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Methodology for the Assessment of Distributed Propulsion Configurations with Boundary Layer Ingestion Using the Discretized Miller Approach

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Abstract – *The growing global environmental awareness has motivated the search for more fuel-efficient aircraft propulsion systems. In this context, a configuration based on distributed propulsion with Boundary Layer Ingestion (BLI) has been found to present potential performance benefits. The concept has been documented and explored extensively during the last few years and various aerodynamic integration issues, such as: high levels of distortion and low intake pressure recovery; have been identified as factors that may be detrimental in realizing the technology full potential. Parametric and parallel compressor (PC) approaches have been used to assess the effect of these aerodynamic issues on propulsors fan performance. However, in the context of BLI, these tools are unable to assess the effects of combined radial and circumferential distortion that are present. In order to assess the combined distortion patterns and the effects of distortion at component and system levels, this study uses a novel method based on semi-empirical correlations denominated the Discretized Miller (DM) approach. This method was developed for BLI systems previously by the author, and it is now incorporated into the propulsor performance method to assess the effects of the combined radial and circumferential distortion patterns. The performance analysis, undertaken at a component and system level, aims to assess several propulsion architectures, using Thrust Specific Fuel Consumption (TSFC) as figure of merit. To define the suitability of the distributed propulsor array in this study, an airframe layout based on the N3-X aircraft concept and High Temperature Superconducting (HTS) electric motor capabilities were assumed. The key contribution of this study is to enable the introduction of the concept of thrust split between energy source and propulsion system in the system analysis, and thereby, allows the assessment of its effects on different propulsion system layouts, while considering the BLI induced distortion. The results obtained with this alternative performance method showed that BLI reduces the fan efficiency of a conventional fan by approximately 2%, whilst corroborating the TSFC trends observed in previous studies. The study also indicates that when sizing effects of propulsors and core-engines were neglected, a propulsion system configuration with 75% thrust split was found optimum.*

***Keywords**: Boundary Layer Ingestion, Distributed Propulsion, Thrust Split, Propulsion Configurations*

Nomenclature

BLI	Boundary Layer Ingestion
C_a	Axial Flow Velocity
DM	Discretized Miller
ε/c	Clearance to Chord Ratio
F_{DP}	Distributed Propulsor Array Thrust
FPR	Fan Pressure Ratio
h/c	Blade Height to Chord Ratio
HTS	High Temperature Superconducting
H_{CS}	Height of the Capture Sheet
h_{BL}	Boundary Layer Height
L_{DP}	Distributed Propulsor Array Width
LE	Leading Edge
mBPR	Main Engine Bypass Ratio
mFPR	Main Engine Fan Pressure Ratio
$\dot{m}_f$	Propulsor mass flow
ml	Minimum Loss
N	Rotational Speed
N_c	CorrectedlRotational Speed
η_f	Fan Isentropic Efficiency
NF	Number of Fans
OC	Optimum Configurations
p	Static Pressure
P	Total Pressure
PC	Parallel Compressor
PW	PropulsorArray Power
r_{EM}	Electrical Motor Radius
r_r	Fan Hub Radius
r_{rt}	Root to Tip Radius

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r_t	Fan Tip Radius
SC	Suitable Configurations
S_{in}	Separation between Propulsors
s/c	Pitch to Chord Ratio
$TeDP$	Turbo-electric Distributed Propulsion
TQ	Torque
T_S	Thrust Split
$TSFC$	Thrust Specific Fuel Consumption
U	Blade Velocity
w_{in}	Mailbox-slot Inlet Width
δ	Deviation Angle
$\dot{m}_c$	Cold Stream Mass Flow of Main Engine
$\dot{m}$	Mass Flow per Propulsor
$\dot{m}_h$	Hot stream mass flow of Main Engine
$\bar{\omega}_{sec}$	Secondary Losses
$\bar{\omega}_P$	Profile losses

I. Introduction

Due to the potential benefits in terms of improved propulsive efficiency, reduced fuel consumption and reduction of environmental pollution, aircraft concepts with Turbo-electric distributed propulsion (TeDP) and BLI have been explored extensively [1], [2]. Studies carried out have shown that implementing (TeDP), and BLI could reduce the fuel burning by 8% and 7-8% relative to today's aircraft respectively [3], [4]. However, these savings may be achieved only with low levels of flow distortion and intake pressure losses [5], [6].

Previous studies [2], [7]-[9] have assessed these aerodynamic issues, and determined the fan performance with one and quasi two-dimensional approaches. However, these methods cannot assess the combined radial and circumferential distortion that BLI systems present. To assess the effects of a combination of these distortion patterns, a method based on semi-empirical correlations [5], [10] has been developed, and incorporated into the propulsor performance tool.

The performance analysis of BLI systems carried out in [11] demonstrated the overall methodology that can be implemented to assess the performance of TeDP systems with BLI. In that analysis, it was highlighted that the parametric approach has certain limitations, which are related with the incapability of assessing the fan performance detriment, when the boundary layer is ingested. In this context, an alternative method denominated the DM approach was developed [10] and examined for the BLI induced distortion in the NASA N3-X aircraft. Since the latter aircraft model is well documented[11], [12], and presents TeDP with BLI, this has been selected for the present work as case of study. In this work, the DM method, aimed for preliminary design of BLI systems, is implemented in the performance analysis of distributed propulsion systems. For this analysis, cruise conditions have been assumed and this correspond to a flight Mach number of 0.84 and an altitude of 12192 m as in [11].

Fig. 1 depicts a scheme of the NASA N3-X conceptual aircraft.

