chord, mm                        |
| $D_{in}$  | = S-duct inlet plane diameter, mm  |
| $D_{out}$ | = S-duct outlet plane diameter, mm |
| EVT       | = Extreme Value Theory             |
| $f_s$     | = HB-PIV acquisition frequency, Hz |
| $H$       | = S-duct vertical offset           |
| $i$       | = incidence angle, °               |
| $L$       | = S-duct length                    |
| $M$       | = Mach number                      |
| $r$       | = radial coordinate, m             |
| $r_e$     | = radial extent, m                 |
| $R_b$     | = rotor blade span, m              |
| $R_{in}$  | = S-duct inlet plane radius, m     |
| Re        | = Reynolds number                  |
| SI        | = Swirl Intensity (SAE), °         |

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<sup>1</sup> Research Fellow.

<sup>2</sup> Senior Lecturer, AIAA Member.

<sup>3</sup> Professor, AIAA Member.

|                 |                                                                                   |
|-----------------|-----------------------------------------------------------------------------------|
| $std$           | = standard deviation                                                              |
| $t$             | = time, ms                                                                        |
| $t_{bp}$        | = blade passing time, ms                                                          |
| $u$             | = rotational speed of the rotor, m/s                                              |
| $U_b$           | = upper bound of the EVT model, °                                                 |
| $v$             | = absolute velocity component, m/s                                                |
| $w$             | = relative velocity component, m/s                                                |
| $x$             | = horizontal coordinate                                                           |
| $y$             | = vertical coordinate                                                             |
| $z$             | = streamwise coordinate                                                           |
| $\alpha$        | = absolute swirl angle, °, $\tan^{-1}(v_\theta/v_z)$                              |
| $\beta$         | = relative flow angle, °                                                          |
| $\beta_{metal}$ | = rotor inlet metal angle, °                                                      |
| $\Gamma$        | = vortex circulation, m/s <sup>2</sup>                                            |
| $\Gamma^*$      | = normalized vortex circulation, $\Gamma/(\langle \overline{v_z} \rangle D_{in})$ |
| $\delta$        | = boundary layer thickness, mm                                                    |
| $\theta_b$      | = angular position of the blade, °                                                |
| $\psi$          | = azimuthal orientation of the inlet boundary layer, °                            |
| $\omega$        | = angular speed of the rotor, rad/s                                               |

#### Operators

|                   |                |
|-------------------|----------------|
| $\langle \rangle$ | = time average |
| $-$               | = area average |

## II. Introduction

In the past decade there has been an increasing interest in closely-coupled propulsion systems as these are expected to provide benefits in reduced drag, emissions and noise [1–3]. However, the engine-airframe integration poses several challenges to the product development as these propulsion systems may be exposed to increased levels of unsteady flow distortion due to the proximity of the engine intake to the aerodynamic surfaces and the interaction of the inlet flow with the potentially convoluted geometry of the air induction system [4–6]. Thus, there is a need to de-risk the aerodynamic integration of these novel configurations by upgrading current distortion measurement and analysis capabilities to offer richer datasets in both space and time in relation to current practices. Non-intrusive, laser-based velocimetry methods, such as stereoscopic particle image velocimetry (S-PIV) were previously used for the measurement of unsteady flow distortion, while novel data analysis methods looking into the interaction effects between the intake and a propulsion system were also put in place using the unsteady velocity data [7].

Recently, a new technique to evaluate the unsteady flow distortion in the relative frame of reference of a notional compressor system was introduced [8]. The exploitation of the high temporal and spatial resolution of the unsteady 3D velocities measured with high-bandwidth Particle Image Velocimetry [9–11] enabled the classification of distortion events based on the magnitude, on the duration relative to the blade rotation, and the relative probability. This method accounts for synchronous spatial and temporal non-uniformities due to the unsteady flow field as well as the relative position and exposure of a set of notional rotor blades located at a given position downstream of the measurement plane [8]. The velocity maps measured at the aerodynamic interface plane were converted into the relative frame of reference of a representative transonic compressor fan (NASA Rotor 67). The rotor geometry and operating point was scaled to match the rig exit diameter and the rotational speed was adjusted to maintain a constant flow coefficient between the baseline and the notional scaled down configuration for a mid-span position. Finally, the analysis considered distortion events by means of variations of the incidence angle ( $\Delta i$ ) with reference to the nominal R67 incidence at peak efficiency. A more thorough explanation of this methodology is reported in Migliorini et. al. [8].

This notional construct allows the correlation of the unsteady distortion events with metrics that are pertinent to compressor stability assessments. A review of the state of the art on the engine response to inlet flow distortion has been included in recent work by Doll et. al [7]. Typically, disturbances extending across 4 to 5 blades may adversely affect the stability limit of the compression system [12]. Similarly, in the context of spike-type stall inception,

experiments by Wenzel and Blaba [13] and Silkowski [14] indicated that compressors respond to disturbances of short length scales as these can potentially trigger inception of stall cells. The application of this analysis method in the relative frame of reference has demonstrated a great value to discern which inlet conditions are more likely to generate unsteady events that could adversely affect the compressor stability. However, Migliorini et. al. [8] focused on the signature of the incidence angle fluctuations at only discrete radial locations. Nevertheless, it was shown that distortion events affected the full blade span and, consequently, the distribution of the incidence perturbation on the blade could generate a synchronous positive or negative change of incidence across the full blade or instead, it could generate distortions with positive incidence perturbation at the root while negative at the tip of the blade. As shown by Giuliani and Chen [15], these conditions represent a non-uniform blade loading blade-to-tip, which can have a notable impact on the blade aeromechanics and the potential to trigger dynamic stall [15]. Thus, arguably, non-uniform hub-tip blade loading is a condition which can more likely cause instabilities [16].

It is of interest and within the scope of this work, therefore, to evaluate which unsteady flow distortion events are more likely to cause instabilities and stall inception within the population of peak distortion events. This study will encompass a range of inlet conditions including the ingestion of boundary-layer type pressure profiles, conditions representative of the operation of the intake at cross-wind, and vortex ingestion at different inlet locations. The main scope of the work is to classify the various types of unsteady distortion from the perspective of the rotating turbomachinery and link them with engine stability metrics for a range of non-uniform flow profiles at the inlet of the convoluted diffuser. These considerations are believed to be key in producing a taxonomy of the various distortion levels based on their likelihood to cause instabilities at the propulsion system.

### III. Experimental setup and methods

#### A. Experimental facility and S-duct configuration

The S-duct configuration used in this study was previously investigated by Zachos et al. [17]. The test rig layout is shown in Fig. 1 and in the direction of the flow it includes a seeding chamber, a flow conditioning section, a honeycomb screen station, a tubular duct of constant inlet diameter, and the S-duct intake. The geometrical characteristics of the S-duct are reported in Fig. 1. This S-duct geometry was thoroughly investigated with experimental and computational studies [18,19], which include evaluation of steady and unsteady total pressure distortion [20], swirl distortion [9], sensitivity to inlet Mach number [17], as well as the effectiveness of passive and active flow control methods [21], and, more recently, the operation under non-uniform inlet conditions [11]. Downstream of the intake, a constant area duct provides optical access for measurements at the Aerodynamic Interface Plane (AIP), and a diffuser duct drives the flow to the suction fan (Fig. 1). The operating point of the rig is set by the velocity of the flow measured in the section upstream the S-duct, at  $1.45D_{in}$  upstream of the S-duct entry plane. For the current work, the reference Mach number was  $M_{ref} = 0.27$  and the reference Reynolds number based on the inlet diameter was  $Re_D = 7.38 \times 10^5$ .

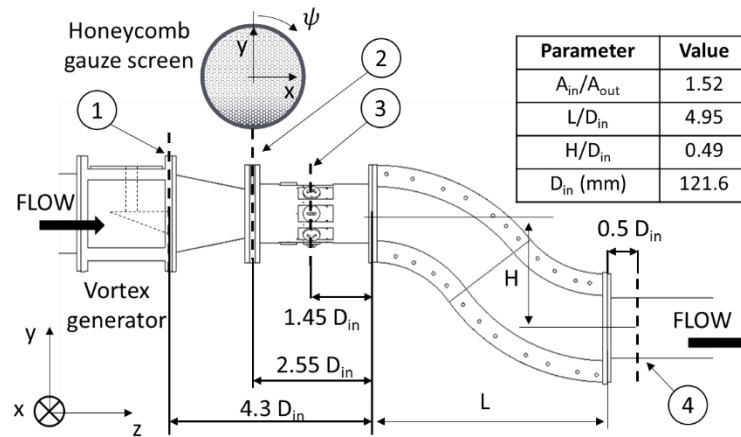


**Fig. 1: Cranfield test facility schematic: 1- Trailing edge of the vortex generator, 2- Position of the honeycomb gauze screen, 3- PIV measurement plane at S-duct inlet, 4- PIV measurement plane at S-duct AIP [11].**

## B. Inlet vortex generation system

Vortices at the inlet of the S-duct were generated with a semi-span delta wing [22,23] which was positioned  $4.3D_{in}$  upstream of the S-duct inlet plane (about 3.35 chords). The setup has been reported in Migliorini et. al. [11] and for brevity it is summarized in Fig. 2. The vortex size and circulation has been controlled by changing the angle of attack (AoA) (Fig. 2). Previous research demonstrated that  $AoA = -12^\circ$  generates a vortex whose strength can alter the flow distortion characteristics at a noticeable level [11], thus this setup has been considered in the current study. Given the negative incidence of the delta wing with reference to the incoming flow, the vortex rotates anti-clockwise when viewed from downstream. The delta wing was also translated along the vertical (y) and lateral (x) axes to assess the influence of the vortex position on the AIP flow distortion.

