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A METHOD FOR THE CHARACTERIZATION OF FANS DOWN TO ZERO SPEED AND ANALYSIS OF BYPASS REVERSE FLOW DURING GROUND START

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ABSTRACT

The sub-idle operation of turbofan engines for ground start and relight has been of interest since the advent of the turbofan engine architecture and more so in recent years. Apart from being able to start the engine on the ground quickly, a significant challenge in the engine design exercise is to demonstrate the capability of in-flight relight under windmill conditions. This becomes more critical for very high bypass ratio (VHBR) turbofans where the core mass flow rates are even lower due to the large bypass ratios. To test the ability of an engine to relight, it is necessary to know the component sub-idle performance characteristics, which are normally unknown. Over the years, substantial and significant work has been published on the generation of mean-line methods to predict the axial flow core compressor sub-idle performance; however, there is practically no previous research published on standard tools for sub-idle regime in axial-flow fans. In this investigation, the appropriateness of a low-order method based on interpolation is examined for the sub-idle performance characterization of the fan. It is shown that although results for the fan root may lack sufficient accuracy, the obtained solutions for the fan tip match CFD predictions very well. Also, a numerical investigation is carried out to study the effect of reverse flow through the bypass duct during ground start. In general, it is shown that reverse bypass duct flow during ground start has very little effect on core entry engine flow.

INTRODUCTION

The study of an aero-engine in the sub-idle regime is necessary to assess its performance during far off-design events, such as ground start, pull-away, windmill and altitude relight. It is then important to characterize the performance and understand the aerodynamics of the turbomachinery components at low and zero speeds (Zachos *et al.*, 2011). This becomes even more critical when there is limited geometric information available and lack of rig test data, which is usually the case (Kuzke, 2019). Despite the various numerical and computational simulation tools available nowadays, it is still a challenge to model accurately and reasonably fast the flow physics of turbo-components at sub-idle speeds for whole-engine performance assessments. For this reason, there is a need to develop robust and computationally inexpensive methods to generate sub-idle maps based on analytical and physical approaches.

Recently, significant work on sub-idle compressor performance has been done regarding the development of loss and deviation correlations (Ferrer-Vidal *et al.*, 2019) and low-order methods for performance characterization (Righi *et al.*, 2020) (Ferrer-Vidal, Iglesias-Pérez and Pachidis, 2020). It is well known that the study of the sub-idle problem in the core compressor is vital during relight as it sets the airflow required for the ignition in the combustor. This, in turn, requires the investigation of the low-pressure compressor (LPC) at low speeds and marginal mass flows. To determine the LPC pressure losses and core mass flow rates it is then necessary to perform a holistic study of the fan, outlet guide vane (OGV), and engine section stator (ESS). It then becomes more evident to investigate sub-idle fan performance in modern VHBR engines since the bypass ratio increases dramatically during windmilling (Jones, 2002). This is well explained, as the airflow tends to follow the path of least resistance (Curnock, 1993). Due to the spanwise variation in fan blade incidence as the blade pitch changes, the fan might experience a different performance operation along the span: the root working as a compressor, whilst the tip operating as a turbine. The turbine action at the tip generates more torque and this tends to accelerate the low-pressure spool in principle up until free windmilling.

In contrast to sub-idle compressor work, there are limited standards methods known on the same topic for fans. Because of the two-dimensional flow effects present in a fan blade component, Jones (Jones, 2002) treated them with the same methodology as in the compressors but with large flow capacity and low-pressure ratio.

The split strategy for fans discussed by Kurzke (Kurzke, 1996), where a primary beta map is defined and a secondary map is derived when the speed and efficiency lines are drawn through the data points, appears to work in principle. Nonetheless, efficiency is not defined in the sub-idle regime and therefore the efficiency lines need to be replaced by torque lines. For this reason, this manuscript intends to present a methodology to characterize fans from locked-rotor to idle speeds. During this exercise, reverse flow through the bypass duct was observed from the early stages of ground start, i.e. at locked-rotor.

METHODOLOGY

This study is based on the geometry of a typical, modern VHBR engine, called hereinafter as ‘Engine A’ for confidentiality purposes. Furthermore, a 3D CFD model is set up to provide reference values to compare against.

The same Engine A CFD model is used to assess the fan performance during ground start. Along the study, characteristics are obtained for both the fan tip and the fan root. A clear definition of the extent of each fan portion is required. The fan tip is the portion of the fan wet by flow proceeding to the bypass. Similarly, the fan root is the portion of the fan wet by flow proceeding to the core engine.

