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Discretized Miller approach to assess effects on boundary layer ingestion induced distortion

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Abstract The performance of propulsion configurations with boundary layer ingestion (BLI) is affected to a large extent by the level of distortion in the inlet flow field. Through flow methods and parallel compressor have been used in the past to calculate the effects of this aerodynamic integration issue on the fan performance; however high-fidelity through flow methods are computationally expensive, which limits their use at preliminary design stage. On the other hand, parallel compressor has been developed to assess only circumferential distortion. This paper introduces a discretized semi-empirical performance method, which uses empirical correlations for blade and performance calculations. This tool discretizes the inlet region in radial and circumferential directions enabling the assessment of deterioration in fan performance caused by the combined effect of both distortion patterns. This paper initially studies the accuracy and suitability of the semi-empirical discretized method by comparing its predictions with CFD and experimental data for a baseline case working under distorted and undistorted conditions. Then a test case is examined, which corresponds to the propulsor fan of a distributed propulsion system with BLI. The results obtained from the validation study show a good agreement with the experimental and CFD results under design point conditions.

1. Introduction

The performance of axial fans under distorted conditions has been studied extensively in the past. Different approaches and tools such as through flow methods,[1] semi-empirical correlations,[2] and fan map based methods (parallel compressor[3]) have been utilized to assess their performance. It has been found that even though through flow methods such as stream-

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Nomenclature

i	incidence, β_{LE} - β'_{LE}
C	absolute flow velocity, m/s
P	total pressure, Pa
p	static pressure, Pa
T	total temperature, K
t	static temperature, K
$()_f$	fan property
OD	off design conditions
BLI	boundary layer ingestion
ε	deflection, β_{LE} - β_{TE}
β	relative air angle
V	relative velocity, m/s
U	tangential velocity, m/s
C_a	axial velocity
α	absolute air angle
δ	deviation angle, β_{TE} - β'_{TE}
ω	total loss coefficient
ω_p	profile loss coefficient
ω_{sec}	secondary loss coefficient
ω_{sw}	shock wave loss coefficient
ΔP_{ideal}	ideal total pressure increment, Pa
ΔP_{real}	real total pressure increment, Pa
P'_{LE}	ideal total pressure at leading edge, Pa
P_{LE}	total pressure at leading edge, Pa
$\bar{\omega}$	average total loss coefficient
$\omega_{p,\ par}$	parametric profile loss coefficient
$\omega_{ew,\ par}$	parametric end wall loss coefficient
V_{LE}	relative velocity at leading edge
V_{TE}	relative velocity at trailing edge
β_{TE}	relative air angle at trailing edge
β'_{TE}	relative blade angle at trailing edge
h	blade height, m
c	blade chord, m
h/c	blade aspect ratio
r	radius, m
y^+	dimensionless distance of the node from the wall
k–ε	k-epsilon turbulence model
k–ω	k-ω turbulence model
H	H grid type
C	C grid type
O	O grid type
ATM	automatic topology and meshing
P_{BL}	total pressure in the boundary layer region at propulsor intake
M_{BL}	Mach number in the boundary layer region at propulsor intake
M_∞	Mach number at free stream conditions
P_∞	total pressure at free stream conditions
TeDP	turboelectric distributed propulsion
y	perpendicular distance from the wall, m
C_{cl}	airframe length
R_c	Reynolds number
ψ	flow coefficient
CFD	computational fluid dynamics
BL	boundary layer
DM	discretized Miller
DC_{120}	distortion coefficient for 120°
θ	angular position, rad or °
ml	minimum loss
$\dot{m}$	mass flow
r_{rt}	root to tip ratio
FPR	fan pressure ratio
V_{tip}	tip velocity, m/s
η_f	fan efficiency
DP	design point
NB	number of blades
r_t	tip radius, m
r_r	root radius, m
$()_1$	properties at rotor entry
$()_2$	properties at stator entry
TSFC	thrust specific fuel consumption

line curvature[4,5] and CFD can predict fan performance with higher accuracy than other methods, they also require more resources in terms of computational power and time. For **boundary layer ingestion** (BLI) systems, streamline curvature and parallel compressor have been combined in order to assess circumferential and radial distortion.[4] In the case of CFD, this tool enables the assessment of the fan performance radially and circumferentially, and for this reason CFD has also been utilized for the assessment of BLI distortion problems. This approach has been preferred for cases where the detailed geometry is known and accuracy is paramount. In this study, CFD has been used to compare some results obtained under uniform conditions with the discretized Miller approach. Some experimental test-rigs have been set for the assessment of BLI type distortion; however testing engines or in this case fans are expensive and the cost increases with advanced engine technology and designs. Furthermore, the cost of the energy required for each run and the possibility of damaging the tested equipment increase the difficulty of carrying out these procedures. Jerez et al.[1] experimentally studied the validation of a CFD model for a fan working under distortion. Redmond[6] described a test-rig and experimental results for BLI type distortion; however in this latter case, the uncertainties achieved are large and it is difficult to assess the real benefits of BLI.

At the preliminary design stage when the detailed geometry of a system/component is still undefined and several configurations have to be tested, reducing requirements of computational resources becomes imperative.

Due to excessive simulation times, these methods have also been found unsuitable in cases where full annular simulation is required and circumferential distortion is present (such as in boundary layer ingesting systems[7–9]). These reasons, therefore, make methods such as the parallel compressor[3] more attractive for preliminary design at design point. However, this method has its limitations, as it only enables to assess circumferential distortion. Hence it may be considered to have limited accuracy in the case of BLI systems where a combination of circumferential and radial distortion of flow is observed.

This paper addresses this limitation of the method and proposes a novel approach to overcome it. Using a semi-empirical

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