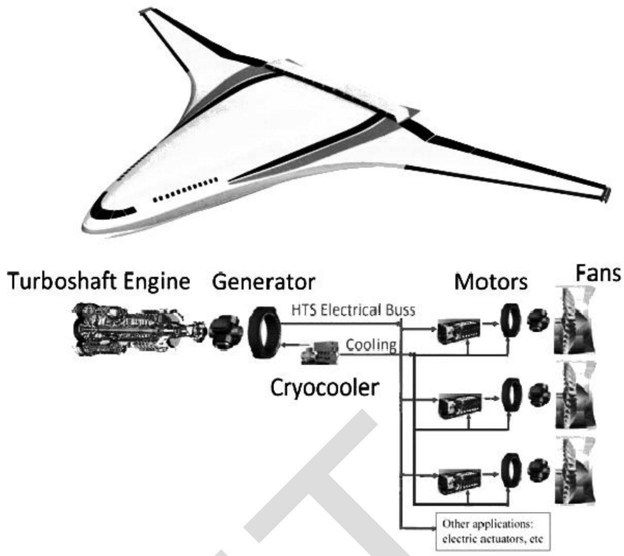


Fig. 1. NASA N3-X aircraft [20]

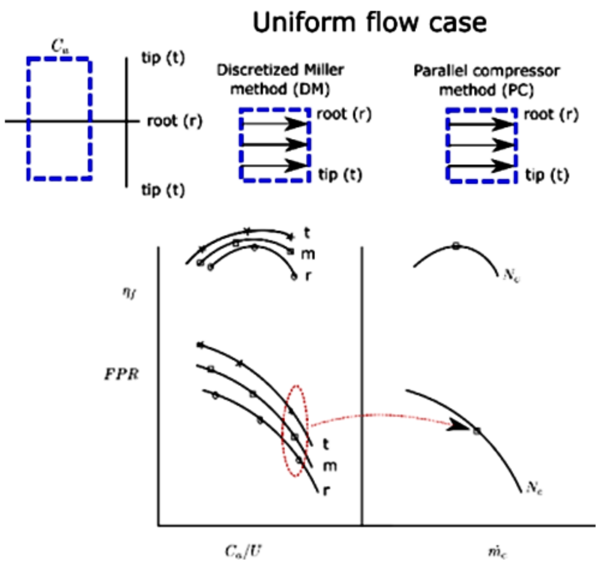
I.1. Distortion Modeling

Modeling distortion enables the incorporation of the inlet flow field characteristics into the analysis. Past studies on effects of distortion [13]-[15] have extensively used the PC approach with this aim.

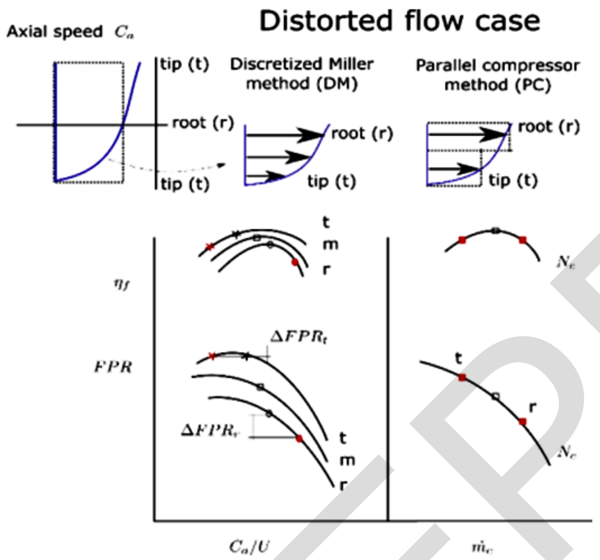
However, the method presents certain limitations which include: assessment of only circumferential distortion, use of two streams in the analysis, and its dependence on a determined compressor map, which can be observed in [16]. These limitations have, therefore, motivated the search of alternative distortion assessment methods.

In this work, the distortion tool developed in [10] is implemented to assess the propulsor and system performance. Some of its advantages include: assessment of combined distortion patterns, fan map independence, low consumption of computer resources and good balance between complexity and accuracy.

Figs. 2 show a comparison between the DM approach and the PC method [17].[18]. The illustrative fan maps presented in Figs. 2 correspond to a fan performing under uniform and distorted conditions. For the DM approach a fan map using the flow coefficient (axial flow velocity (C_a) over meanline blade velocity (U)), as independent variable is used, whilst for the PC approach a conventional fan map with mass flow as variable is plotted. The fan map for the DM approach enables to capture the change of blade performance (fan isentropic efficiency (n_f), and fan pressure ratio (FPR)) in the spanwise direction. Since flow coefficient as variable enables the assessment of different operating points along the blade span, this fan map is used in the DM approach for the flow analysis. To highlight the latter three blade spanwise locations (tip, mid-line and root) are selected and plotted in Fig. 2(a). For the PC method, the corrected blade rotational speed (N_c), and previous fan performance variables are plotted against the mass flow.



(a) Uniform case



(b) Distorted case

Figs. 2. Comparison of DM and PC methods

This conventional fan performance plot, which is used commonly in the PC approach, shows how this assesses the incoming flow (uniform or distorted) as one stream (Fig. 2(b)). The comparison of these two distortion assessment approaches shows that, the assumptions of the DM approach resulted in each stream working at a particular operating condition. In other words, each stream has its own pressure ratio and an efficiency [6].

This enables the assessment of each stream particularly and hence the discretization in radial and circumferential streams. Fig. 2(a) depicts the aforementioned aspect and hence the three points selected in the analysis (root, mid, tip) for the DM approach translates to one point when using the PC method.

Fig. 2(b) shows the trends expected in the operating conditions (red points) when distortion is present. As observed in this figure, whilst the DM approach can assess a large number of streams, the PC method is constrained to two streams.

An important condition in the PC method is the equality of static pressures at the back of the fan, which is assumed to simplify the problem of assessing vorticity and distorted flow issues after the fan. For the DM approach is difficult to assume a similar static pressure at the back of the rotor, due to the difference in pressure increment along the blade span. Therefore, a modified static pressure relationship was implemented. For the DM approach, the axial speed at the rotor exit was iterated till the difference between the static pressure of the blade passage operating at the fan top (highest axial velocities), and bottom (lowest axial velocities) was less than 5%. This value was found as a compromise between accuracy of the method and computing time in the iteration process [10].