This work has been produced as part of the PROTEUS project, under the H2020 CleanSky2 program, with Cranfield University as the lead partner and Rolls-Royce as the topic manager. PROTEUS stands for PeRformance and Operability of Turbofan Engines Under Sub-idle.

3D CFD Analysis

In this section, solver general aspects and mesh convergence are discussed. Figure 1 shows the CFD model of Engine A, which consists of three domains: fan, OGV and ESS. The fan domain includes the splitter.

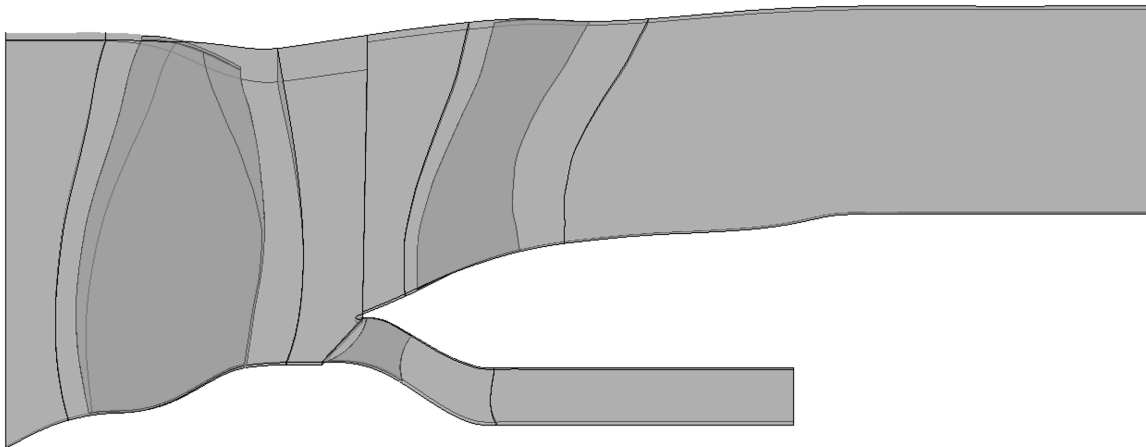


Figure 1 Engine A fan environment CFD model illustration. Fan domain includes the splitter and is attached to the OGV or bypass domain, on the top right, and to the ESS or core domain on the lower right. Both bypass and core domains are extended about 10 chords of their corresponding blade. Image aspect ratio has been modified for confidentiality reasons.

The fan blade, splitter, OGV and ESS of Engine A are modelled within ANSYS CFX TurboGrid 19.1 to be used with ANSYS CFX Solver 19.1, a CFD software widely used in turbomachinery.

The low-pressure system geometry was provided by the sponsor. Outlet domains have been extended to mitigate the effect of constant boundary conditions on component performance. Flow is admitted axially at the fan inlet for convenience. This may induce some inaccuracy near the hub due to the spinner’s slope, but it is deemed minimal especially at sub-idle.

All studies are RANS simulations with $k-\omega$ SST turbulence model, which is the usual turbulence model used in turbomachinery. This turbulence model includes an automatic near-wall treatment method as wall function. To save computation time, single and double passage simulations with periodic interfaces along the domain are run. For the advection term and turbulence numerics, a high-resolution scheme was used.

The mesh sums up to 5.5 million elements at approximately 0.5 million elements per passage, with $y^+ \approx 30$. A Grid Convergence Index (GCI) was achieved of 1.5% for torque, 0.2% for mass flow and 0.1% for pressure ratio. These are the typical parameters used to characterize fan performance.

Low-order Method

A low-order mean-line method developed within the PROTEUS project for compression systems (Ferrer-Vidal et al., 2019) (Righi et al., 2020) (Ferrer-Vidal, Iglesias-Pérez and Pachidis, 2020) (Ferrer-Vidal, Pachidis and Tunstall, 2020) (Roig Tió et al., 2020) was adapted to generate fan sub-idle maps, for both tip and root. This method interpolates between locked-rotor line and above-idle speed lines to produce sub-idle characteristics. It admits the torque-free windmill line as an input to trim the interpolation.

Above idle data were provided by the sponsor. These are the official maps used within the company for Engine A's fan. They are obtained from a combination of rig tests and CFD simulations. Characteristics are defined in terms of speed, flow, work and efficiency, which is not convenient at sub-idle. Therefore, original data were converted to speed, flow, pressure ratio and torque. Locked-rotor and windmill lines come from the RANS model results.

