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Inlet ground vortex aerodynamics under headwind conditions

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ABSTRACT

Quantitative velocity flow field measurements of the vortex system for a small scale model intake have been taken using a three component PIV system along with fan face total pressure distortion measurements. The effect of velocity ratio, non-dimensional height and approaching boundary layer thickness have been assessed under quiescent and headwind conditions. A range of inlet vortex flow modes are identified which depend on the intake velocity ratio and are characterised by the primary vorticity source. As the headwind velocity increases, and the velocity ratio reduces, the vortex strength initially increases until a local maximum is reached. Further reductions in the velocity ratio leads to a strong reduction in the vortex strength until a 'blow-away' condition is achieved at which the vortex no longer forms. A clear link is established between the external vortical flow-field and the intake internal flow-field. Consequently, these characteristics are also observed for the total pressure distortion coefficient within the intake. As the ground clearance is increased the peak vortex strength reduces and the corresponding velocity ratio increases. At intermediate velocity ratios, the vortex strength is greater at higher ground clearances. At the selected external vortex measurement plane, the vortex strength is generally insensitive to the approaching boundary layer thickness. The intake total pressure distortion increases with boundary layer thickness due to increased total pressure loss for a given ingested mass-flow. The vortex strength and distortion distributions are shown to be self-similar when non-dimensionalised by the peak values and associated velocity ratio. This dataset establishes a quantitative map for headwind ground vortices which presents a new formation criterion as well as a measure of the vortex strength as a function of ground clearance and intake velocity ratio.

1. Introduction

When an engine intake is operating in close proximity to the ground, at high power, a vortex can form which is ingested into the intake (Fig. 1). This vortex can be responsible for foreign object damage [5,21], mass flow and total pressure distortion [9,14,16] as well as strong changes in flow angularity, which can effect fan vibration [6]. The formation of this vortex is primarily a function of the capture stream tube size (which is a function of the velocity ratio, U_i/U_∞) and the height-to-diameter ratio, h/D_l (Fig. 2). Ground vortex avoidance design rules currently rely on the classic vortex criterion map [3,17]. However this map is primarily based on flow visualisations and provides no information on the severity of the vortex at different operating conditions. Furthermore Nakayama and Jones [17] indicate from their very limited experimental results that the minimum velocity ratio required is even lower than previously reported criteria [3,17].

Although there is a wide variety of published work focusing on ground vortex formation and characteristics, very few provide

Fig. 1. Ground vortex ingestion on a RB211-524G in static aircraft conditions (photograph by Peter Thomas).

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Nomenclature

D_i	Intake throat diameter	m
D_l	Highlight diameter	m
h_L	Measurement plane height from ground	m
h	Vertical distance from lowest point of highlight plane to ground	m
M_i	Intake Mach number	
P_∞	Free-stream total pressure	Pa
P	Local total pressure	Pa
P_{60}	Minimum average 60 degree sector total pressure	Pa
q_f	Fan face dynamic pressure	Pa
U_i	Average intake velocity	$\mathrm{m\,s^{-1}}$
U_∞	Free-stream wind velocity	$\mathrm{m\,s^{-1}}$
DC_{60}	Fan face distortion coefficient based on the lowest average 60 degree sector total pressure ($=(P_{60}-P_f)/q_f$)	
Γ	Total vortex system circulation	$\mathrm{m^2\,s^{-1}}$
Γ^*	Non-dimensional vortex strength ($=\Gamma/D_lU_i$)	
r	Radial distance from centre of vortex	m
r_c	Vortex core size	m
r^*	Non-dimensional radial distance ($=r/r_c$)	
σ	Standard deviation	
ω_Z	Out-of-plane vorticity component	$\mathrm{s^{-1}}$
P_f	Area weighted fan face average total pressure	Pa
δ^*	Approaching boundary layer displacement thickness	m
V_θ	Swirl velocity	$\mathrm{m\,s^{-1}}$
n	Vatistas vortex model shape factor	
U^*	Velocity ratio (U_i/U_∞)	