I.2. System Analysis

In Valencia's work [11], a system analysis of a TeDP system with BLI using a parametric model, for the fan performance detriment due to BLI, was carried out. In that work, the lack of a tool to assess the detriment in fan performance when BLI is implemented was identified as one of the major constraints to define optimum propulsion architectures. Furthermore, it was observed that this aerodynamic integration aspect, together with the intake pressure losses, were main drivers in the optimum propulsor unit arrangements selection. These results are also corroborated in the work of Liu [19], and the author [15]. As aforementioned, a previous developed parametric methodology [11] was upgraded using the DM approach for the propulsors performance assessment. For this, the inner control volume approach [20] was utilized for the thrust accounting in the propulsor array and main engines. In Fig. 3 is shown an illustration of the propulsion system with the stations included into the calculations. As observed for the configuration proposed the main engines can produce electrical energy for the propulsor array and thrust. In order to define how much thrust is delivered engines and distributed propulsor array is incorporated as design space variable in the system analysis.

The expressions by the main engines, the thrust split (T_s) between main utilized for the thrust calculation and thrust split are described in Table I. In this Table, NF corresponds to the number of fans, $\dot{m}$ corresponds to the mass flow per propulsor, $\dot{m}_h$ corresponds to the mass flow through the main engine core and $\dot{m}_c$ corresponds to the main engines bypass mass flow. Since the total net thrust is assumed constant for a set flight condition, this is equal to the distributed array thrust added to the main engines thrust [21].

It is important to note, that to assume that the total net thrust (F_N) is constant for a set flight condition, it is assumed that the distributed array is embedded and hence any of the configurations for the distributed propulsors do not affect the external airframe drag [20].

TABLE I
DEFINITION OF TeDP SYSTEM PARAMETERS

Parameter†	Definition
Propulsors array thrust (F_{DPd})	$F_{DP} = NF\,(\dot{m}\,(V_4 - V_1) + (p_4 - p_\infty)\,A_4 - (p_1 - p_\infty)\,A_1)$
Thrust of two main engines (F_{ME})	$F_{ME} = 2\,(\dot{m}_h\,(V_{VII} - V_0) + \dot{m}_c\,(V_{VIII} - V_0) + (P_{VIII} - P_\infty)\,A_{VIII} + (P_{VII} - P\infty)\,A_{VII})$
Net thrust (F_N)	$F_N = F_{DP} + F_{ME}$
Main engine bypass ratio ($mBPR$)	$mBPR = \frac{\dot{m}_c}{\dot{m}_h}$
T_S	$T_S = \frac{F_{DP}}{F_N}$

† The thrust is considered in these equations as the intrinsic net thrust [1].

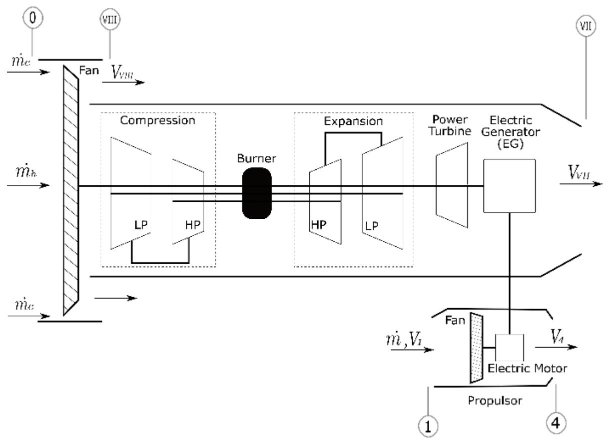


Fig. 3. Conceptual design of the TeDP system

II. Methodology

The methodology for the analysis implementing the DM approach is shown in Fig. 4. In this figure, it can be observed the operating conditions and restrictions (blue boxes), the design space variables (red boxes), the studied systems (green boxes) and the distortion model (mustard box). The operating condition boxes set the flight condition, the geometry of the airframe, and the boundary layer conditions. The design space variables are used to determine the spectrum of propulsion conceptual designs. In this study, there are two thermal parameters that affect the main engine: its bypass ratio (mBPR) and its fan pressure ratio (mFPR). For the distributed propulsor array the design space variables are: the number of propulsors and the thrust split. The NF affects the adequacy of the propulsor unit arrangement, which is based on the airframe geometry and electric equipment characteristics. The geometrical aspect refers to the space occupied by the propulsor unit arrangement over the airframe, which needs to be set in order to leave space available for the flight control surfaces such as: flaps, ailerons, etc.