CHARACTERIZATION OF FANS

The fan characterization in 3D RANS used the following boundary conditions, as shown in Table 1: total pressure and total temperature at fan inlet, static pressure at bypass outlet and static pressure at core outlet. Axial flow is imposed at fan inlet. Inlet conditions are kept constant throughout the study. Static pressure at both outlets is used as mapping parameter to produce different points along a speed line. When producing tip characteristics, the mapping parameter is naturally the static pressure at bypass outlet, whereas the static pressure at core outlet is kept constant along the speed line. An equivalent procedure is applied when producing root characteristics: the mapping parameter is then the static pressure at core outlet, whereas the static pressure at bypass outlet is kept constant along the speed line. Simulated speeds are 0%, 10%, 20%, and 30% of the fan design speed.

Fan inlet	Total pressure	Total temperature
	1 atm	288.15 K
Tip map	Spool speeds (Core pressures)	Static pressures at bypass outlet
	0% (87 KPa)	100 KPa
	10% (89 KPa)	95 KPa
	20% (90.5 KPa)	85 KPa
	30% (92.5 KPa)	70 KPa
Root map	Spool speeds (Bypass pressures)	Static pressures at core outlet
	0% (90 KPa)	98 KPa
	10% (93 KPa)	90 KPa
	20% (97 KPa)	75 KPa
	30% (101 KPa)	

Table 1 Boundary conditions used to produce fan tip and fan root maps of Engine A CFD model

In general, interfaces between domains (fan to bypass and fan to core) are set as mixing plane. This will circumferentially average the incoming total pressure and deliver an axisymmetric total pressure profile. This setting washes away the fan wake, but produces accurate results for any parameter relevant to performance results (Sanders et al., 2009). When simulating locked-rotor, bypass and core domains are duplicated, thus achieving a pitch ratio close to 1:1 with the fan domain. Interfaces between domains can then be set to frozen rotor. This will not average any variable but will scale them according to the pitch ratio.

Locked-rotor line is a direct output from this CFD activity. With regards to the windmilling line, an interpolation is carried out along each speed line to calculate mass flow and pressure ratio for zero torque.

Low-order Method

Locked-rotor and windmill lines from the CFD study mentioned above are input to the low-order code together with above idle data provided by the sponsor for Engine A. Sub-idle maps are then generated.

Figure 2 shows both low-order and CFD results for fan tip characteristics. Low-order results appear to match CFD results. Mismatch is calculated as the difference of results with the same exit corrected mass flow (and, naturally, the same speed). Exit corrected mass flow acts then as a beta parameter conveniently when beta lines are not defined (Ferrer-Vidal et al., 2018). Mismatch is normalized by the CFD corresponding result for mass flow and pressure ratio (Equation 1), and by a representative mid-map value for torque (Equation 2).

$$e = \frac{|x_{LOC} - x_{CFD}|}{x_{CFD}} \quad (1)$$

$$e = \frac{|\tau_{LOC} - \tau_{CFD}|}{\tau_{ref}} \quad (2)$$

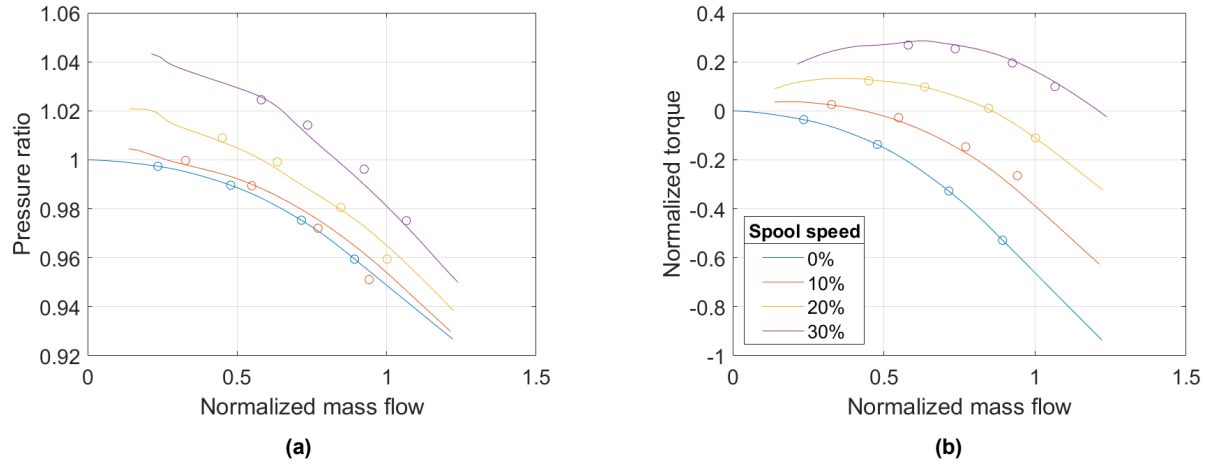


Figure 2 Comparison of low-order generated characteristics for the fan tip (lines) with CFD results (circles). Characteristics are represented as 2a pressure ratio vs mass flow and 2b torque vs mass flow. Locked-rotor line is input to the low-order method from CFD. Mass flow and torque values have been normalized with a mid-map point at 74% speed for confidentiality reasons.

