EXPERIMENTAL ANALYSIS OF THE UNSTEADY, TURBULENT FLOW THROUGH THE FAN STAGE OF A HIGH-BYPASS TURBOFAN IN WINDMILLING CONDITIONS

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ABSTRACT
A detailed study of the unsteady airflow through the fan stage of a bypass turbofan is proposed. Experiments are conducted in the turbofan test facility of ISAE, specially suited to reproduce windmilling operation in an ambient ground setup. Hot-wire anemometry is used to obtain steady Mach number and flow angle profiles as well as to characterize the unsteady, turbulent flow, at different stations across the fan stage (fan inlet, outlet and rotor/stator interface). Phase averaging of unsteady signals and integral length scale estimations provide further evidence of the presence of a vortex shedding from the stator, as well as the fact that it is correlated to the rotor blade passing frequency. Self-similarity of mean Mach number, flow angle and turbulent intensity profiles is observed. Furthermore, turbulent scale profiles are found to scale well with blade passing period.

KEYWORDS
TURBOFAN, WINDMILLING, HOT-WIRE ANEMOMETRY, TURBULENT SCALES

NOMENCLATURE

<table>
<thead>
<tr>
<th>Latin letters</th>
<th>Greek letters</th>
<th>Operators</th>
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<tr>
<td>$A_2$ Inlet cross section (m$^2$)</td>
<td>$\alpha$ Absolute azimuthal angle (°)</td>
<td>$N_{\text{fan}}$ Rotational speed (rpm)</td>
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<td>$\vec{e}$ Unit vector</td>
<td>$\beta$ Relative azimuthal angle (°)</td>
<td>$N_{tr}$ Number of blade passings (-)</td>
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<td>$h$ Distance to hub (m)</td>
<td>$\Phi_2$ Dimensionless mass flow parameter (-)</td>
<td>$\mathcal{R}$ Ideal gas constant for air (287.04 J/kg/K)</td>
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<tr>
<td>$h/h_{\text{max}}$ Normalized distance to hub (-)</td>
<td>$\sigma_v$ Standard deviation of $v$ (m/s)</td>
<td>$R_{vv}$ Auto-correlation function (-)</td>
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<tr>
<td>$i_r$ Rotor incidence (°)</td>
<td>$\tau$ Correlation time lag (s)</td>
<td>$T$ Temperature (K)</td>
</tr>
<tr>
<td>$i_s$ Stator incidence (°)</td>
<td></td>
<td>$T_r$ Blade passing period (s)</td>
</tr>
<tr>
<td>$I_v$ Turbulence intensity</td>
<td></td>
<td>$v$ Velocity magnitude (m/s)</td>
</tr>
<tr>
<td>$L_t$ Temporal turbulent length scale (s)</td>
<td></td>
<td>$\sigma_v$ Standard deviation of $v$ (m/s)</td>
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<tr>
<td>$\overline{M}$ Time averaged Mach number (-)</td>
<td></td>
<td>$\tau$ Correlation time lag (s)</td>
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<tr>
<td>$M_{2A}$ Mach number at engine inlet (-)</td>
<td></td>
<td>$\sigma_v$ Standard deviation of $v$ (m/s)</td>
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<tr>
<td>$\beta_{\text{rotor}}$ Rotor leading edge metal angle (°)</td>
<td></td>
<td>$\tau$ Correlation time lag (s)</td>
</tr>
<tr>
<td>$\alpha_{\text{stator}}$ Stator leading edge metal angle (°)</td>
<td></td>
<td>$\sigma_v$ Standard deviation of $v$ (m/s)</td>
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INTRODUCTION