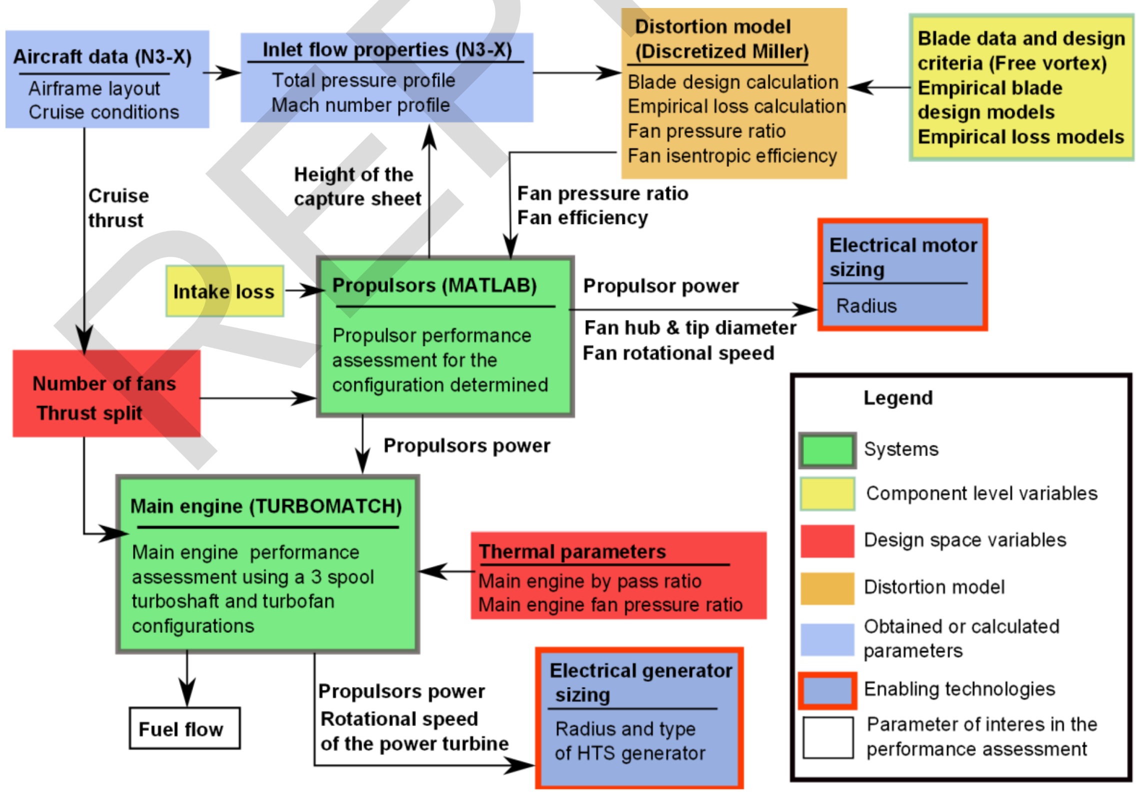


Fig. 4. Propulsor performance analysis implementing the DM approach

The separation between the propulsors is calculated based on NF and the distributed propulsor array width (L_{DP}) [4], [11]. An assumption included in the analysis is that the external geometry of the distributed propulsor unit remains unaltered for all the propulsor array configurations, and hence it does not affect the airframe drag. This can be achieved by embedding the propulsor array within the airframe.

On the other hand, the electrical components play an important role in defining the actual size of each propulsor, as each fan has an electrical motor mounted in its hub [4] and hence each propulsor requires enough space in the hub to allocate this component. Therefore, the fan size needs to satisfy this constrain based on the hub to tip ratio selected and the fan mass flow for the set operating condition. Since the hub to tip ratio is fundamentally a fan design parameter, which will change depending on the fan design, this is not included in the system analysis.

Thrust split (T_s) is other design space variable, which affects the distributed array configuration. However, this not only affects the distributed propulsor array, but the main engines as well. T_s defines how the thrust required for certain flight condition is shared between both. For instance, if the thrust split is high (more thrust delivered by the distributed propulsor unit) the main engines' thrust will be less and hence their size will reduce.

On the other hand, if the thrust split is low, the amount of thrust delivered by the propulsor unit will reduce and hence the size of the distributed propulsors will decrease. Since the change in the propulsor array configuration will change the main engine size, and therefore, the aircraft drag, they are included in the internal control volume analysis of the propulsion system. In this way, the thrust assumed for a determined flight condition is set, and the BLI benefit comes only from the properties of the flow ingested by the propulsor array. This assumption is useful, as there are not information regarding turbofan designs for TeDP systems. However, this is an important contribution that a mission level analysis could implement to size the main engines and define its size (drag) variation for different propulsor array configurations. The effect of T_S in the propulsion system is further explained in the results section.

The main issue when carrying out the system analysis of TeDP configurations with BLI was the difficulty to implement the BLI induced distortion [11]. This caused a major restriction in the assessment of optimal propulsion configurations, as the effect of distortion on fan performance when the boundary layer characteristics changed could not be incorporated into the analysis. In this work, the performance of the propulsor array includes a module (mustard box in Fig. 4) for the evaluation of the BLI induced distortion, this module uses the DM approach [10]. As aforementioned, the propulsor array performance assessment was performed using the internal control volume approach [22],[23], which encompasses only the propulsor unit. This approach is useful, as it assumes the net thrust fixed for the set flight condition. In other words, it does not account for the airframe ingested drag, neither the wake, and hence the benefit from BLI is introduced by the deficit of the inlet velocity (momentum drag reduction), due to the viscous forces and the pressure distribution along the airframe. In this way, this approach has the advantage of uncoupling the airframe configuration and propulsion system. However, the internal control volume approach requires the inlet flow properties to determine the propulsion system performance. These inlet flow properties data were taken from the NASA N3-X airframe [4].

The method of Fig.4 enables the definition of propulsion system layouts, which are compatible with the characteristics of the electric components, and airframe configuration. To assess the sensitivity of the distortion tool, for the inlet flow characteristics, a propulsor performance analysis, using different boundary layer profiles, is also developed. Since the aim of this work is to highlight the suitability of the method presented in Fig. 4, and the influence of thrust split in the assessment of optimum architectures, TSFC has been selected as the figure of merit, and the installation aspects, such as weight and drag, have not been considered. However, the latter are of major importance in defining the actual optimum architectures, and consequently, their implementation will be part of a future work.

In this work, the performance analysis focuses on the aerodynamic integration aspects between propulsor array and airframe, the energy production system, and the electrical equipment. In this analysis, the main-engines and electrical systems are assumed with the same characteristics as the ones in a previous work [11]. In the case of the propulsor assessment tool, an alternative subroutine, which incorporate the design modules, required by the DM approach, is employed. As previously mentioned, the N3-X aircraft concept was selected due to the presence of TeDP and BLI. Furthermore, this concept presents several novel technologies, which are expected to be achieved for the N+3 timeframe [3], such as: HTS, liquid H_2 cooling and blended wing body airframe. Table II summarizes the flight conditions and main parameters used in the analysis.

TABLE II
FLIGHT CONDITION AND INLET FLOW PROPERTIES AT DESIGN POINT

Parameter	Value
F_N at cruise (12192 m) [N]	73952.6
Mach number at cruise	0.84
Propulsors pressure ratio (FPR) †	1.15-1.45
Inlet Mach number †	0.6
Inlet total pressure † [kPa]	29.07
Inlet total temperature [K]	244.9
Tip velocity [m/s]	Function of FPR [4]
Intake pressure losses	1-2 %

† These properties correspond to uniform conditions.