The vortex characteristics have been assessed with High-Bandwidth Particle Image Velocimetry (HB-PIV) at the S-duct inlet plane (Fig. 1). The vortex core size, core radius [24], were identified with the vorticity disk method [25]. The vortex position was assessed with a conditional average of the vortex over 10,000 HB-PIV snapshots. Only the negative vorticity was considered to compute the vortex circulation to focus on the vorticity generated by the delta wing only. A domain of  $r/D_{in} = 0.20$  and a resolution of  $0.12 r_{core}$  was sufficient to capture 98% of the total vortex circulation. The measured vortex characteristics for the different inlet positions are reported in Table 1.

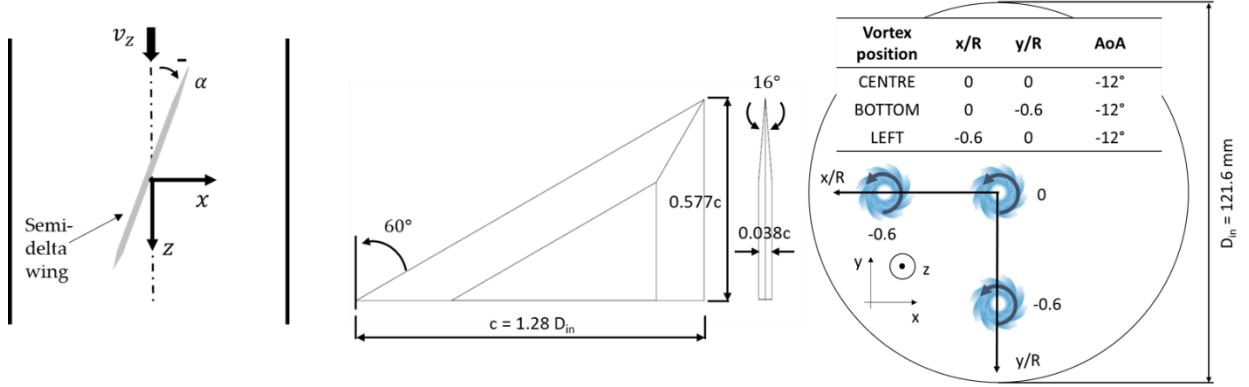


Fig. 2: Semi-span delta wing dimensions and definition of the angle of attack (AoA) relative to the incoming flow (top view) [11].

| x/R   | y/R   | AoA  | $r_{core}/D_{in}$ | $\Gamma_0/(\langle v_z \rangle D_{in})$ |
|-------|-------|------|-------------------|-----------------------------------------|
| 0.04  | 0.00  | -12° | 0.04              | -0.151                                  |
| 0.12  | -0.65 | -12° | 0.04              | -0.158                                  |
| -0.54 | -0.05 | -12° | 0.04              | -0.184                                  |

Table 1: Measured inlet vortex characteristics at  $1.45 D_{in}$  upstream the S-duct intake [11].

## C. Inlet total pressure profiles

For the generation of non-uniform total pressure profiles at the inlet of the S-duct, distortion gauzes were placed at station 3 (Fig. 1),  $2.55D_{in}$  upstream the S-duct entry plane. A honeycomb screen [26] was used to produce a boundary layer-type total pressure profile [27], with a thickness of  $\delta/D_{in} = 0.332$  (Profile A) [15] and  $Re_\delta = 6.3 \times 10^4$ , which is thicker than the nominal profile with  $\delta/D_{in} = 0.04$  and  $Re_\delta = 4.6 \times 10^3$ . Profile A is representative of a full scale Blended Wing Body (BWB) aircraft, which is expected to have a boundary layer near the wing-body trailing edge of about  $\delta/D_{in} = 0.30$  [28]. An additional total pressure profile (Profile B) with  $\delta/D_{in} = 0.572$  was also included in this study to simulate the approaching conditions of a thick boundary layer under higher angles of attack. The baseline configuration of the profiles presented the main total pressure loss region in the lower part of the inlet. These could also rotate azimuthally by  $\psi = 90^\circ$  to simulate an operating condition of the intake at angles of pitch, yaw or cross-wind [10].

#### D. HB-PIV experimental setup

High-bandwidth PIV measurements were performed at the Aerodynamic Interface Plane (AIP) located  $0.5 D_{in}$  downstream of the S-duct exit plane (Fig. 1). A dual cavity pulsed Nd:YAG laser was used to illuminate the cross-flow plane. Di-Ethyl-Hexyl Sebacate particles, with an average diameter of approximately  $1 \mu m$ , were used to seed the flow. PIV images were recorded by a pair of CMOS cameras in a stereo arrangement. The cameras' sensor resolution was  $1280 \times 800 \text{ px}^2$  (1MP) with a maximum straddle frame rate of 16,600 fps. The acquisition frequency of the velocity flow fields was 4 kHz, which is 10 times greater than the expected dominant flow frequency of around  $St = 1.0$  [9]. Each HB-PIV dataset consists of 20,000 instantaneous velocity snapshots, which is sufficient for the convergence of the out-of-plane velocity component and the standard deviation to 0.2% and 0.4% respectively [9]. The acquired 3-component velocity maps had a spatial resolution of  $0.0153 D_{out}$  ( $2.3 \text{ mm}^2$ ) across the AIP. Only the data within  $r < 0.95 R_{AIP}$  is used in the current analysis, to ensure that no spurious vectors near the domain boundaries caused by laser light reflections influence the outcomes. This results in a total of approximately 2,900 3-component velocity vectors across the AIP, which is notably richer than a conventional flow distortion measurement system that would usually provide 40 total pressure measurements across the plane [29]. A disparity correction reduced the bias errors due to misalignment between the laser light and the calibration plate. The estimated uncertainty on the velocity components was 3.3% of the area-averaged, time-averaged out-of-plane velocity at the AIP based on the method outlined by Raffel et al. [30].

#### E. Unsteady swirl distortion in the relative frame of reference

The majority of the past work on canonical test cases such as S-ducts with circular cross sections evaluated the steady and unsteady distortion in an absolute frame of reference and the related industry standard metrics including total pressure and swirl distortion descriptors are also based on an absolute frame of reference [31,32]. However, high bandwidth PIV measurements can provide data with much richer spatial and time resolution, and this opens the route to more advanced distortion analysis methods. Recently, Migliorini et. al. [8] introduced a novel method to evaluate the distortion in the relative frame of reference of compressor blades. This represents a notable step forward for the dynamic distortion characterization, as suggesting that the characteristic signature of the flow distortion perceived by the propulsion system would also depend on the rotational speed of the blades through the unsteady distorted flow field. This variation is not typically evaluated with pressure probes as it is difficult to integrate the sensors into the rotating machinery, and similarly, arrays of unsteady pressure probes in a stationary frame have insufficient spatial resolution for this assessment.

Migliorini et. al. [8] considered a notional NASA fan rotor (Rotor 67 [33]) to convert the PIV velocity maps into the relative frame of reference of the fan to quantify the unsteady characteristics in terms of the incidence angle. Velocity triangles are illustrated in Fig. 3, where the nominal operating conditions of the compressor with clean inlet flow with no swirl are represented by the dashed vectors and a set of velocities  $v_{nom}$ ,  $u$  and  $w_{nom}$ . Due to the swirl distortion ( $\alpha$ ) and unsteady conditions generated by the S-duct intake, variations in the relative velocity  $w_{\theta}'$  and axial velocity  $v_z'$  are introduced. The effect of unsteady distortion on the blades can be evaluated with the perturbation on the incident angle due to the local swirl distortion versus the nominal incidence, defined by:

$$\Delta i = i' - i_{nom}$$

where  $i_{nom}$  is the incidence angle on the rotor blades for nominal inlet conditions and  $i'$  is the incidence angle for the S-duct inlet flow configuration, defined as:

$$i_{nom} = \beta_{nom} - \beta_{metal}$$

$$i' = \beta' - \beta_{metal}$$

where  $\beta_{nom}$  is the relative flow angle in nominal conditions,  $\beta'$  the relative flow angle under S-duct flow distortion and  $\beta_{metal}$  is the metal angle of the compressor blade. A more detailed explanation is included in [8].

