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Assessment methods for unsteady flow distortion in aero-engine intakes

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ABSTRACT

Peak events of unsteady total pressure and swirl distortion generated within S-duct intakes can affect the engine stability, even when within acceptable mean distortion levels. Even though the distortion descriptors have been evaluated in S-duct intakes, the associated flow field pattern has not been reported in detail. This is of importance since engine tolerance to distortion is usually tested with representative patterns from intake tests replicated with steady distortion generators. Despite its importance in intake/engine compatibility assessments, the spectral characteristics of the distortion descriptors and the relationship between peak unsteady swirl and both radial and circumferential total pressure distortion has not been assessed previously. The peak distortion data is typically low-pass filtered at a frequency associated with the minimum response time of the engine. However the engine design is not always known a priori in intakes investigations and a standard approach to reporting peak distortion data is needed. In addition, expensive and time-consuming tests are usually required to capture representative extreme distortion levels. This work presents a range of analyses based on Delayed Detached-Eddy Simulation and Stereo Particle Image Velocimetry data to assess these aspects of the unsteady flow distortion. The distorted pattern associated with different swirl distortion metrics is identified based on a conditional averaging technique, which indicates that the most intense swirl events are associated with a single rotating structure. The main frequencies of the flow distortion descriptors in a representative S-duct intake are found to lie within the range in which the engine stability may be compromised. The peak total pressure and swirl distortion events are found to be not synchronous, which highlights the need to assess both types of distortion. Peak swirl and total-pressure distortion data is reported as a function of its associated time scale in a more general way that can be used in the assessment of intake unsteady flow distortion. Extreme Value Theory has been applied to predict peak distortion values beyond those measured in the available dataset, and whose measurement would otherwise require testing times two orders of magnitude longer than those typically considered.

1. Introduction

Convoluted aero-engine intakes are needed in highly integrated power plants in which the engine is fully or partially embedded into the airframe, and are expected to play a major role in the next generation of aircraft [1,2]. A notable drawback of these configurations is the high levels of unsteady flow distortion that are delivered to the fan, as a consequence of flow separations and secondary flows within the intakes. The distortion in the flow typically reduces the surge margin and can eventually result in surge or rotating stall engine instabilities [3]. Therefore, intake/engine compatibility assessments must be addressed early in the aircraft design program to avoid extensive and expensive re-designs at later stages of the development [4]. Substantial research has been dedicated to reduce the flow distortion within these convoluted intakes with passive [5] and active [6,7] flow control, as well as through optimisation of S-duct geometries [8].

Historically, flow distortion assessments were limited to steady total pressure distortion measured with low-bandwidth pressure probes, and its effect on the fan stability is relatively well stablished [9]. However, swirl distortion more recently proved to be also a potential source of engine instabilities and caused time-consuming and expensive modifications in later stages of the development of several aircraft [10]. The effect of the unsteady component of the flow distortion was also identified as a major source of engine instabilities, and peak instantaneous values of the distortion descriptors that exceed the engine tolerance were reported to cause engine surge events even within acceptable mean distortion

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Nomenclature

A	S-duct cross section area	mm^2
AR	Area ratio, A_{AIP}/A_{in}	
D	S-duct cross section diameter	mm
$DC60$	Distortion Coefficient	
f	Frequency	Hz
H	S-duct centerline offset	mm
L	S-duct axial length	mm
L_s	S-duct length measured along the centerline	mm
M	Mach number	
m	Reciprocal of the probability, $1/p$	
p	Probability	%
p_0	Total pressure	Pa
PDF*	Normalized Probability Density Function	
q	Compressible dynamic head	Pa
r	Radial coordinate from the AIP center	mm
R	S-duct cross section radius	mm
R_c	Curvature radius of the S-duct bend	mm
RDI	Radial Distortion Index	
Re_D	Reynolds number based on the inlet plane diameter	
s	S-duct centerline co-ordinate	mm
SD	Swirl Directivity distortion descriptor	
SI	Swirl Intensity distortion descriptor	deg
St	Strouhal number, $fD_{AIP}/\langle\overline{w}\rangle_{AIP}$	
t_c	Convective time, L_s/w_{in}	
t_d	Duration of the peak distortion	s
V	Modulus of the velocity vector	m/s
VDC60	Velocity-based estimator of DC60	
v_θ	Circumferential velocity component	m/s
w	Out-of-plane velocity component	m/s
α	Swirl angle, $\arctan(v_\theta/w)$	deg
γ	Curvature ratio based on the inlet-section radius, R_{in}/R_c	
$\Delta PC/P$	Total pressure distortion circumferential intensity	
$\Delta PR/P$	Total pressure distortion radial intensity	
Δt	Unsteady simulation time step	s
Δt^*	Time spacing between samples of the unsteady simulation, $3\Delta t$	s
ξ	Shape parameter of the Generalized Pareto Distribution	
σ	Scale parameter of the Generalized Pareto Distribution	
τ_c	Characteristic time, $D_{AIP}/\langle\overline{w}\rangle_{AIP}$	s