The following subsections describe the modeling of the propulsor array, main engines and electrical system modules.

II.1. Propulsor Array Modeling

Similarly, to the parametric study [11], the thrust delivered by the propulsor unit corresponds to the intrinsic net thrust, and is based on the internal control volume [20] presented in Fig. 5. The propulsor's thrust for cruise is defined by T_s. Then the propulsor's pressure ratio operating under uniform conditions is assessed in the fan performance tool, which calculates the mass flow and defines the blade design for the uniform condition.

For the distorted case assessment, the three-dimensional flow field characteristics are required, the two-dimensional profiles obtained from the N3-X concept [11] are converted to three dimensions, by assuming that they are constant along the airframe. The aforementioned 2D inlet profiles are assumed to be at a distance of x = 0.85c over the N3-X airframe centerline [4]. For simplicity, at this station is assumed that compression or diffusion effects have not taken place, and, that the height of the intake is equal to the height of the boundary layer capture sheet.

Additionally, as the duct geometry is still undefined at this preliminary design stage, it is necessary to make certain assumptions to calculate the three-dimensional profiles at the fan face. Therefore, it is assumed that the gradient of the total pressure, and Mach number profiles, remains the same from the control volume inlet up to the fan face and that the duct produces a drop in total pressure between 1-2%.

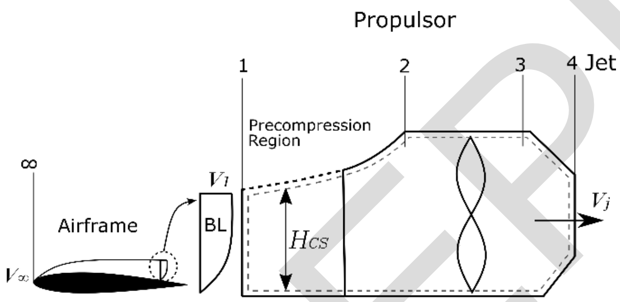


Fig. 5. Control volume for the analysis of the propulsor performance

TABLE III
PROPULSORS FAN DESIGN CHARACTERISTICS

Parameter	Value
Root to tip ratio (r_{rt})	0.52
Clearance to chord ratio(ε/c)	0.01
Blade height to chord ratio midspan (h/c)	2.86
Pitch to chord ratio midspan (s/c) †	0.6
Thickness to chord ratio midspan (t/c)	0.007

† This parameter is calculated using the approach shown in Cohen [24]. The remaining geometrical parameters are taken from the NASA rotor 53 [25].

This latter is incorporated as a parameter of analysis, due to the high sensitivity of the propulsion system to duct pressure losses [11]. To define the velocity profile, a mass average Mach number of 0.6 is assumed at the fan face. The inlet total pressure, and Mach number, are calculated using the equations of the centerline profiles documented for the N3-X aircraft [4]-[11], and are valid for the range of capture sheet heights investigated in this study. The intake pressure drop through the duct is calculated using equation (1):

$$\Delta P_{in} = \frac{\Delta P_{1\text{-}2}}{P_1} \quad (1)$$

The DM approach defines the blade design and fan performance for uniform conditions, and then, it assess the distorted case as a particular off-design case [10]. The assumption of the fan ingesting uniform flow, as considered in this study, is found useful in estimating the detrimental performance, when ingesting a distorted flow field. The properties described for the uniform case in Table II correspond to the ones used in the blade design, and the performance modules. The distortion module also requires some blade design data, some of which are based on NASA 53 fan stage characteristics, and are described in Table III.

For the DM approach the capture sheet height (amount of boundary layer ingested) determines the inlet flow profiles, and hence, the fan operating point. However, as the mass flow and the capture sheet height are unknown, both variables are used as handles in an iterative calculation, using the propulsor array thrust (F_{DP}) as the matching condition. The capture sheet height can be calculated using continuity and assuming a mailbox intake shape. In this study, it has been assumed that the width of the duct is equal to the fan diameter and the height of the duct is defined based on the fan mass flow and the duct shape (mailbox intake). Since the precompression region is neglected the latter height is assumed equal to the height of the capture sheet.

The space available to fit the propulsors (L_{DP}), and the number of propulsors (NF) allow the calculation of the space between propulsors, and the adequacy of the distributed propulsor configuration. In this analysis, L_{DP} is equal to 23 meters, and NF is a variable in the analysis. The calculated propulsors' mass flow based on the thrust required for a set flight conditions, together with the fan input geometry, allows defining the fan and hub diameters. The fan diameter is used to check the possibility to allocate the set number of fans in the distributed propulsor space and the hub diameter enables the assessment of the suitability of the electric motor, as the latter is assumed to be mounted in the fan shaft.

After defining the fan geometry, and operating condition, the distortion tool calculates the mass averaged fan pressure ratio, and isentropic fan efficiency for the distorted condition. These values are then used to define the exit flow conditions. To calculate it, a nozzle pressure loss of 1% is assumed in this study. The methodology shown in Fig. 4 uses the propulsor intrinsic net thrust as input data, with the aim of enabling later the optimization study for different thrust split settings. The distortion and propulsor performance modules are integrated such that the fan performance characteristics can be determined for a set thrust requirement. The synthesized algorithm for the combination of distortion and propulsor performance modules is shown in Fig. 6.