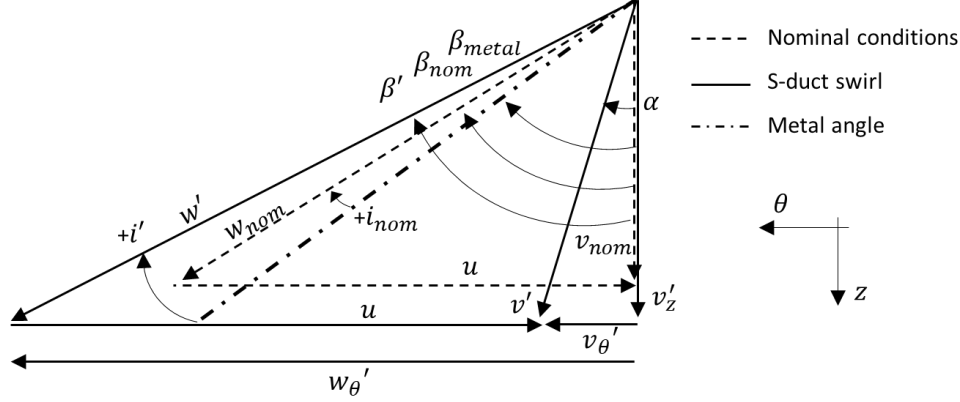


**Fig. 3: Velocity triangles at the rotor leading edge for nominal conditions (dashed line) and in case of swirl distortion (continuous line).**

The unsteady distortion in the relative frame of reference was also coupled with the envisaged rotation of compressor blades in the distorted domain [8]. Indeed, although the flow distortion is characterized by temporal and spatial variations across a range of frequencies, the fluctuation of incidence is also a function of the position of the compressor blade which is rotating in the unsteady distorted domain. Hence, the flow distortion perceived of the blade depend on the nominal starting position, its rotation of the distorted domain and the temporal and spatial variation of the distorted domain. In the proposed method [8], the unsteady high-bandwidth PIV measurements have been coupled with the envisaged rotation of the NASA R67 in the distorted field (Fig. 4). The unsteady distortion field has been sampled as a function of the starting position of the blade  $\theta_{b0}(t_0) = 0^\circ$  and the rotation of the blade  $\theta_{b0}(t_1)$  in the subsequent PIV timesteps ( $t_1 - t_0 = \Delta t_{PIV}$ ), described as:

$$\theta_{b0}(t_1) = \theta_{b0}(t_0) + \omega(t_1 - t_0) \sim 28.0 \text{ deg}$$

where  $\omega$  is the rotor angular speed in rad/s and the time between timesteps is dictated by the acquisition frequency of the PIV system ( $f_s = 4\text{kHz}$ ) and yields  $\Delta t_{PIV} = t_1 - t_0 = 1/f_s = 0.25 \text{ ms}$ . The time is then normalized by passing time of the rotor blades ( $t_{bp}$ ). In this method, additional steps have been also taken to improve the spatial sampling of the distorted domain and to eliminate the dependency of coupling the unsteady distorted field with an arbitrary starting position of the rotor blades. This was achieved with the sampling of the distortion field with all the 22 blades of the NASA R67 and the use of a set of different starting positions of the rotor. For brevity, the reader is referred to previous work for a more detailed explanation [8].

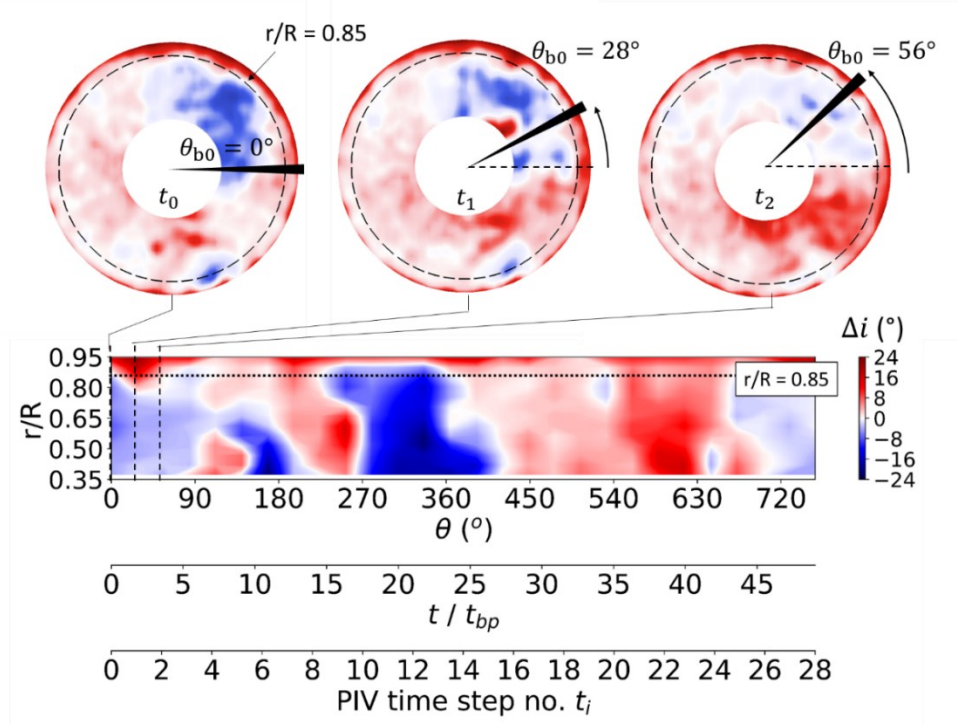


**Fig. 4: Time coupling between the HB-PIV dataset snapshots and the rotation of the compressor rotor [8].**

A key advantage of this assessment consists in the evaluation of the fluctuations of the incidence angle ( $\Delta i$ ) as it would be perceived by the rotating compressor blades, which are exposed to a unique signature of flow distortion which also varies spanwise (Fig. 4). Moreover, it enables the characterization of the flow distortion with metrics which are pertinent to assess the compressor stability. In the population of distortion events at a specific radial span, some extreme distortion fluctuations known as “peak distortion events” ( $\Delta i_{peak}$ ) could trigger separation on the blades that could lead to spike-type stall inception [34]. To identify these, previous work used the following condition:

$$\exists \Delta i_{peak} \leftrightarrow \Delta i_{peak} > \langle \Delta i \rangle_e + std(i')$$

Where  $\langle \Delta i \rangle_e$  is the mean incidence perturbation within the distortion event and  $std(i')$  is the standard deviation of the incidence fluctuation. When this condition is valid, each peak event is classified again by two quantities: the exposure time ( $t_e$ ) and the magnitude value (Fig. 5). In this case, the exposure time is defined as the time in which the change in incidence is above 50% peak height, while the magnitude value is the maximum incidence ( $\Delta i$ ) of the peak event.

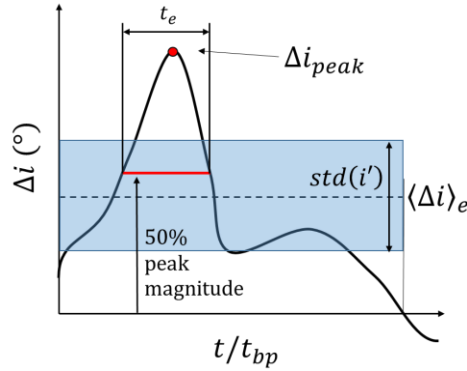


**Fig. 5: Definition of peak events that exceed mean value and one standard deviation of the unsteady distortion population [8].**

## IV. Results

### A. Flow distortion for uniform and non-uniform inlet conditions in the absolute and relative frame of reference

Recent work by the authors focused on the assessment of the impact of non-uniform inlet conditions onto the S-duct flow distortion in the absolute frame of reference. These studies included the ingestion of inlet total pressure profiles with variable thickness, and inlet vortices [10,11,8]. A synthesis of the results is presented in this section of the current paper to enable a comparative assessment of the flow distortion characteristic between absolute and relative frame of reference.

In the absolute frame of reference, and relative to uniform inlet conditions, the presence of inlet total pressure profiles had a stronger impact on the flow distortion compared to the ingestion of inlet vortices (Fig. 6). Inlet total pressure profiles caused an overall increase of swirl angle unsteadiness, whose maximum increased from approximately  $14.6^\circ$  to  $21.1^\circ$  with the thickest inlet total pressure profile ( $\delta/D_{in} = 0.572$ ,  $\psi = 0^\circ$ ) relative to uniform inlet conditions ( $\delta/D_{in} = 0.04$ ) (Fig. 6). Previous studies attributed this increase of unsteadiness to the augmentation of the secondary flows generated within the intake [10]. However, when the inlet total pressure profile was biased in one direction ( $\psi = 90^\circ$ , Fig. 1), a predominance of the bulk swirl topology was observed [11]. This lead to a more stable flow as opposed to the typical alternating bulk-twin swirl topology [9,35], and an overall reduction in swirl angle unsteadiness. For example, for the thickest inlet total pressure profile ( $\delta/D_{in} = 0.572$ ),  $std(\alpha)$  reduced from  $21.1^\circ$  to  $14.3^\circ$  when the profile orientation was changed from bottom dead centre ( $\psi = 0^\circ$ ) to starboard side ( $\psi = 90^\circ$ ) (Fig. 6). The configurations with inlet vortices at the inlet centre and left side produce only a minor change in the swirl angle unsteadiness whose maximum values were  $14.2^\circ$ ,  $13.2^\circ$ , respectively (Fig. 6). for the inlet vortex position at the and lower side of the S-duct inlet plane,. Instead, for the ingestion of the vortex at the inlet lower side, a considerable reduction of the maximum unsteadiness level down to  $11.6^\circ$  was observed (Fig. 6). It was deemed to be similar to the one caused by passive flow control devices which re-energize the low momentum flow and suppress the separation in convoluted intakes [11,21].