This provides relative errors to assess low-order results accuracy. The average of errors in mass flow is 0.3%, in pressure ratio is 0.3%, and in torque is 1.7%. Locked-rotor line has not been taken into account in these error averages, as it was input directly to the low-order method from CFD.

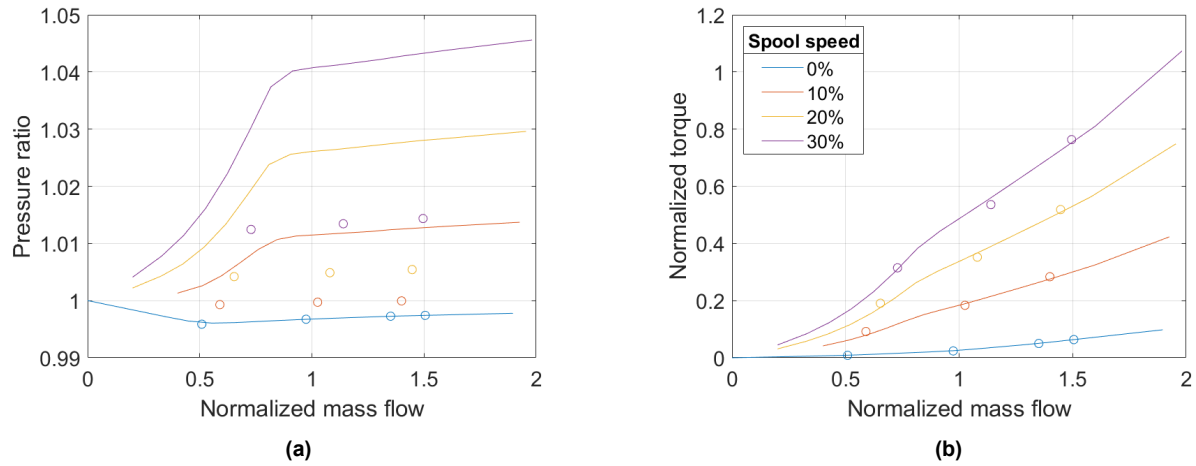


Figure 3 Comparison of low-order generated characteristics for the fan root (lines) with CFD results (circles). Characteristics are represented as 3a pressure ratio vs mass flow and 3b torque vs mass flow. Locked-rotor line is input to the low-order method from CFD. Mass flow and torque values have been normalized with a mid-map point at 67% speed for confidentiality reasons.

Figure 3 shows low-order generated fan root characteristics in terms of pressure ratio and torque. It is clear that the low-order prediction does not match CFD results in pressure ratio. Pressure ratio mismatch error increases with speed, as shown in Table 2. The interpolation distributes speed lines at similar intervals. However, the root configuration changes significantly from locked-rotor to above-idle speeds. As the speed increases, the height of the root portion decreases. Therefore, the blade profile metal angles differ from one speed line to the next. As a consequence, the flow experiences a gradual effect of the increasing speed. In short, low speed lines show a trend to linger around $PR = 1$. The interpolation strategy is incapable of predicting such behaviour.

Therefore, a different approach is proposed for fan root pressure ratio characteristics. Pressure ratio characteristics are fairly horizontal lines, as seen in CFD results of Figure 3a. Indeed, all lines are fairly horizontal, showing very little dependence on mass flow. This allows the averaging of each speed line pressure ratio. Figure 4 displays those pressure ratio averages against rotational speed. Standard deviations are plotted as error bars for reference. Standard deviations are especially small at sub-idle. This means that the assumption of speed lines as horizontal lines is accurate. Therefore, a low order approach for the generation of fan root pressure ratio characteristics could establish a relationship between rotational

Spool speed	10%	20%	30%
Mismatch in pressure ratio	1.0%	1.8%	2.4%

Table 2 Mismatch error in pressure ratio of low-order generated fan root characteristics

speed and pressure ratio. Figure 4 seems to suggest a parabolic shape for that relationship. A least squares fit is applied and showed in Figure 5 which tightly matches given data.