Abbreviations

DDES	Delayed Detached-Eddy Simulation
EVT	Extreme Value Theory
MTAW	Moving Time-Averaged Window
PDF	Probability Density Function
PS	Power Spectrum
RMS	Root Mean Square
SAE	Society of Automotive Engineers
SPIV	Stereo Particle Image Velocimetry
URANS	Unsteady Reynolds-Averaged Navier–Stokes

Subscripts

60	Most spoiled 60° sector at the AIP
AIP	Aerodynamic Interface Plane ($0.41D_{out}$ downstream of the S-duct outlet plane)
hub	Evaluated at the hub, inner-most ring $i = 1$
i	Ring index, where $i = 1$ refers to the inner ring
in	S-duct inlet plane
max	Maximum value across the rings
ref	Reference plane ($0.9D_{in}$ upstream of the S-duct inlet plane)
tip	Evaluated at the tip, outer-most ring $i = 5$

Operators

$\langle\cdot\rangle$	Time-average
$\overline{\cdot}$	Spatial average over a ring or area
std(.)	Standard deviation
peak(.)	Maximum value in a temporal signal

levels [11]. Consequently the peak value of the instantaneous distortion metrics has become an important parameter in inlet/engine compatibility assessments [12]. However, the fan response not only depends on the instantaneous distortion level but also on the time duration and frequency associated with the perturbation [13]. This is due to the finite response time of the fan, that needs time to adapt to the unsteady inlet conditions [14]. For perturbations with time-periods less than the fan critical response time the engine is unable to follow the inlet variations and is broadly unaffected by the unsteady component of these perturbations. In these cases, the fan is mainly sensitive to the time-averaged level of these perturbations [14]. Cousins [15] defined the critical response time for a fan rotor blade as the time for a flow particle to travel from the leading edge to the throat of the blade. Therefore the distortion data is typically low-pass filtered at the frequency associated with the minimum critical response time of the compression system [11,16–18]. However this is not always possible during the early experiments of the intake as the engine design may not be known yet. This is the case in investigations focused on the intake flow field where an engine application is not considered, and often peak distortion data is reported without any explicit consideration of the compression response time [19,20].

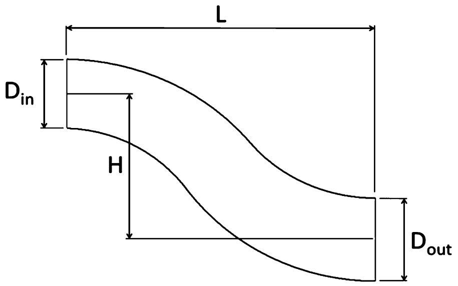

Fig. 1. S-duct geometry sketch.

The distorted flow within complex intakes has been widely investigated. Wellborn et al. [21] investigated the distorted flow within an S-duct intake ($H/L = 0.27$, $AR = 1.52$, $L/D_{in} = 5.0$, Fig. 1) with low-bandwidth instrumentation. The mean flow at the Aerodynamic Interface Plane (AIP) was characterised by a main loss region (Fig. 2a, d) and a symmetric pair of vortices (Fig. 2b, e), due to the presence of flow separation and secondary flows within the intake. Garnier [19] measured the unsteady total pressure field at the AIP of a more aggressive S-duct intake ($H/L = 0.49$, $AR = 1.52$, $L/D_{in} = 4.95$) using 40 high-bandwidth pressure transducers. At $M_{AIP} = 0.2$ ($Re_D = 7.5 \times 10^5$) the spectral analysis revealed a dominant unsteady structure that consisted of a lateral movement of the main loss region (Fig. 2a, d) associated with a frequency of St = 0.48. A region of high unsteadiness at the upper boundary of the mean loss region was also reported and associated with frequencies between St = 0.60–1.09 [19]. MacManus et al. [20] simulated the flow within the same non-dimensional geometries

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