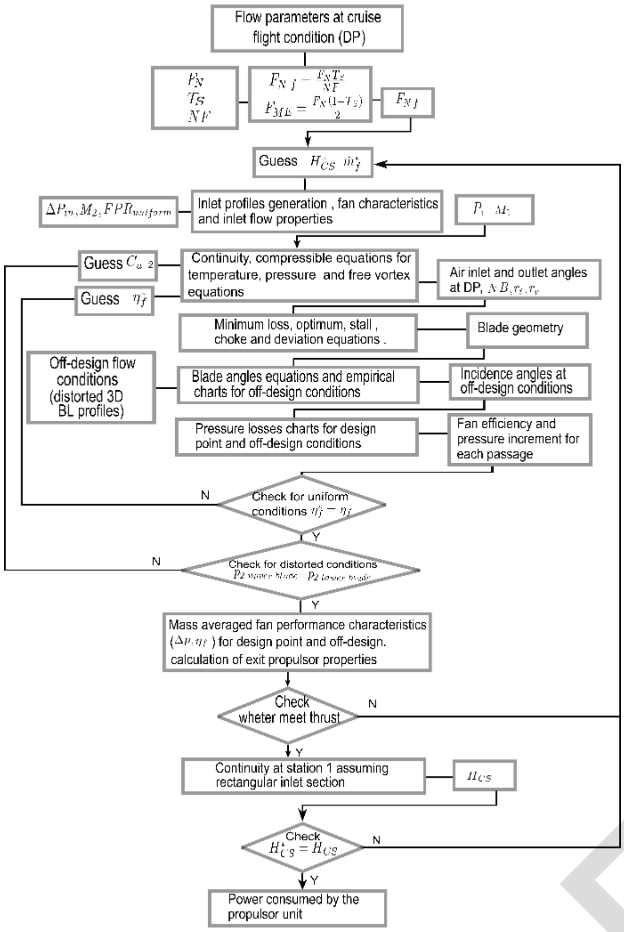


Fig. 6. Propulsor performance calculation methodology

Discretized Miller (DM) method: The DM approach requires of three subroutines: the fan design module, the fan performance code for uniform conditions and the fan performance code for distorted conditions [10].

To define the fan design, the mean-line method is used. This uses the Euler equations, and velocity triangles to calculate the air exit angles. These angles and empirical correlations for blade geometry and pressure losses enable calculation of the fan performance. The blade arrangement studied in this work comprise a rotor, and a stator. For the calculation of the air exit angles, a free vortex condition, and a constant axial velocity through the fan assembly are assumed.

These assumptions allow simplification of the model at an expense of loss in accuracy. The blade geometry in the DM method is determined using Carter's rule [26],[28] for deviation angle (δ). This approach was preferred over the Miller's [27],[28],[30] definition, due to its simplicity and better prediction capability for the uniform case. For the non-uniform cases the deviation angle, calculated as a function of the stagger, and camber angles through empirical charts [27]-[30]. Then, this parameter allows determining the minimum loss (ml), optimum stall, and choke incidence angles. The loss coefficient calculation is carried out with these angles using the empirical correlations described in [25]-[31]-[32]. The loss coefficient definition used in the fan performance calculation is given by equation (2):

$$\bar{\omega} = \frac{\Delta p_{ideal} - \Delta p_{real}}{P'_{LE} - p_{LE}} = \bar{\omega}_p + \bar{\omega}_{sec} \qquad (2)$$

In equation (2) $\bar{\omega}_p$ and $\bar{\omega}_{sec}$ stands for profile, and secondary losses respectively. The secondary losses implemented in the model correspond to the end wall, and shock wave effects. The ideal static pressure increment is calculated based on the assumption of constant relative total pressure across the rotor or constant total pressure for the case of the stator. As the fan assembly for the test case presents one stage, and is expected to operate at low pressure ratio, the density variation, and blockage effects across the blade arrangement are neglected [24]. These assumptions essentially simplify the model by enabling the use of incompressible flow equations. These equations can be used to calculate the static pressure increment, which for the case of constant axial speed is equal to the total pressure increment in the absolute frame of reference. This latter parameter together with the total loss coefficient are then, used to determine the isentropic efficiency [24]. To assess the radial and circumferential effects of ingesting a distorted flow field on fan performance, the mean-line design, as previously described, is modified. This modification consists on uniformly discretizing the inlet rotor area, into several blade passages, and radial stations. The flow and blade characteristics at each position are then used to calculate their empirical losses. This enables the definition of the static pressure increments, and fan efficiency for each stream. Finally, to obtain the fan efficiency and static pressure increment at the fan exit, these values are mass averaged [10]. Since the DM method requires the geometrical description of a fan to set semi-empirical correlations for performance and geometry the fan NASA 53, which has its information available in the open domain [10] was assumed for this analysis. It is important to mention that although this fan has a large hub to tip ratio the information available about it made it a better option to test the present methodology. Nevertheless, the method can be adapted to any other fan design with a lower hub to tip ratio or any other geometrical characteristic.

II.2. Main Engine, Electrical and Cooling Systems Modelling

The main engine models and their specifications have been maintained from the ones utilized in the previous work [11], where a parametric analysis and TURBOMATCH gas turbine performance code was utilized to assess the performance of the main engines. The illustrative configuration of the main engines can be observed in Fig. 3. To avoid repetition and save space, their specifications are further described in the work encompassing the parametric analysis [11]. Moreover, for the electrical system is assumed an electric transmission efficiency, between the electric generators and electrical motors of 99%.

II.3. Assessment of Propulsion Architectures

The system analysis uses a similar methodology as the one developed for the parametric analysis [11]. The difference in the methodology, however, lies on the use of the distortion assessment model to calculate fan pressure ratio and fan efficiency. The methodology is illustrated in Fig. 7.