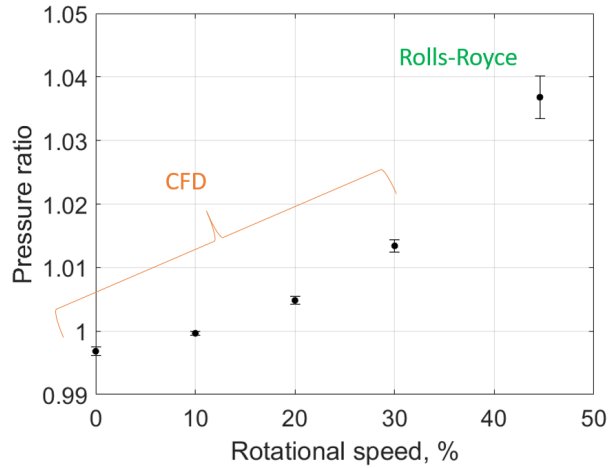


Figure 4 Average of root pressure ratio against rotational speed. Standard deviation is displayed as error bars. A low sub-idle point from sponsor's data is added for reference.

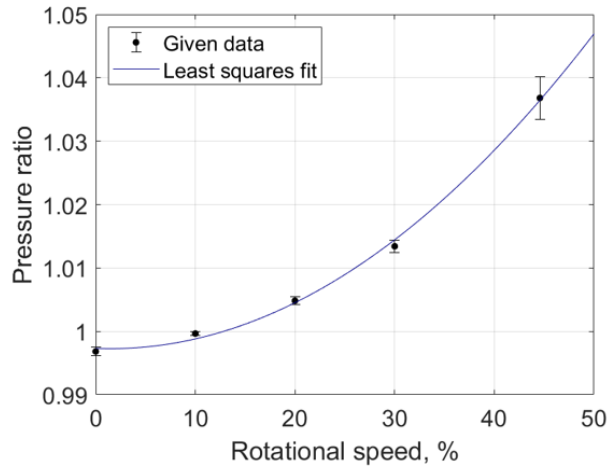


Figure 5 Best parabolic fit to given data of pressure ratio vs rotational speed.

Unfortunately a least squares fit is unrealistic as it needs more data than is usually available. Instead, a parabola using the above idle and the locked rotor points will be defined. A third condition is needed: the assumption of zero slope at zero rotational speed. Figure 6 shows this new relationship together with the least squares fit. It can be seen that both approaches produce very accurate matching to CFD results.

Moreover, the average of errors in mass flow is 1.7% and in torque is 0.6%. This supports the idea that low-order results still match CFD results in mass flow and torque. Note that fan root never performs as a turbine, i.e. reducing flow's enthalpy. The torque-free windmilling line is formed by the points at which a component neither increases nor reduces flow's enthalpy. In a torque vs mass flow graph, this line would appear as a horizontal line at $\tau = 0$. In other words, it is the boundary between stirrer operation and turbine operation. Hence, a torque-free windmilling line is not physically defined for the fan root.

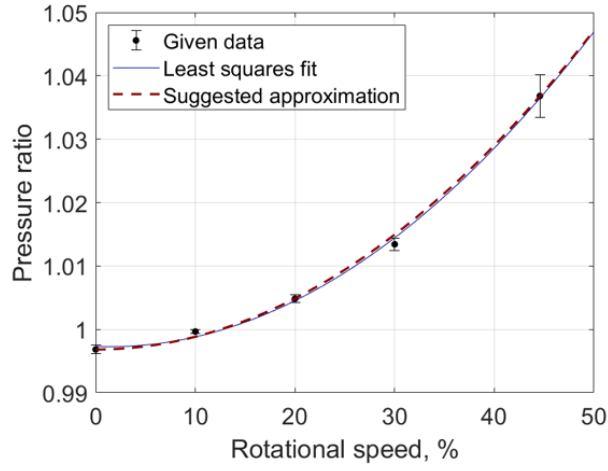


Figure 6 *Suggested parabolic fit using only one above idle point and the locked rotor point. Best parabolic fit appears in the background for reference together with given data.*

GROUND START ANALYSIS

Engine A is used to study reverse flow through the bypass during ground start. A set of four simulations with different core throttle settings is launched. The core throttle setting is determined by a static pressure boundary condition. The boundary conditions applied on both fan and bypass inlets for total pressure and total temperature remain the same as in the performance characterization analysis. However, the bypass outlet is considered this time as inlet to account for the reverse flow. This ground start study runs all simulations at zero speed, as the interest is in the earliest stage of a ground-start operation. Because of the zero-speed condition, a frozen rotor interface is used for all interfaces and the blade passages were duplicated to satisfy the pitch ratio requirements. The boundary conditions applied to the ground start analysis are summarized in Table 3.