Previous work also monitored the maximum swirl intensity that was generated at the AIP for the various inlet configurations. This is key to evaluate the compatibility between S-duct intakes and propulsion systems, which often is dictated by the maximum level of distortion presented to the engine. The maximum values of swirl intensity were estimated with a statistical model, the Extreme Value Theory (EVT), which provided an estimate of the peak swirl intensity ( $\overline{SI}_{peak}$ ) for a number of observations ( $m = 10^6$ ) beyond than the experimental ones ( $m = 2 \times 10^4$ ) [11]. This model provided also a projected upper bound of the peak events ( $U_b$ ) and also a normalized growth rate of the peak distortion events relative to  $m = 10^1$  observations ( $\overline{SI}_{peak}/\overline{SI}_{peak,m=10^1}$ ) [11]. Among the tested configurations, the highest levels of swirl distortion ( $U_b$ ) were estimated for the configurations with the thick inlet total pressure profiles aligned at the inlet lower side ( $\delta/D_{in} = 0.332$  and  $\delta/D_{in} = 0.572$ ,  $\psi = 0^\circ$ , Fig. 7). Instead, the configurations with the inlet total pressure biased towards one side and with an inlet vortex produced upper bounds ( $U_b$ ) comparable or slightly lower than the uniform inlet conditions case ( $\delta/D_{in} = 0.04$ , Fig. 7). The growth rate of the peak swirl intensity between  $m = 10^1$  and  $10^6$  observations ( $\overline{SI}_{peak}/\overline{SI}_{peak,m=10^1}$ ) for baseline and different inlet configuration was comparable, with the exception of the inlet total pressure profiles biased to one side ( $\psi = 90^\circ$ , Fig. 7). In light of these considerations, it is inferred that inlet total pressure profiles aligned with the S-duct symmetry plane increase the levels of distortion presented to the engine and may represent a more challenging operating condition.

However, arguably, the analysis of the flow unsteadiness and peak distortion level enables only a partial assessment of the intake-engine compatibility. Although the SI parameter can be used in combination with other distortion descriptors to derive the sensitivity of the propulsion system to the inlet flow distortion and the influence on the surge margin, it is believed that the response of the engine is linked with the time of exposure of the compressor blades to the incoming distortion [12,36]. A possible way to address this is the analysis of the peak distortion in the relative frame of reference of the compressor rotor.

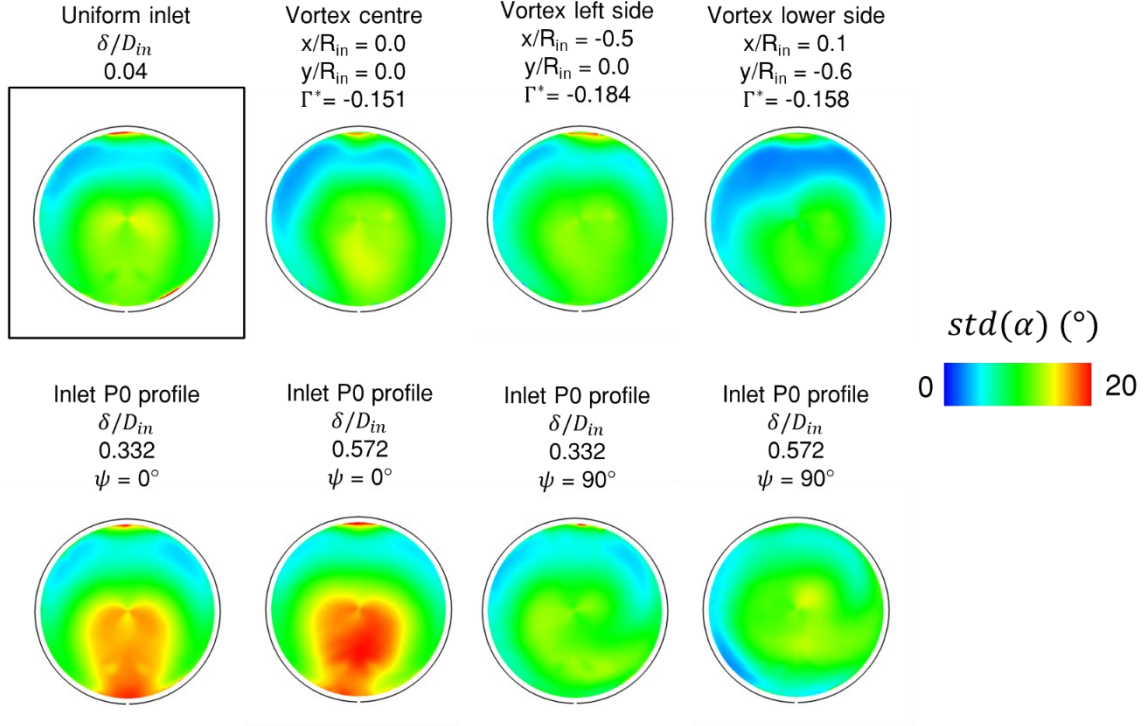


**Fig. 6: Swirl angle unsteadiness ( $\text{std}(\alpha)$ ) measured  $0.5D_{in}$  downstream of the S-duct intake under different inlet conditions [11].**

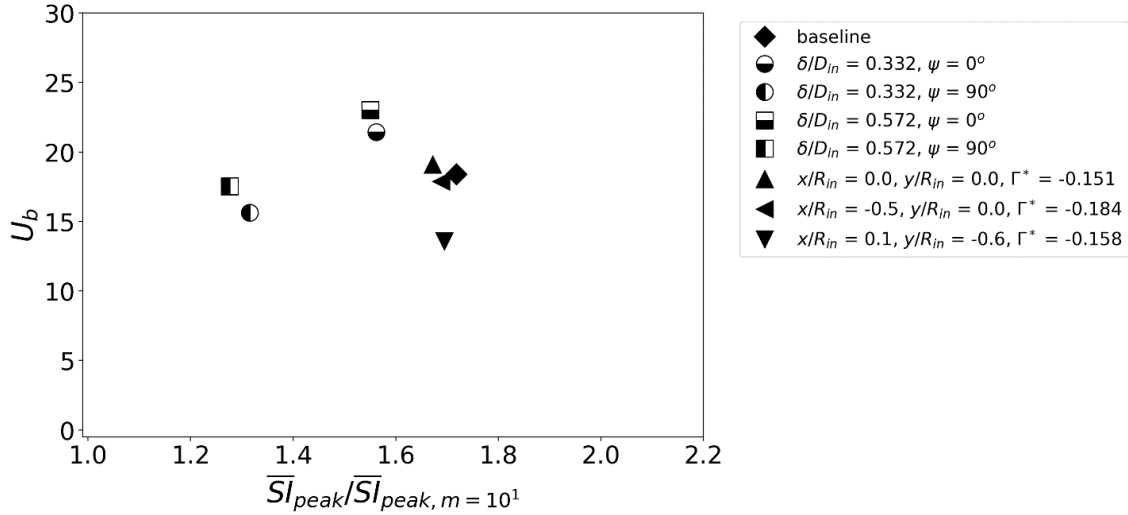


**Fig. 7: Comparison of the peak distortion levels based on the upper bound ( $U_b$ ) and growth rate ( $\overline{S_I}_{peak}/\overline{S_I}_{peak, m=10^1}$ ) of the extreme events modelled with EVT for different inlet configurations.**

### B. Characterization of the radial distribution of peak distortion events

Probability maps of the peak incidence fluctuations were obtained at discrete radial locations by sampling the blade span history at locations representative of the blade hub and tip ( $r/R = 0.51$  and  $0.85$ , respectively, Fig. 8) and this was used for a comparative assessment of the flow distortion for the different inlet conditions [8]. It was shown that thicker inlet total pressure profiles ( $\delta/D_{in} = 0.332$ ) were found to have a strong influence on the likelihood and

the magnitude of distortion events with long exposure sector, which are more likely to undermine the compressor stability [36]. However, this previous assessment [8] revealed that the probability distribution and the magnitude of the distortion events, and consequently the considerations on the effects on the engine stability, strongly depend on the radial position at which the change in incidence is evaluated. A noticeable tendency towards positive incidence perturbations was observed at the tip while at the hub the events were distributed more equally between positive and negative incidence (Fig. 8). The analysis of the radial distribution of these events has not been carried out yet and thus it is in the remit of the current work.