When an aircraft engine flames out during flight, the ram pressure at the fan inlet creates an internal airflow that causes spool rotation, leading to windmilling operation. The prediction of key performance parameters in these conditions, such as the in-flight relight capability, the fan rotational speed, or the drag of an inoperative engine in flight, is crucial for engine designers. Studies on turbofan windmilling and, more generally, on sub-idle operation, focus on the whole engine by resorting to either thermodynamic engine cycle modelling (Braig et al., 1999; Riegler et al., 2003; Fuksman and Sirica, 2012) or performance experiments (Wallner and Welna, 1951; Mishra et al., 2008). Although this global approach provides with essential information on engine performance, it brings little insight into the aerodynamics of the different turbomachinery elements. Yet a detailed understanding of the flow features inside the critical components is essential for a reliable prediction of the overall performance, especially in severe off-design operating conditions. Available detailed experimental and numerical studies, conducted on a compressor cascade (Zachos et al., 2011) and on a contemporary high-bypass ratio turbofan in an altitude test cell (Prasad and Lord, 2010) indicate that, in windmilling operation, the fan stage operates under severe off-design (negative) angle-of-attack conditions, leading to the development of flow separation on both rotor and stator. These observations were confirmed by a previous experimental study on a small, geared turbofan, at ground level (García Rosa et al., 2015). These studies agree that the relative flow leaves the fan at nearly the metal angle, and that the bulk of the pressure loss occurs in the stator. A recent study (Dufour et al., 2015) has further shown that a steady numerical approach fails to reproduce some important features of the flow. The authors conducted unsteady simulations on a 2D section of the fan stage. They show that the presence of flow separation in both the rotor and stator leads to a strong rotor/stator interaction, in which the rotor wake triggers a periodic movement of the reattachment point at the trailing edge of the stator, leading to vortex shedding. Due to the 2D nature of the simulated section, the results are not directly representative of the 3D flow, and the question is still open whether the vortex shedding occurs synchronously with the rotor wake passage. This paper aims at developing a better understanding of the unsteady, turbulent flow features through the fan stage. At the same time, a first experimental database is constituted, for the validation of steady numerical simulations.

EXPERIMENTAL SETUP

The engine under consideration is an advanced, high bypass ratio, unmixed flow geared turbofan developed by Price Induction. Figure 1 shows a schematic view of the engine layout and instrumentation.

The engine is equipped with conventional instrumentation consisting of steady pressure and temperature measurements as depicted in the upper part of Figure 1. A set of radial intrusion ports completes this setup. For each station in the lower part of Figure 1, a number of ports
Figure 1: Engine conventional instrumentation, traverse positions and station nomenclatures.

located at the different azimuthal positions allow the introduction of probes. Tests are carried out on the ISAE turbofan test facility, which has been suited to simulate windmilling conditions at ground level. A 75 kW centrifugal fan is used to blow air through the engine, up to 6 kg/s mass flow rate and a local Mach number of 0.16 at the engine inlet. Fuel feed is naturally cut off. A more complete description of the setup as well as the windmilling operating range under study can be found in García Rosa et al. (2015). The operating point is defined by the dimensionless flow parameter at engine inlet

\[
\Phi_2 = \frac{\dot{m}_2}{p_{i,2}} \sqrt{\frac{\theta_i}{T_{i,2}}} A_2.
\]  

The values of rotational speed, and the resulting blade passing frequency (BPF) are recalled in table 1.

<table>
<thead>
<tr>
<th>(\Phi_2) (–)</th>
<th>0.09</th>
<th>0.11</th>
<th>0.13</th>
<th>0.15</th>
<th>0.18</th>
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<td>(N_{\text{fan}}) (rpm)</td>
<td>1050</td>
<td>1330</td>
<td>1610</td>
<td>1900</td>
<td>2200</td>
</tr>
<tr>
<td>BPF (Hz)</td>
<td>245</td>
<td>310</td>
<td>375</td>
<td>440</td>
<td>510</td>
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Table 1: Rotor parameters as a function of the tested windmilling operating points.