Inlets	Total pressure	Total temperature
Fan inlet	1 atm	288.15 K
Bypass outlet		
Outlet	Core pressures (as ratio of inlet total pressure)	
	0.8	
	0.85	
	0.9	
	0.95	
Spool speed	0 rpm	

Table 3 *Boundary conditions used to study reverse bypass flow during the very early stages of a ground start*

Figure 7 shows the losses through the bypass in reverse for all cases. They are very small and can be neglected (for comparison, losses around the fan blade are in the range of 200 – 500 Pa, depending on the case). These losses refer strictly to the OGV and do not include the turning over the splitter. A loss factor is calculated as well (Equation 3), also shown in Figure 7. Nonetheless, it may be deemed misleading due to the small values of both pressure loss and dynamic head. For the calculation of pressure loss, total pressure is mass flow averaged before and after the OGV blade. Dynamic head is calculated by subtracting area averaged static pressure to the total pressure measurement.

$$\Omega = \frac{\Delta P_t}{q} \quad (3)$$

Furthermore, the core throttle setting does not affect the balance between flow through fan inlet and flow through bypass (Figure 8). This balance must then be determined by their corresponding inlet conditions only.

The effect that reverse bypass flow has on core inlet conditions is studied by comparing those results with their equivalent cases without any bypass flow. That is why a new set of simulations is launched where the bypass outlet is artificially closed by a wall. All other parameters remain unchanged. A comparison of flow on these two configurations is presented in Figure 9.

Most performance parameters at core inlet appear nearly unaffected. There is however a consistent increase in flow (Figure 10a) and a consistent increase in total pressure (Figure 10b) in the absence of reverse bypass flow. This certainly

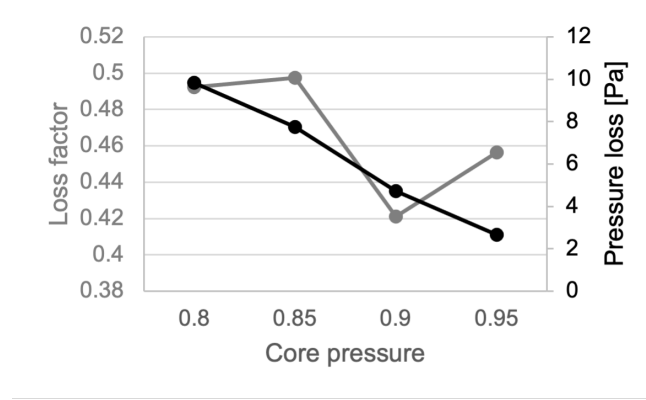


Figure 7 Loss factor and pressure loss across the OGV in reverse for the four cases studied. Note that loss factor does not seem to follow any pattern. This is because of both pressure loss and dynamic head have small values, comparable to the sensitivity of the model. Core pressure given as fraction of inlet total pressure.

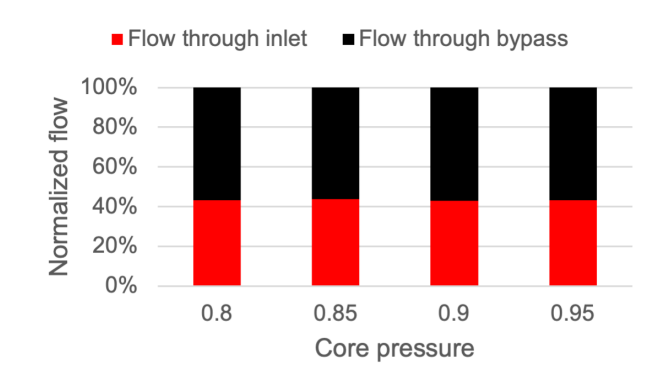


Figure 8 Comparison between flow origin for the four cases studied. Flow is normalized by the total flow proceeding to the core in each case. Core pressure given as fraction of inlet total pressure.

accounts for the small additional losses that a reverse bypass flow adds to the core flow. Total enthalpy remains constant along the domain as there is no work input or output in a zero speed scenario. Figure 10c shows the comparison on torque for cases with bypass reverse flow and cases without flow through the bypass. Fan torque is the only parameter greatly affected by reverse bypass flow. When flow comes from both fan inlet and bypass outlet, the fan blade is mainly wet by a radial flow from tip to root that barely produces any torque. This situation changes if flow comes only from fan inlet, as streamlines proceeding to the core will then produce some amount of negative torque. Still, this amount is in the order of 0.1% of nominal fan torque.

Figure 11 show the streamlines around the ESS in a blade-to-blade representation at 50% span. Flow will hit the ESS on the suction side, with a slightly negative incidence, in both cases. This is because both the fan blade (at zero speed) and the OGV (in reverse) will add similar swirl to the flow. This swirl lingers up to the ESS leading edge regardless of the splitter turning. Nevertheless, circumferential velocity is small with regards to axial velocity, resulting in an almost axial flow at the ESS leading edge.