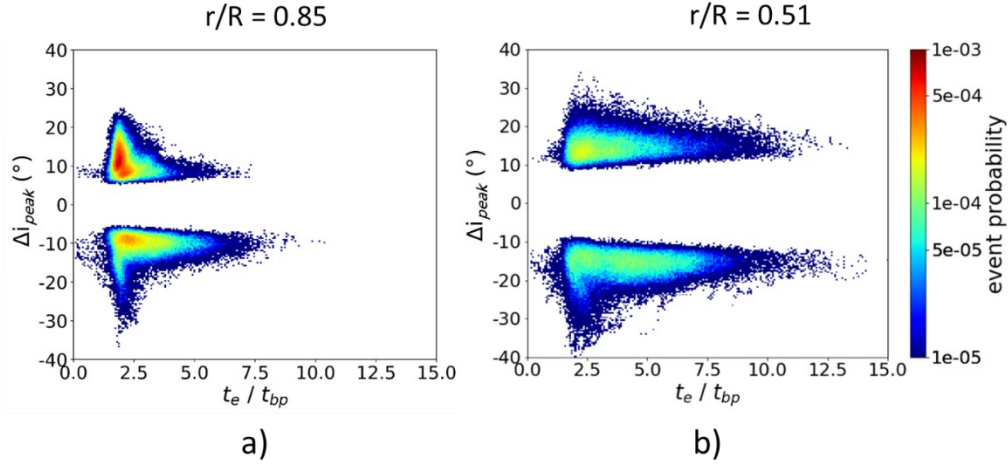


**Fig. 8: Probability maps for distortion events with nominal inlet boundary layer ( $\delta/D_{in} = 0.04$ ) for hub ( $r/R = 0.51$ ) and tip ( $r/R = 0.85$ ) positions.**

As highlighted in Fig. 9, it can happen that the blade is exposed to synchronous hub-tip incidence fluctuations or instead, only just a small portion of the blade is exposed to peak incidence. Thus, it is of interest to evaluate the radial extent of positive incidence events, to examine if these peak events ( $\Delta i_{peak}$ ) recorded at the blade tip affect only a small portion of the blade or if they are part of a root-to-tip bulk incidence variation. These considerations can give insights on the potency of the peak events and the severity of the non-uniform blade loading. Since it is believed that spike-type stall inception originates from instabilities localized at the blade tip [34], the investigation is focused on the positive high-incidence events at the blade tip, which are likely to increase the blade loading and the pressure ratio, and consequently, to reduce the surge margin. For example, when the blade tip is exposed to very high positive incidence at the tip ( $r/R = 0.85$ ), different scenarios can be outlined for the incidence distribution across the blade:

1. localized tip distortion (Figure Fig. 9a), in which the tip is exposed to a positive incidence variation while the incidence is close to design conditions elsewhere;
2. extended hub-tip distortion (Figure Fig. 9c), in which the majority of the blade span is exposed to a positive incidence variation;
3. extended hub-tip distortion with phase delay (Figure Fig. 9b), in which the majority of the blade span is exposed to a positive incidence but the peak incidence fluctuations between hub and tip have a phase delay;
4. dual polarity distortion (Figure Fig. 9d), in which hub and tip locations are exposed to a large variation of incidence of opposite polarity (e.g. positive incidence at the tip and negative incidence at the hub).

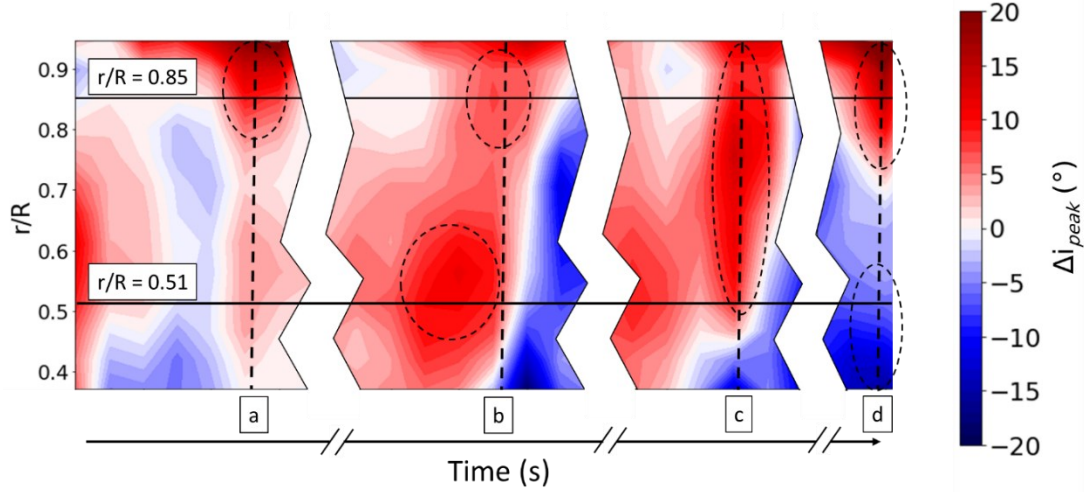


**Fig. 9: Example radial distribution of incidence fluctuations during peak events ( $\Delta i_{peak}$ ) at the blade tip ( $r/R = 0.85$ ). The red scale corresponds to positive incidence variation and blue scale represents a negative variation with respect to nominal conditions.**

Within this context, the radial distribution of the incidence fluctuations is analyzed. The aim is not to provide a thorough characterization of the incidence distribution across the blade span but rather to explore the benefits and useful insights of this method. Firstly, the magnitude of peak incidence fluctuations in case of synchronous peak events at the hub and at the tip was considered. Events with the greatest magnitude had negative incidence fluctuations both at the hub and tip of the blades (Figure Fig. 10a, quadrant III). However, these are expected to reduce the blade loading and the pressure ratio, and thus increase the surge margin [32]. On the contrary, events with fluctuations that result in synchronous positive incidence across the hub and tip had a relatively small magnitude (Figure Fig. 10a, quadrant I) and extremes were much less probable compared to synchronous negative incidence fluctuations (Figure Fig. 10a). This is highlighted especially when a filter based on the vectorial sum of the magnitude of the incidence fluctuations at the tip and hub and an arbitrary moderate-to-high threshold ( $\Delta i_{peak} > 15^\circ$ ) is applied to the population:

$$\sqrt{(\Delta i_{peak}^{r/R=0.85})^2 + (\Delta i_{peak}^{r/R=0.51})^2} > 15^\circ \quad (1)$$

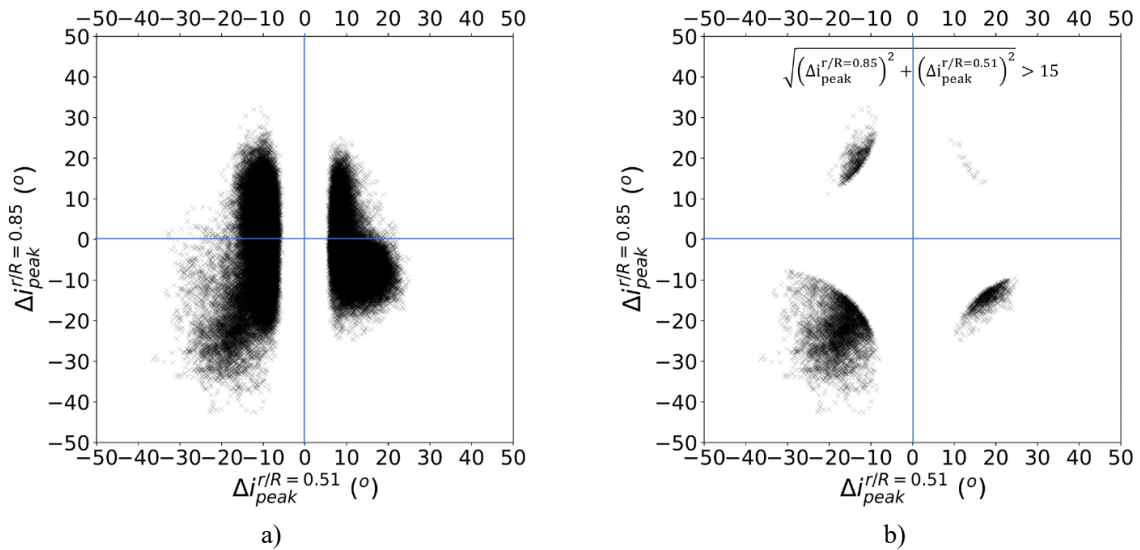


**Fig. 10: Correlation between the magnitude of the peak incidence events ( $\Delta i_{peak}$ ) at the blades tip ( $r/R = 0.85$ ) and the magnitude of the peak incidence events ( $\Delta i_{peak}$ ) at the blade hub ( $r/R = 0.51$ ) considering a) all the events recorded at tip, and b) only the events which satisfy the selected condition (Eq. 1).**

Synchronous events with peak positive incidence (Figure Fig. 10b, quadrant I) are considered an unfavorable condition for the compressor stability since these events are expected to increase the blade loading and the pressure ratio and thus reduce the surge margin; therefore, the fact that there are only a few of them is a positive result [32]. Finally, a considerable number of events had incidence fluctuations with different polarity at the tip and hub of the blades (Figure Fig. 10b, quadrants II and IV). These events may generate variation from the nominal blade loading distribution across the blade span, and thus can generate forced excitation on the blades which can undermine the mechanical compatibility [37].