The flow velocity magnitude and azimuthal angle are measured across the fan stage by using a dual hot wire probe. The anemometer is a Dantec 2D fiber-film-probe 55R52 connected to Dantec conditioners operating in the constant temperature mode. Velocity and directional calibrations have been performed by exposing the probe to a set of known velocities and flow angles in the free jet of the Dantec calibration unit. During the experiments the probe output voltages are reduced into measured velocity and flow angle by applying a look-up table method, and temperature correction is applied according to Jorgensen (2002). The probes are radially introduced in the flow, so that the plane of the wires coincides with the local azimuthal, blade-to-blade plane \((\hat{e}_x, \hat{e}_\theta)\) depicted in figures 2.b and 5. Precision stepper motors allow the probes to traverse the flow radially, and rotate along their axis. The initial positioning consists in
Probes for hot-wire anemometry

Pt-plated tungsten wire, diameter 0.5 mm, for low-turbulence flows of temperatures up to 150°C and cover velocities up to 500 m/s in pure air. Nickel film deposited on 70 µm diameter quartz fiber. Overall length 1 mm, ... 1 mm in the radial direction and 1° in the azimuthal direction. Radial explorations have been carried out at the fan inlet (station 2A, port B-08), between rotor and stator (station 2R, port B-01) and the fan outlet (station 21A, port B-06), as shown in Figure 2. The unsteady and turbulent components of the flow field are extracted using phase averaging procedure thanks to the high frequency response of hot-wire probe. For the experiments performed, the sampling frequency ranges from 50kHz at stations 2A and 2R, and up to 84kHz at station 21A. For each measurement point, the sampling time is fixed to 50 rotor revolutions so that phase averaging is computed over 700 blade passing periods. The phase averaging is performed thanks to an optical sensor capturing the rotor blade passings. The output signal of the optical encoder is sampled at the same sampling rate as the hot-wire signals.

STEADY ANALYSIS

A steady analysis is performed by time averaging the velocity and flow azimuthal angle at each location independently of the rotor blade passing period. This analysis specifically highlights the existence of flow separation on both the rotor and stator blades leading to the stagnation pressure loss that is typically found in windmilling conditions.

The time averaged Mach number profiles at stations 2A, 2R and 21A are shown in Figure 3. For each station, the results for the different windmilling operating points are displayed. Profiles are non-dimensionalized with the engine inlet Mach number $M_{2A}$, measured at mid-span ($h/h_{max} = 0.5$), in order to observe the inlet conditions dependency. Results are consistent with previous work (García Rosa et al., 2015; Dufour et al., 2015). At engine inlet (Figure 3 (a)), the Mach number is uniform across the first 75% of the span, then decreases near the shroud. This is attributed to the large boundary layer that develops along the 4m long duct linking the windmilling blower to the engine. Downstream of the rotor (Figure 3 (b)), the results show a flow acceleration compared to engine inlet 2A. A large part of this acceleration is due to streamtube contraction, between 2A (upstream of the spinner) and the fan plane, and then across the rotor. This effect is more pronounced close to the hub due to the meridional channel geometry (Figure 1). In windmilling, the inner sections of the fan operate in compressor mode, while the outer sections operate in turbine mode (Prasad and Lord, 2010; García Rosa et al., 2015). However, since the inlet flow is purely axial, the absolute velocity increases along the entire
span. This effect is more pronounced at the hub because the flow turning (in the absolute sense) is more important there due to the shape of the blade. Downstream of the stator (Figure 3 (c)), a strong velocity deficit is observed with a minimum Mach number located at $h/h_{max} = 0.65$. This corroborates the existence of another flow separation on the stator blades. According to Dufour et al. (2015), this flow separation has a more complex topology than on the rotor blade and takes the shape of a massive 3D separation. Indeed, the separation on the stator blade increases in size along the span and reaches a maximum at around 60% span, where the flow separates on the leading edge without reattachment. A massive flow separation is thus observed at this position, leading to a high velocity deficit as observed in Figure 3.c. For the same tested engine in windmilling conditions, García Rosa et al. (2015) state that stagnation pressure losses are encountered in the turbine-like mode zone along the fan stage, that is, for $h/h_{max} > 0.4$. More specifically, the massive flow separations that develop on stator blades, around 60% span, widely contribute to losses, which is consistent with the conclusions of Prasad and Lord (2010). Finally all the profiles presented in Figure 3 show a fairly good self-similarity with respect to the range of tested inlet windmilling operating points. Indeed, the size of flow separations on both the rotor and the stator as well as the strength of velocity deficit observed in the wakes are independent of the inlet flow parameter. The presence of flow separations on both the rotor and the stator blades can be explained by highly negative incidences in windmilling conditions. Time averaged profiles of incidence at the rotor and the stator inlets are presented in Figure 4. In both cases, the incidences are negative along the whole span, which is likely to generate separation on concave surfaces of the rotor and stator blade. Additionally, it can be observed that the incidence is less negative on the rotor than on the stator, which suggests that the flow separation is more pronounced in the latter, as sketched in Figure 5. Remarkably, a local minimum of incidence is observed around $h/h_{max} = 0.65$, which matches the maximum of velocity deficit in the stator wake as described in Figure 3 (c). This explains the larger size of the stator
separation around 60% span observed by Dufour et al. (2015). Finally, similarly to the Mach number profiles, a fairly good self-similarity of incidence profiles is observed in the range of inlet flow parameters being tested.