CONCLUSIONS

A low-order method based on interpolation between locked-rotor and above-idle characteristics has been proved capable of generating fan tip maps down to zero speed. It succeeds in generating fan root torque characteristics down to zero speed. However, it fails to generate accurate pressure ratio characteristics down to zero speed for a fan root. A new strategy is proposed for the fan root pressure ratio characteristics. The horizontal shape of the characteristics is used to determine a relationship between its pressure ratio average value and the rotational speed. This new approach produces accurate maps that complete the whole low-order method for fan characteristics generation down to zero speed.

The very early stage of a ground start has been analysed. The performance, under these circumstances, of a reverse bypass flow has been studied. Losses through an OGV in reverse have been calculated and shown negligible. This does not include the turning over the splitter. Also, the balance between flow through fan inlet and flow through bypass has been found to be insensitive to the throttle setting of the core during a ground start. This balance must then be determined by the corresponding inlet conditions ratio only.

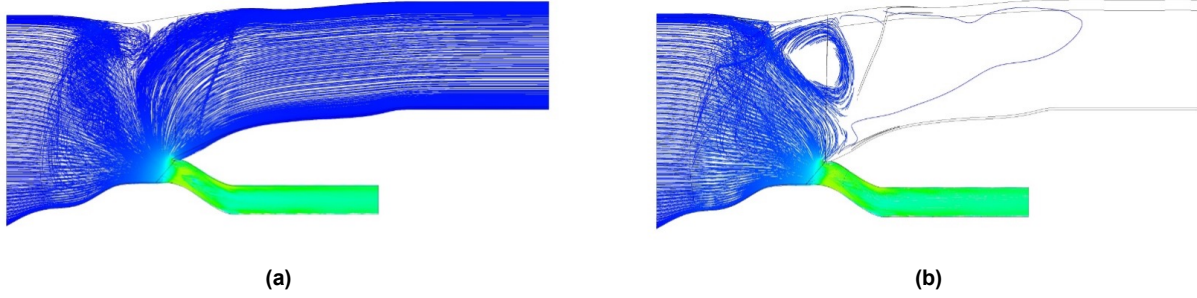
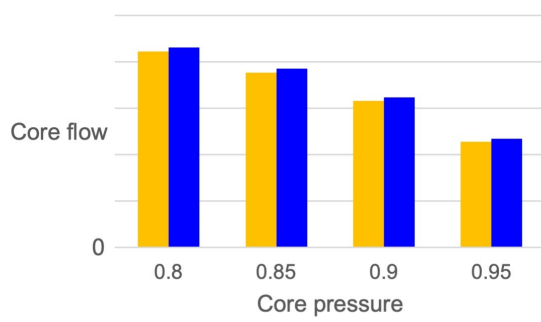
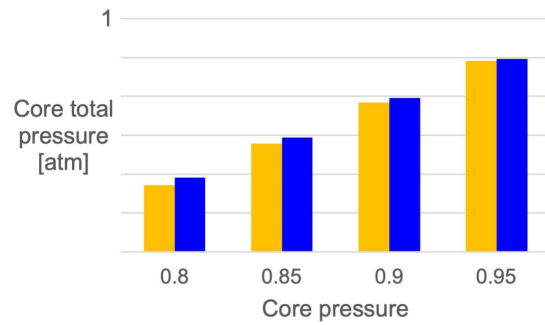


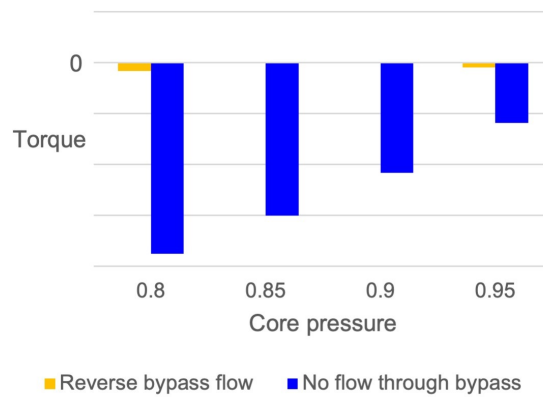
Figure 9 Streamlines through the whole domain for a case 9a with reverse bypass flow and a case 9b without bypass flow. In both cases, core pressure is set to 0.85. Image aspect ratio has been modified for confidentiality reasons.



(a) Comparison on core flow.



(b) Comparison on core total pressure.