The magnitude of synchronous peak incidence events at the hub and tip of the blades gives insights on the potential changes in the blade loading. However, it cannot evaluate the potency of the distortion events, since only discrete representative locations have been analyzed ( $r/R = 0.85$  and  $r/R = 0.51$ , Fig. 10). To evaluate the potency of the distortion events, the magnitude and exposure time of tip peak events ( $r/R = 0.85$ ) can be correlated with the radial extent of the events across the blade span. As introduced in Section III.E, the 50% peak height of a disturbance was used as a threshold to measure the duration of peak distortion events (Fig. 5). Similarly, in this section, the radial extent ( $r_e$ ) is defined as the portion of the blade exposed to at least a magnitude of 50% of the peak incidence at the blade tip ( $\Delta i_{peak}^{r/R=0.85}$ ) and it is reported relative to the blade span ( $R_b$ ) (Fig. 11). Thus, peak events at the tip can be classified with the magnitude of the incidence fluctuation ( $\Delta i_{peak}$ ), the exposure time ( $t_e/t_{bp}$ ), and the radial extent ( $r_e/R_b$ ) as shown in Fig. 12. In this analysis, only the radial distribution of peak distortion events with positive incidence fluctuations at the blades tip (Figure Fig. 10b, quadrants I and II) will be considered ( $\Delta i_{peak} > 0$ ). Two key characteristics of the peak events at the blade tip are highlighted. The peak events with relatively high magnitude and exposure time below 5 blade passings ( $t_{bp}$ ) tended to affect only a portion of the blade ( $r_e = 0$ -40% approximately, Fig. 12 region A). For these events, the radial distribution of incidence may correspond to the cases a) and d) listed in Fig. 9. Alternatively, peak positive events with a relatively large exposure time (above  $5t_{bp}$ ) tended to affect a large portion of the blade (above 50% approximately, Fig. 12 region B). These events are more aligned with the incidence distribution of cases b) and c) in Fig. 9.

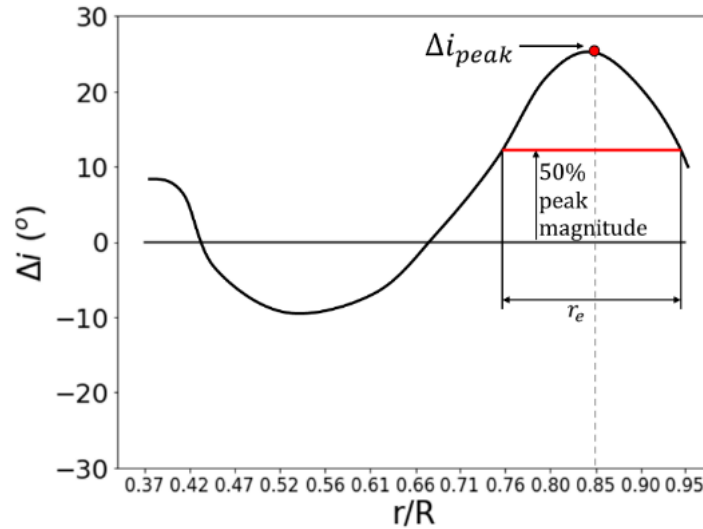


**Fig. 11: Definition of the radial extent of peak events at the blade tip.**

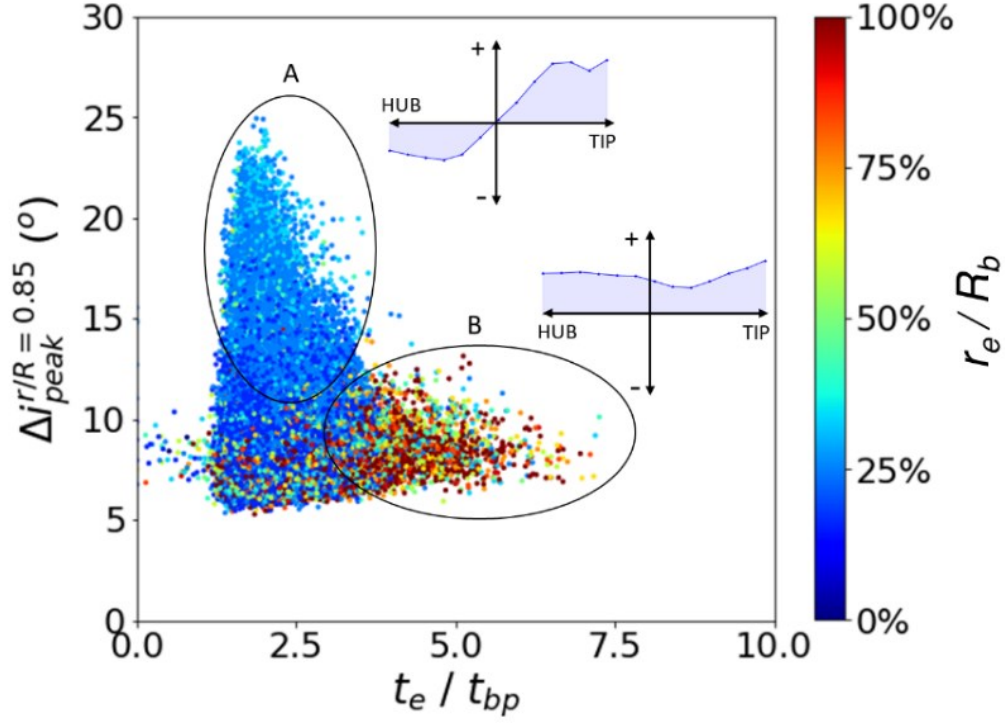


**Fig. 12: Magnitude, exposure time and radial extent of the peak events at the blade tip ( $r/R = 0.85$ ) for baseline inlet conditions ( $\delta/D_{in} = 0.04$ ) with no inlet vortex.**

Understanding the radial distribution of distortion events is a key consideration to analyze the formation of stall cells. Interestingly, incidence fluctuations which affect only a portion of the blade (as for events in Fig. 12- region A), may generate a stall cell. Indeed, Giuliani et Chen [15] demonstrated that when the incidence is not uniform across the blade the path line of the flow does not travel in the streamwise direction only, but instead it tends to travel radially. This may happen when in one radial location (path 1, Fig. 13) the incidence is higher than the neighbor location (path 2, Fig. 13). The higher lift generated by the flow path with higher incidence (path 1) generates a low suction pressure which drives the flow of the other path (path 2, with less incidence) to turn radially and move across the blade span. This may interact with the tip vortex and it may separate or reattach depending on the following distortion event. This is believed to generate and accentuate unsteady incidence fluctuations which may have a notable impact on the blade aeromechanics and the potential to trigger dynamic stall [15]. Thus, arguably, non-uniform hub-tip blade loading is a condition which can more likely cause instabilities [16] compared to a distortion extending over a larger fraction of the blade span.

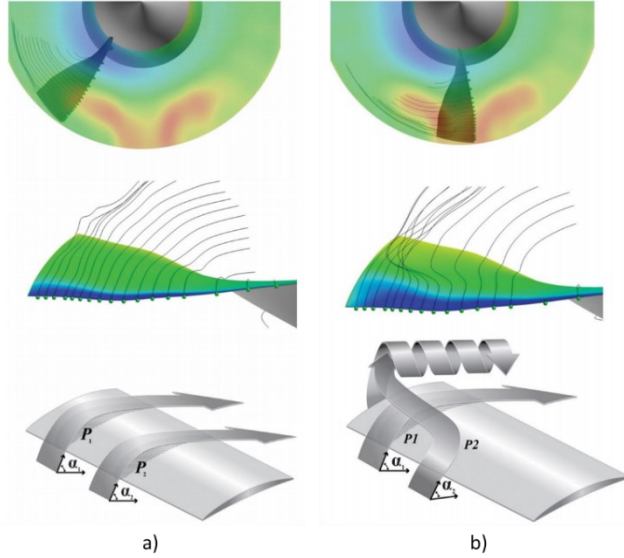


**Fig. 13: Expected flow path lines in case of a) spanwise uniform perturbation in rotor incidence or b) spanwise non-uniform perturbation in rotor incidence at  $r/R = 0.5$  and  $0.7$  identified by Giuliani et Chen<sup>4</sup>.**

### C. Peak distortion events and radial distribution for uniform and non-uniform inlet conditions

Considering the classification of peak distortion events that includes also the radial distribution of the incidence fluctuation, the peak distortion events have been re-evaluated for the different inlet configurations. The scope is to identify, for each configuration, the portion of events which are more likely to cause instabilities and stall inception. Based on the current state of the art, modern axial compressors are likely to respond and develop instabilities if exposed to disturbances which last the equivalent of the passing time of 4-5 blades [12]. Thus, the initial population of peak positive tip events have been filtered to identify only the events in a conservative range of 3-6 blade passing time, which are believed to cause instability issues. Then, these were further divided into events which affect more than 50% of the blade span (Fig. 14a) or affect less than 50% of the blade (Fig. 14b). This distinguished events of bulk incidence variation from localized changes of incidence which generated non-uniform blade loading, such as in Giuliani et Chen scenario [15]. Events with radial extent less than 50% exhibited a peak incidence up to about  $20^\circ$  and represented the 10.2% of the overall peak event population (Fig. 14a). Events which instead affected more than 50% had a similar likelihood (10.1% of the overall population) and contained events with peak incidence up to about  $15^\circ$  (Fig. 14b). In light of Giuliani et Chen findings [15], it is believed that a non-uniform blade loading condition (less than 50% radial extent, Fig. 14a) is more likely to generate stall cells and instabilities, as discussed in the previous section.