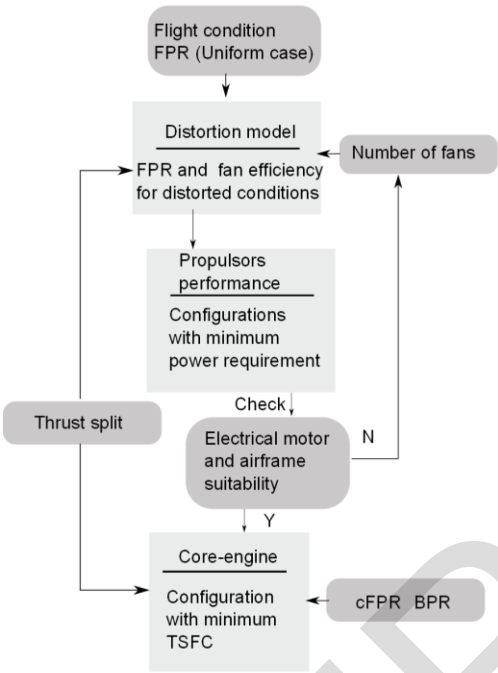


Fig. 7. System analysis method

In this diagram, the darker boxes correspond to the propulsion architecture variables. To determine the number of propulsors (NF) for the arrangement, a separation between propulsors of 4-20 cm has been considered suitable, this configuration has been selected to maximize the amount of BLI and reduce the height of the capture sheet. The diameter of the electrical motor is determined using the electric motor sizing approaches recommended in [33], and [34], which have been developed for HTS motors operating at an efficiency higher than 99%. Their diameter is important as this are assumed to be mounted in the fan shaft [35] and hence it is required that they can be allocated inside of the fan hub. This enables to take advantage of the DC-link transmission system, reducing the space occupied for the motors and the weight by avoiding the use of gearbox or any other mechanical installation [35].

III. Results and Discussion

This section describes and discusses the results obtained at the design point (cruise condition) using the aforementioned models.

III.1. Propulsor Performance Analysis

The results obtained from the propulsors unit performance analysis are described and discussed in the following paragraphs.

III.1.1. Distributed Propulsor Array

In order to define the optimum and suitable configurations is utilized the method shown in Fig. 7. The sizing of electrical motors depends on its type, and the assumptions used for its assessment. In this work, the two motors, operating at different rotational speeds have been sized (in terms of electric motor radius), using the approach described in Masson [33] and Snyder [34]. In order to enable the assessment of distributed propulsor configurations taking into account the technology development level for HTS equipment, two criteria have been considered. The first criterion allows to define the denominated Suitable Configurations (SC), which correspond to configurations, where the electrical motor requirements and geometry adequacy for the propulsor array are satisfied. To check these aspects after the calculation of the propulsor size and hub radius, it is revised if the electrical motor required for the set operating condition can be mounted in the fan's hub and also if the number of fans selected can be allocated in the distributed propulsor unit. On the other hand, the second criterion allows to define the optimum configurations (OC), which correspond to configurations, where the lowest power consumption and geometry adequacy for the propulsor array are satisfied. As it will be described later the comparison of OC and SC indicates that the power consumed could still be optimized by implementing alternative fan-electric motor configurations, or intake designs, where the electrical motor characteristics do not limit the number of propulsors allocated in the propulsors unit.

In Table IV the width of the mailbox-slot inlet (w_{in}) is assumed equal to the fan diameter, the separation between fans (S_{in}) is calculated based on L_{DP} and NF. Additionally, electrical motor parameters used for their selection, such as: torque (TQ), rotational speed (N), electrical motor radius (r_{EM}), fan tip radius (r_t) and fan hub radius (r_r); are shown in Table IV.

Table IV corroborates the trends found through the parametric approach [11]. These results indicate that, when the height of the capture sheet decreases, it results in a decrease, in momentum drag, and a corresponding decrease in power consumed. Furthermore, the implementation of the distortion tool, to model the effects of distortion, helped to determine that the benefit in terms of power consumption (due to momentum drag reduction), offsets the effects of deterioration in fan performance. These latter effect is caused by the ingestion of the low momentum boundary layer region (higher velocity gradient).

TABLE IV
DISTRIBUTED PROPULSOR ARRAYS FOR DIFFERENT THRUST SPLITS

Parameter	Configurations							
T_s [%]	50(SC)	50(OC)	65(SC)	65(OC)	75(SC)	75(OC)	95(SC)	95(OC)
FPR	1.3	1.35	1.25	1.35	1.25	1.35	1.3	1.35
Number of fans	19	31	17	29	19	27	15	21
PW *[MW]	9.404	9.053	12.682	12.234	14.663	14.376	19.585	18.95
TQ [Nm]	1387.86	321.386	1956.71	554.924	2058.954	1809.45	3465.002	1713.174
r_{EM} †[m]	0.087	0.077	0.0985	0.0855	0.0993	0.106	0.119	0.103
r_{EM} ‡[m]	0.274	0.254	0.290	0.268	0.2915	0.291	0.313	0.297
N [rpm]	3405.71	8677.85	3640.75	7529.687	3579.314	6494.36	3465.002	5029.916
r_r [m]	0.263	0.156	0.2908	0.187	0.2958	0.2092	0.35	0.27
r_t [m]	0.506	0.301	0.5593	0.359	0.5689	0.4022	0.673	0.5193
w_{in} [m]	1.0124	0.602	1.118	0.7196	1.1378	0.8044	1.295	1.0386
H_{CS} [m]	0.574	0.301	0.6343	0.3969	0.6344	0.4561	0.693	0.5749
S_{in} [m]	0.2	0.1446	0.248	0.0761	0.0767	0.0492	0.2	0.0594

* This value corresponds to the power required by the set of distributed propulsors.
† Sized with model for 3000 rpm HTS synchronous electric motor [33].
‡ Sized with model for 6000 rpm HTS synchronous electric motor [34].

The results indicate that with the DM approach, and assumed fan face properties, reducing the capture sheet height improves the distributed propulsor performance. For this reason, the OC cases were found for arrangements with a large number of propulsors, with small diameters, rather than configurations with few large propulsors. In this context, the OC cases are only limited by the size of the electrical motors as they cannot be fitted in the fan's hub.

To illustrate the power consumed by each of the propulsors arrangements the optimum configurations are plotted in Fig. 8, for different FPR's. For comparison of the trends obtained with the DM approach, the same case has been plotted in this figure using the parametric approach [11]. The difference presented in the trends can be attributed to three reasons. The first reason is the higher sensitivity to intake losses due to higher mass flow required at low FPR's with the DM approach.