(c) Comparison on fan torque.

Figure 10 Comparison of performance parameters between a case with reverse bypass flow and a case with no flow through bypass. Core pressure given as fraction of inlet total pressure.

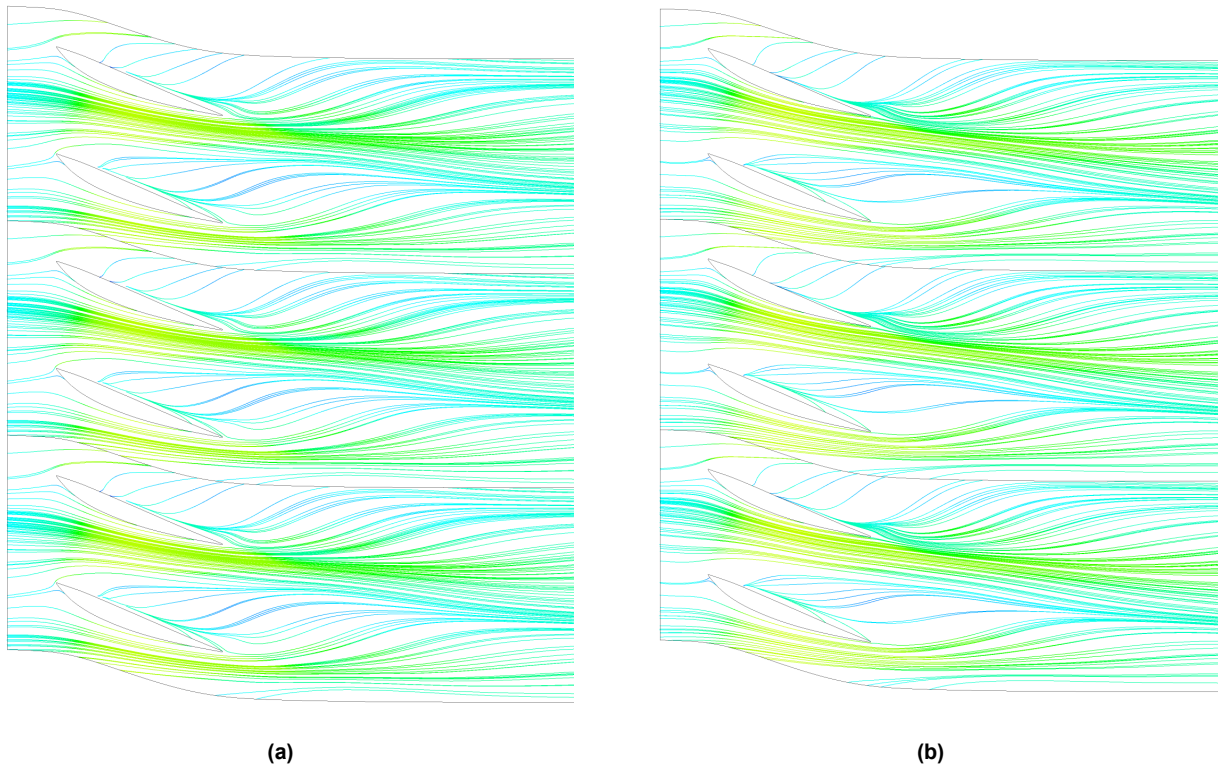


Figure 11 *Illustration of flow streamlines across the ESS at 50% span for a case 11a with reverse bypass flow and a case 11b without bypass flow. In both cases, core pressure is set to 0.8. Image aspect ratio has been modified for confidentiality reasons.*

Furthermore, a sensitivity study has been carried out to assess the effect of reverse bypass flow on core performance. It has been shown to have a very limited effect in terms of mass flow and total pressure at core inlet. A more significant effect has been found about fan torque, even though we believe that numbers are anyway unlikely to amount to something relevant to core performance (the effect is at most in the order of 0.1% of nominal fan torque). Flow streamlines across the ESS have been carefully analysed. They show a large insensitivity to their upstream path, suggesting that both fan blade and OGV in reverse add similar swirl to the flow.

NOMENCLATURE

CFD	Computational Fluid Dynamics
e	Matching error
ESS	Engine Section Stators
GCI	Grid Convergence Index
LOC	Low-Order Code
LPC	Low-Pressure Compressor
OGV	Outlet Guide Vanes
PR	Pressure Ratio
Pt	Total pressure
q	Dynamic pressure
RANS	Reynolds-Averaged Navier-Stokes equations
ref	Reference value
SST	Shear Stress Transport
VHBR	Very High Bypass Ratio
x	Any variable
τ	Torque
Ω	Loss factor

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