Thus, the different S-duct inlet conditions were compared based on the radial extent and the exposure time ( $t_e/t_{bp}$ ) of these localized tip distortions, to assess the effects of the different inlet profiles and inlet vortices. The aim was to identify distortions which 1) caused non-uniform blade loading, and 2) had a duration in the range of  $3-6t_{bp}$ . It is observed that an increase of the inlet profile thickness from baseline condition to Profile A ( $\delta/D_{in} = 0.332$ ) or B ( $\delta/D_{in} = 0.572$ ) increases the number and magnitude of these events (Fig. 16a, b) relative to uniform inlet conditions ( $\delta/D_{in} = 0.04$ , Fig. 15a). The change of the azimuthal orientation of inlet total pressure profiles (Fig. 16c, d) also increased the likelihood of non-uniform blade loading by about 7% but the magnitude of these events slightly decreased compared to the baseline conditions (Fig. 15a). The configurations with the inlet vortex at the centre and left side (Fig. 15b, c) generated more events with great incidence across the range of exposure time of interest ( $3-6t_{bp}$ ) relative to baseline conditions without inlet vortex (Fig. 15a). Instead, as observed in previous sections, the ingestion of the vortex at the inlet lower side (Fig. 15d) suppressed the magnitude of peak events. Thus, in general, the inlet vortices generally had a smaller effect on the likelihood and magnitude of these distortion events (Fig. 15).

<sup>4</sup> From Giuliani, J. E., and Chen, J.-P., "Fan Response to Boundary-Layer Ingesting Inlet Distortions" [15]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

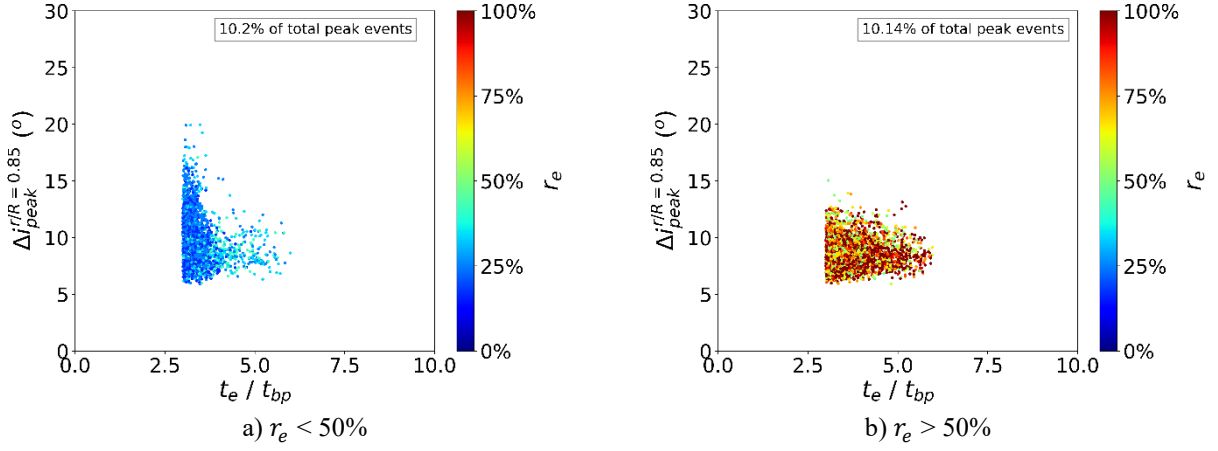


**Fig. 14: Magnitude, exposure time and radial extent of the peak events at the blade tip ( $r/R = 0.85$ ) for baseline inlet conditions ( $\delta/D_{in} = 0.04$ ) with no inlet vortex, blade exposure of  $3-6t_e/t_{bp}$  and a) radial extent  $r_e < 50\%$  or b)  $r_e > 50\%$ .**

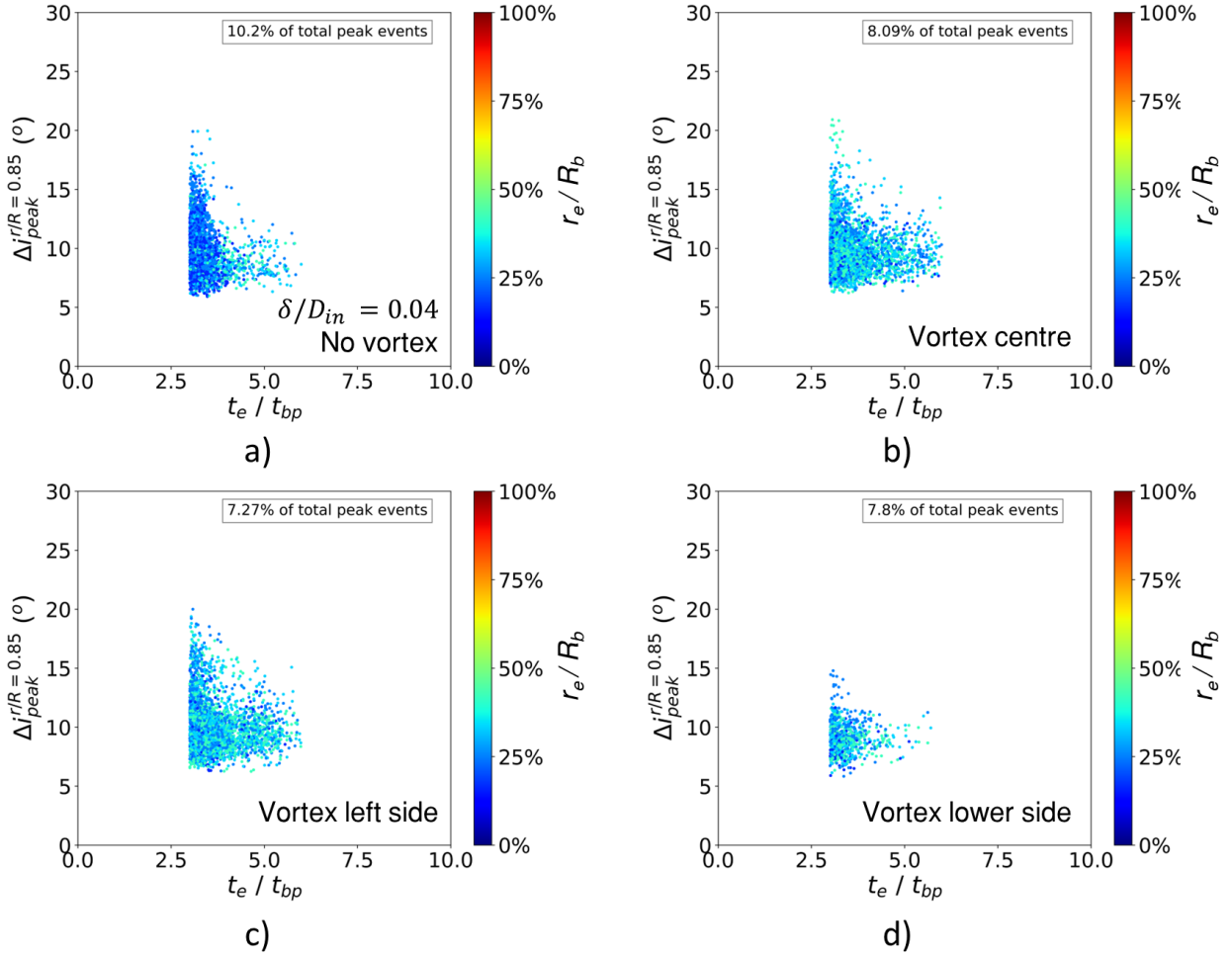


**Fig. 15: Positive peak events ( $\Delta i_{peak}$ ) at the blade tip ( $r/R = 0.85$ ) within  $3-6t_{bp}$  and with radial extent  $r_e < 50\%$  with baseline inlet conditions with no vortices ( $\delta/D_{in} = 0.04$ ), and with a vortex at the inlet centre, left and lower side measured  $0.5D_{in}$  downstream of the S-duct intake.**