an extensive quantitative investigation of the vortex parameters. In particular there is very little work on the distortion generated by the vortex at the fan face, which is of major importance in determining its effect on the engine. Motycka [9–11] presents quantitative distortion information at the fan face; however this is predominately during reverse thrust operation and is of limited scope. In addition, although the work of Shin et al. [22] showed that the vortex strength diminished with increasing ground clearance it was only assessed in a semi-quantitative manner under cross-wind conditions. In an initial investigation conducted by the authors [16] an intake in cross-wind was found to generate a significantly stronger vortex in comparison to quiescent (no-wind) conditions with a twenty fold increase in total pressure loss compared to no-wind conditions. More recent studies of the crosswind ground vortex show that under certain conditions premature lip separation occurs due to the presence of the ingested ground vortex [14]. The present work focuses on the quantitative evaluation of the inlet aerodynamics under headwind conditions.

2. Experimental apparatus and procedures

2.1. Test facility and model

The experiments were conducted in the Cranfield University low-speed wind tunnel which has a 2.4 m × 1.8 m working section. The intake was represented using a cylindrical model of approximately 1/30th scale, with an inside diameter of 0.1 m. The intake Reynolds number ranged between $1.4\text{–}6.5 \times 10^5$ based on the inner diameter and average intake velocity. Due to the low Reynolds number transition strips were placed on both the inside and outside of the intake lip to promote transition and to avoid premature laminar separations. In addition, the lip geometry was modified relative to a large-scale intake and consisted of elliptical elements, with a major-to-minor axis ratio of 2. The model did not include a central hub or a rotating fan. The intake mass-flow was provided by a suction system which was connected to a 60 $\mathrm{m^3}$ vacuum tank. The flow was controlled using a quick release shutter valve and the required steady mass flow was achieved approximately two seconds after initiation. A run time of approximately 20 seconds was achieved at a constant maximum mass flow of approximately 1.51 $\mathrm{kg\,s^{-1}}$ ($M_i = 0.58$). The mass flow was monitored for the duration of the experiments using static pressure measurements in the intake and was found to be steady throughout.

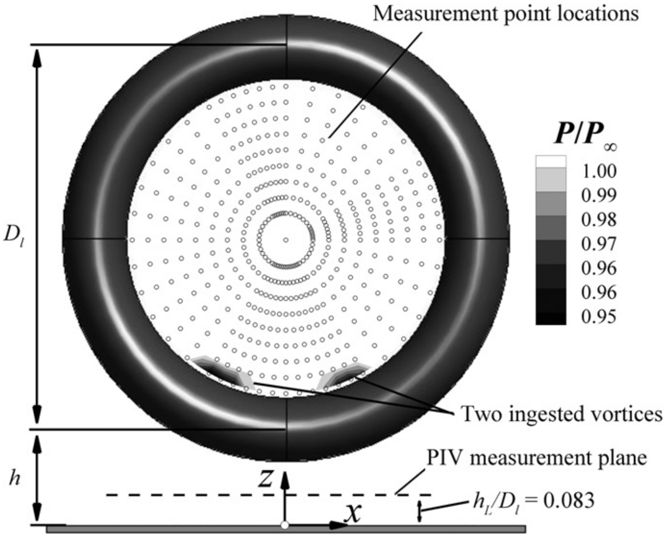

Fig. 2. Typical total pressure contour plot for the no-wind ground vortex ($h/D_l = 0.25$, $M_i = 0.58$).

2.2. Intake total pressures system

The intake was fitted with four total pressure rakes, each comprising nine total pressure probes with a head diameter of 1.5 mm. Total pressure measurements were taken at a location equivalent to a nominal aerodynamic interface plane $0.7D_i$ from the highlight plane. A set of 36 equi-spaced static pressure ports are also positioned around the inner circumference at an axial location in-line with the total pressure measurement plane. The pressure measurements were taken using a set of 40 PX139-005D4V differential pressure transducers. Each pressure transducer has a range of $+/-5$ psi with typical repeatability of 0.1% full-scale and the measurements were acquired simultaneously. For each configuration, an acquisition time of 5 seconds was used with a sampling frequency of 600 Hz. A total of 432 measurement points were obtained for each configuration by rotating the model around its axis (Fig. 2).

2.3. PIV methodology

A TSI stereoscopic PIV system was used to acquire all three-components of velocity on a plane. The PIV system consists of two four-mega pixel cameras used with 60 mm focal length lens. The