Figure 4: Incidence through the fan stage: (a) rotor inlet, (b) stator inlet. $\beta_{\text{rotor}}$ and $\alpha_{\text{stator}}$ are the metal angles of the rotor and stator leading edge, respectively.

UNSTEADY AND TURBULENT FLOW STRUCTURES

The existence of flow separation on both the rotor and stator in windmilling conditions leads to complex unsteady interaction between the rotor and stator wakes. The recent numerical study of Dufour et al. (2015) has shown that the rotor wake triggers a periodic movement of the stator flow separation leading to vortex shedding. In order to confirm experimentally this mechanism, the hot-wire signals have been post-processed using phase averaging method as suggested by Fernández Oro et al. (2007). In this case, each time series of velocity $v(r, t)$ (and flow angle $\alpha(r, t)$) is decomposed into a periodic, deterministic component $\tilde{V}(r, t)$, and a random component $v'(r, t)$, as per

$$v(r, t) = \tilde{V}(r, t) + v'(r, t),$$

where the deterministic component $\tilde{V}(r, t)$ is obtained by phase averaging over the $N_{tr} = 700$ rotor blade passing periods. This is defined by

$$\tilde{V}(r, t) = \frac{1}{N_{tr}} \sum_{n=0}^{N_{tr}} v(r, t + n \cdot T_{tr}),$$

where $T_{tr}$ is the blade passing period. Note that in order to get in-phase information at all measurement locations, a reference time is defined and locked to a blade passing signal by...
triggering the data acquisition with the optical blade detector signal. Using this formulation, the unsteady component of the velocity $\tilde{V}(r, t)$ can be decomposed into

$$\tilde{V}(r, t) = \overline{V}(r) + V(r, t),$$  \hspace{1cm} (4)

where $\overline{V}(r)$ is the steady time averaged component and $V(r, t)$ is the fluctuating component. From this formulation, the level of velocity fluctuations around the phase averaging can be expressed as an unsteady turbulence intensity $\tilde{I}_V(r, t)$ by

$$\tilde{I}_V(r, t) = \frac{\sqrt{\overline{v'^2}}}{\overline{V}(r, t)} = \frac{1}{\overline{V}(r, t)} \left[ \frac{1}{N_{tr}} \sum_{n=0}^{N_{tr}} v'^2(r, t + n \cdot T_r) \right]^{1/2} \hspace{1cm} (5)$$

Contours of the phase averaged unsteady component of Mach number $\tilde{M}$, as a function of the blade passing period $T_r$, is plotted in Figure 6 for both the rotor and stator outlet. In Figure 6 (a), the periodic emission of the rotor wake is clearly visible and is distinguished by periodic diagonal stripes of low Mach number for $h/h_{\text{max}} < 0.6$. Moreover, for $h/h_{\text{max}} > 0.6$ a periodic passing of strong velocity deficit in line with the diagonal stripes is observed.