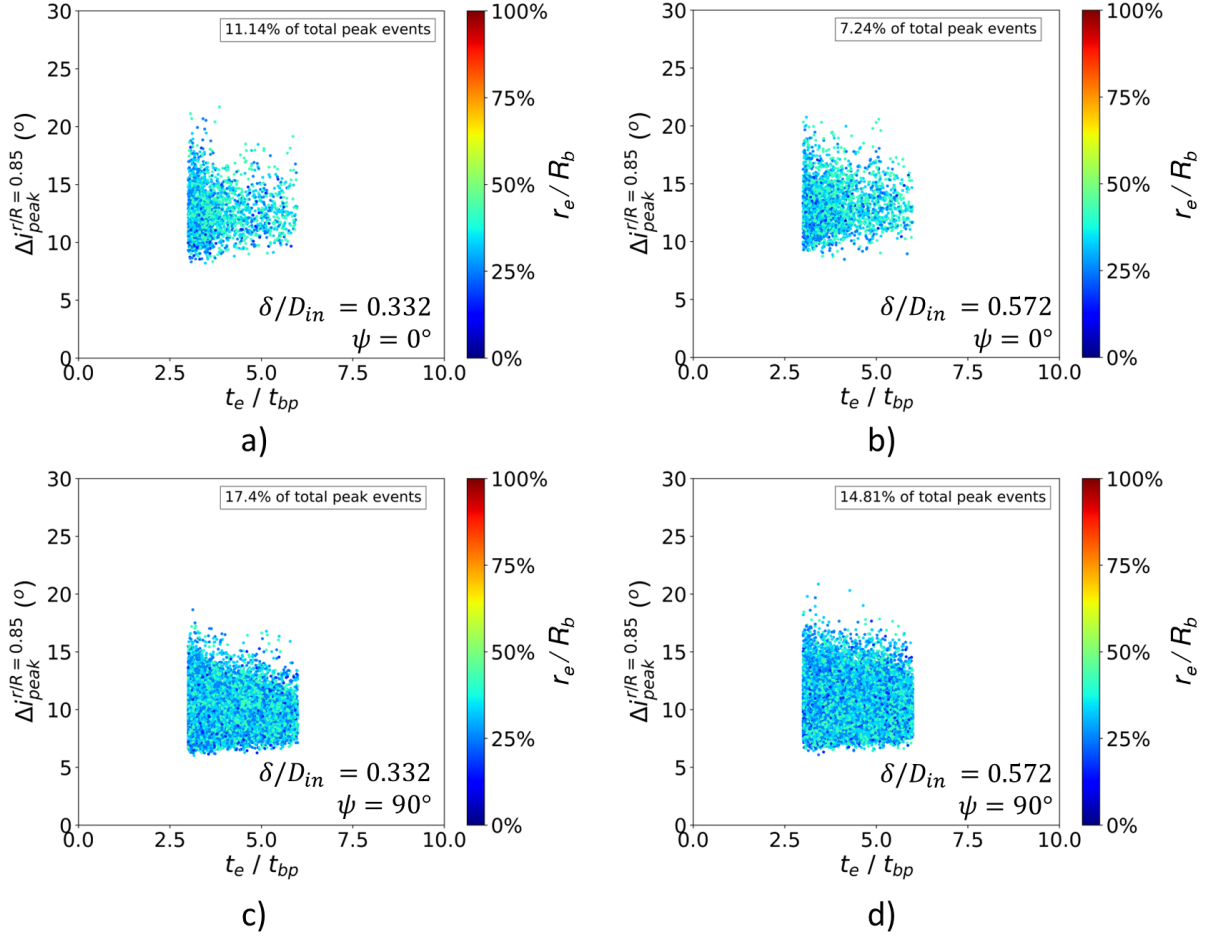


**Fig. 16: Positive peak events ( $\Delta i_{peak}$ ) at the blade tip ( $r/R = 0.85$ ) within  $3-6t_{bp}$  and with radial extent  $r_e < 50\%$  with inlet Profile A ( $\delta/D_{in} = 0.332$ ) (a,c) and inlet Profile B ( $\delta/D_{in} = 0.572$ ) (b,d) oriented at  $\psi = 0^\circ, 90^\circ$  measured  $0.5D_{in}$  downstream of the S-duct intake.**

To synthesize the results, the impact of the S-duct inlet configurations can be evaluated based on the distortion event that caused a maximum positive change in incidence ( $\Delta i_{peak}$ ) in a exposure range of  $3-6t_{bp}$  ( $\max(\Delta i_{peak, 3-6t_{bp}})$ ), and the relative probability of peak distortion events within  $3-6t_{bp}$  ( $P[E]|_{3-6t_{bp}}$ , Fig. 17). With these criteria, it is inferred that the ingestion of vortices at the S-duct inlet has a relatively minor effect on the considered localized tip distortions, since their relative probability and magnitude is comparable to the baseline case with uniform inlet conditions (Fig. 17). The ingestion of the vortex at the lower inlet side could even be beneficial for the engine intake integration since the maximum peak incidence fluctuation at the AIP reduces by about  $5^\circ$  (Fig. 17). On the other hand, the inlet configuration with total pressure profiles worsened the AIP peak distortion levels. The relative probability of peak incidence fluctuations in the range of interest increased by about 65% and the peak magnitude increased from about  $20^\circ$  up to about  $24^\circ$  relative to uniform inlet conditions (Fig. 17). Initially, based on the more conventional analysis in the absolute frame of reference, it was concluded that while the  $\psi = 0^\circ$  orientation of thick inlet total pressure profiles increased the levels of peak distortion (Fig. 6), the  $\psi = 90^\circ$  produced a relatively lower swirl unsteadiness, a lower growth rate of the extreme events and a lower upper bound of the swirl intensity (Fig. 7). The novel relative frame of reference analysis, however, shows that the  $\psi = 90^\circ$  orientation presents a relatively high probability of peak distortion events which could be detrimental for the operation of the propulsion system; this illustrates the potential of this novel analysis.

Thus, in general, it is concluded that inlet total pressure profiles at both  $\psi = 0^\circ$  and  $90^\circ$  may adversely affect the stability of the engine. On the other hand, inlet vortices are likely to have a relatively minor impact on the engine stability. Therefore, for future investigations it is recommended to prioritize the evaluation of the effect of inlet total pressure profiles with respect to that of inlet vortices, as they are likely to generate the most challenging operations for the compressor.

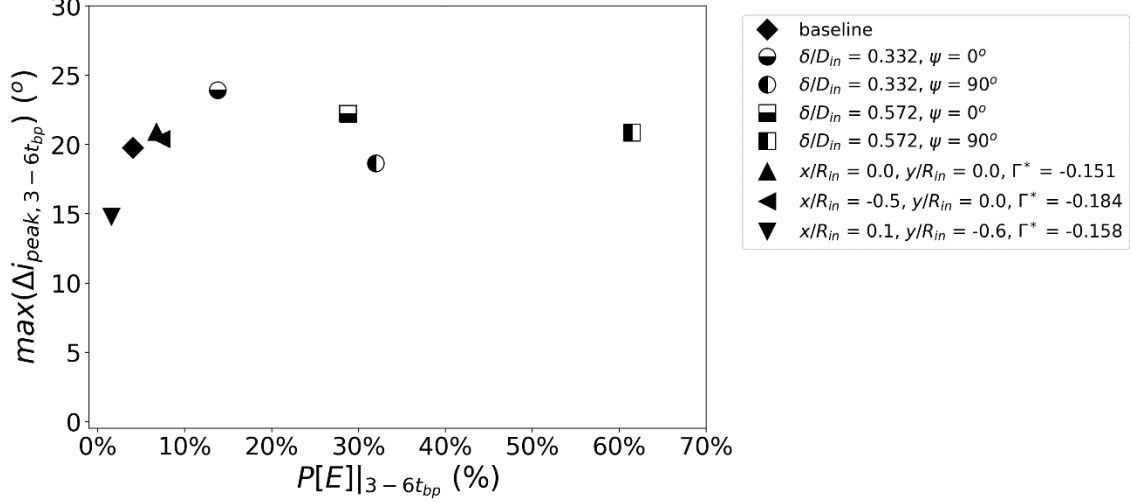


**Fig. 17: Maximum positive peak events ( $\Delta i_{peak}$ ) at the blades tip ( $r/R = 0.85$ ) within  $3-6t_{bp}$  and associated relative probability ( $P[E]$ ) for different inlet configurations measured  $0.5D_{in}$  downstream of the S-duct intake. The relative probability is computed considering the number of the events detected at the tip with uniform inlet conditions ( $\delta/D_{in} = 0.04$ , with no inlet vortex).**

## V. Conclusion

A distortion characterization method has been introduced to assess the distortion events in a relative frame of reference taking both spatial and temporal variations into account. This work was proposed as a route to move away from conventional distortion metrics based on total pressure measurements taken with a fixed rake. The high spatial and temporal resolution of the HB-PIV data enabled the analysis of the incidence fluctuations into the envisaged compressor relative frame of reference. The analysis considered the unsteady fluctuations caused at the same time by both the unsteady variation in position and magnitude of the flow distortion, but also on the azimuthal position of the blade during its rotation. In the current work, additional considerations on the radial distribution and extent of the peak distortion events have been introduced. Peak events have been further classified as a function of the location of the peak distortion events along the blade span, the sign of the incidence fluctuation and the portion of the blade exposed to the distortion. It is believed that some of the peak distortion events are linked with the generation of stall cells and thus these could provide indications on the expected response of the propulsion system. The characteristics of the peak distortion events highlighted by the current analysis, together with current knowledge on spike-stall inception, allowed to compare the unsteady flow distortion generated with different S-duct inlet configurations. It was found that configurations with inlet total pressure profiles produced a higher number of distortion events that are considered critical for the operation of the propulsion system, whereas the presence of vortices at the inlet of the S-duct had a relatively minor effect on the characteristics of these distortion events.

Overall, this demonstrates that this type of analysis in the frame of reference gives additional information on how the distortion is perceived by the rotor blades, and represents a step forward in understanding flow distortion compared to conventional distortion analyses based on the absolute frame of reference. Moreover, the unsteady swirl fluctuations are translated to metrics of interest for the compressor stability and response. This strengthens the argument that this novel analysis can offer a more advanced characterization of unsteady flow distortion features compared with conventional assessment methods. The application of this methodology on future computational and experimental studies on unsteady flow fields is recommended, and is expected to enable the integration of complex ducts with future propulsion systems.

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## **Characterization of unsteady distortion events for S-duct intakes under non-uniform inlet conditions**

**Migliorini, Matteo; Zachos, Pavlos K.; MacManus, David G.**

**2023-01-19**

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