Interestingly, this strong velocity deficits are located along the last 40% span, close to the rotor blade tip where the separation bubble on the rotor blade roughly fills the last 75% of chord, as pointed out by Dufour et al. (2015) through numerical simulation. This suggests that the periodic high-velocity deficit observed near the shroud may correspond to the periodic emission of wakes generated by the flow separation on the rotor blades. Downstream of the stator (Figure 6 (b)) another unsteady process is observed. Contours of unsteady Mach number display large periodic velocity deficit patches being convected downstream of the stator blades. These patches are located between $h/h_{\text{max}} = 0.6$ and $h/h_{\text{max}} = 0.8$, with maximum of velocity deficits observed at $h/h_{\text{max}} \approx 0.65$, which corresponds to the position of the massive flow separation on the stator blade, as concluded in steady analysis. In this case, the periodic signature of strong velocity deficit downstream of the stator blades seems to be correlated to a periodic convection of the stator flow separation wake in the form of a vortex shedding. Finally, the observed periodicity of this process is connected to the rotor blade passing period which confirms that the unsteady wake of the stator is modulated by the rotor wake.
The rotor/stator wakes modulation has been explained numerically by Dufour et al. (2015), stating that the stator vortex shedding is triggered by a periodic variation of the stator incidence, under the periodic passing of the rotor wakes. Experimental results presented in Figure 7 confirm this description. Figure 7.a shows the phase averaged unsteady components of the absolute flow angle $\bar{\alpha}$ at the stator inlet and Figure 7.c presents its associated time series at the specific height $h/h_{\text{max}} = 0.65$, where vortex shedding from stator is observed. It is observed that the passing of the rotor blade wake generates a periodic variation of the absolute flow angle. More specifically, for $h/h_{\text{max}} > 0.4$, negative values of flow angle are observed with high level of periodic fluctuations at $h/h_{\text{max}} = 0.65$, certainly associated with the existence of flow separation on the rotor blades. At $h/h_{\text{max}} = 0.65$, the time averaged component of the flow angle $\bar{\alpha}$ displays a severe off-design value leading to flow separation on the stator blade as suggested in the steady analysis ($\bar{\theta} = -42^\circ$). However, the unsteady component of flow angle $\tilde{\alpha}$ fluctuates from highly to weakly negative values leading to a periodic fluctuation of the stator incidence. This confirms the findings of Dufour et al. (2015) that this unsteady mechanism triggers a periodic movement of the reattachment point at the trailing edge of the stator, leading to vortex shedding.

The phase averaged unsteady component of turbulent intensity $\tilde{I}_v$ downstream of the stator is presented in Figure 7.b while its associated time series at $h/h_{\text{max}} = 0.65$ is shown in Figure 7.d. At stator outlet, contours of $\tilde{I}_v$ display periodic patterns of high turbulence levels (up to 21%) in phase with the strong velocity deficit described in Figure 6.b and located at $h/h_{\text{max}} = 0.65$. Consequently, it can be said that vortex shedding from the stator is connected to the highly turbulent patches periodically convected downstream. By considering that the centers of convected large scale structures are associated to maximum of $\tilde{I}_v$ at $h/h_{\text{max}} = 0.65$, it can be observed that frequency signature of the stator vortex shedding matches the rotor blade passing frequency as suggested by Dufour et al. (2015).

Thanks to phase averaging procedure, turbulent velocity fluctuations are obtained by subtracting the unsteady component from velocity time series. Therefore, the steady turbulence intensity is assessed using

$$I_v(r) = \frac{\sqrt{\bar{v}^2(r)}}{\bar{V}(r)},$$

(6)
Figure 7: Contours of the phase averaged absolute flow angle and turbulence intensity and phase averaged time series for $\Phi_2 = 0.18$: (a) contours of $\tilde{\alpha}$ at rotor outlet (2R), (b) contours of $\tilde{I}_v$ at stator outlet (21A), (c) time series of $\tilde{\alpha}$ at $h/h_{\text{max}} = 0.65$ at station (2R), (d) time series of $\tilde{I}_v$ at $h/h_{\text{max}} = 0.65$ at station (21A).

and the turbulent time-scale $L_t$ is obtained from the auto-correlation function,

$$R_{vv}(r, \tau) = \frac{\langle v'(r, t) \cdot v'(r, t + \tau) \rangle}{\nu^2}, \quad (7)$$

where $\tau$ is the correlation time lag. $L_t$ is then assessed by integrating $R_{vv}(r, \tau)$ until the first zero crossing.

Profiles of turbulence intensity $I_v$ are shown in Figure 8 at the different stations 2A, 2R, 21A along the fan stage. Turbulence intensity profiles show that the level of turbulence is globally unchanged across the fan stage, along the first 20% of the blade span ($I_v \approx 3\%$). Turbulence is uniform at the inlet (2A) for $h/h_{\text{max}} < 0.7$, despite a higher level observed near the shroud, caused by the development of the upstream boundary layer. Downstream of the rotor (2R) increasing values, up to 12%, are observed in the last 50% of the span. This is caused by the rotor flow separation which generates a shear layer downstream of the rotor, producing turbulence. At stator outlet (21A) substantial levels of turbulence (up to 18%) are observed at $h/h_{\text{max}} = 0.65$, which is consistent with the vortex shedding mechanism previously described.

Figure 9 presents the profiles of the $T_r/L_t$ ratio across the fan stage, for the different inlet windmilling conditions. The ratio $T_r/L_t$ gives the number of turbulent scales being convected during a blade passing period. The results demonstrate a fairly good self-similarity, which indicates that turbulent timescales across the fan stage scale well with the blade passing period in
Figure 8: Turbulence intensity profiles across the fan stage.

Figure 9: Turbulent time scale profiles across the fan stage.
windmilling conditions. Moreover, turbulent time scale profiles are consistent with the variation of turbulence intensity. Indeed, the number of turbulent scales increases in the regions of high turbulence intensity, especially in the wake of both the rotor and the stator. Interestingly, the $T_r/L_t$ profiles downstream of the stator display a sharp increase for $h/h_{\text{max}} > 0.3$, in accordance with the presence of the stator flow separation. However, the smallest timescales (ie. the maximum of $T_r/L_t$) are observed at $h/h_{\text{max}} = 0.4$, while the maximum of turbulence intensity is found at $h/h_{\text{max}} = 0.65$. These results are not still completely understood and need further investigations.

CONCLUSION

An experimental investigation of the unsteady, turbulent flow through the fan stage of a bypass turbofan in windmilling condition has been performed using hot-wire anemometry. The steady analysis of the flow corroborates the existence of flow separations on both the stator and the rotor, independently of the inlet flow parameter. The massive flow separation on the stator blades is found to be triggered by highly negative incidence. The unsteady characterization of the flow field, through phase averaging, allows the observation of vortex shedding downstream the stator. Results demonstrate that the periodic variation of stator incidence modulates the vortex shedding downstream the stator, with a frequency signature linked to the blade passing frequency. Flow separations through the fan stage generate higher level of turbulence and smaller turbulent length scales. Finally, vortex shedding downstream of the stator is captured, in the form of a periodic advection of highly turbulent patches.

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REFERENCES