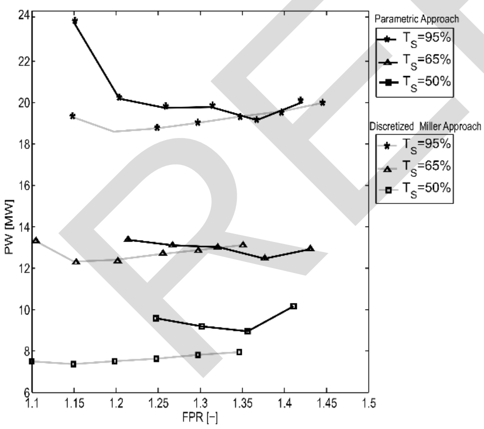


Fig. 8. Power required for the propulsor unit for different thrust splits

For the DM method, with the fan efficiency calculated by the blade design module, the maximum fan efficiency occurred around 1.3 FPR, whereas, for the parametric approach the highest efficiency occurred at 1.15 FPR.

This produces that the thermal efficiency of the propulsor were lower for the DM approach at lower FPR, and therefore, larger mass flows were required to deliver the set net thrust.

This increment in mass flow at low FPR's produces a higher sensitivity to intake losses for the propulsor unit, when using the DM approach. In other words, the effect of intake losses at low FPR's become more relevant and contribute to shift the minimum to higher FPR's when using the DM method.

Secondly, in the case of using the DM method, the power consumed and the sensitivity to intake losses change, as the fan is not 100% thermal efficient, and each stream will have different thermal efficiency, and pressure ratio in the analysis (this will not be the same as modeling averaged flow properties for one stream). For instance, in the case of the streams with low velocity a higher-pressure rise will be experienced, due to fan's ability of impart more energy to the lower momentum flow. Thirdly, when using the DM approach, the margin of convergence used for the fan efficiency at clean conditions, and capture sheet height to achieve convergence of the model, include some inaccuracies in the performance assessment.

In the parametric approach, it is observed that for lower thrust split the minimum shifts towards lower FPR's, which is due to the less sensitivity of the propulsor array power to intake losses (as the mass flows are lower), similarly to the effect of increasing the FPR for a set thrust split.

Nevertheless, when reducing thrust split the propulsive efficiency will be benefited by the reduction in momentum drag, and jet velocity when the mass flow, and hence, the capture sheet height reduces as thrust split decreases (this is only based on the propulsor unit propulsive efficiency). For the DM approach, there is not a strong trend for the optimum configurations to shift towards lower FPR's, and the reason behind is that, the DM tool predicts optimum efficiencies at higher FPR's, which drive the minimum power to the right (Fig. 8).

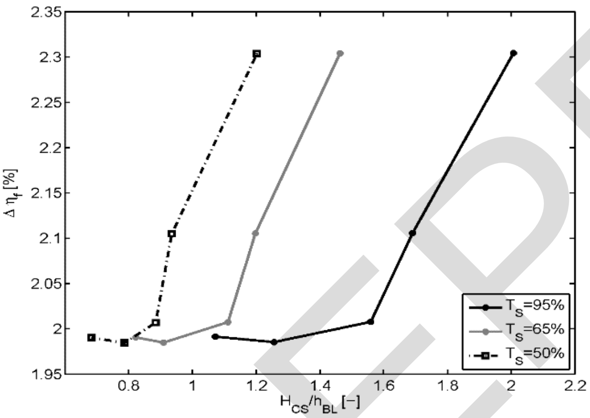
III.1.2. Effects of Distortion on the Performance of Distributed Propulsors

In order to show the prediction of the DM approach, for different capture sheet heights, and thrust splits, the detriment in fan efficiency is plotted in Fig. 9(a) versus these variables.

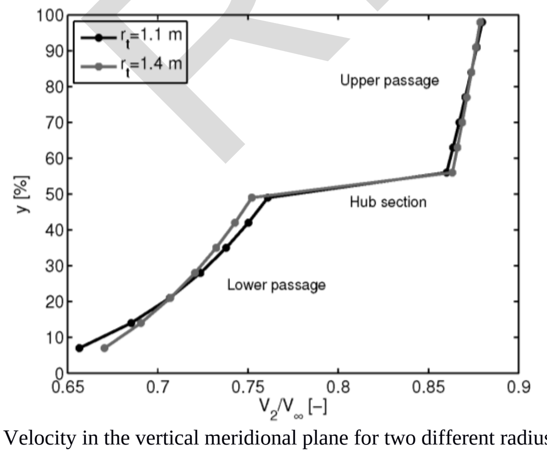
As observed in this figure, the difference in drop of fan efficiency is very small for different thrust splits, which can be attributed to the way of how the profiles were modeled.

As shown in Fig. 9(b), for two different radius (which is equivalent to capture sheet height), the velocity profiles at the fan face are very similar. Therefore, the assumptions made to scale up the intake velocity profiles limit, to a certain extent, the ability of the DM approach to capture the trends in distortion effects. At the moment, it is beyond the scope of the current study to define the inlet fan face velocity profiles, and how they change for different operating conditions (T_S and *FPR*), therefore, the previous assumption is necessary for the implementation of the DM method.

To refine this study is important to address this aspect to enable the connection between the physical behavior of the flow and the aircraft operating conditions, such that the actual variations in performance can be determined. To illustrate how the fan efficiency is related to the propulsor unit mass flow, in Fig. 10, the fan efficiency for the clean, and distorted conditions for a set thrust split, are plotted. The case shown corresponds to the presented in Figs. 9.



(a) Drop in isentropic fan efficiency for different thrust split. The h_{BL} for this case is assumed equal to 0.45 m [4]



(b) Velocity in the vertical meridional plane for two different radius

Figs. 9. Fan efficiency detriment and velocity profiles at fan face

Fig. 10 shows an optimum efficiency for certain mass flow and FPR, which in this case is produced due to the combined effect of the following: i) the pressure losses through the blade passage, which at low pressure ratios (high mass flows), are a larger fraction of the overall pressure rise, and therefore, reduce in larger extent the fan efficiency; ii) the increment in pressure losses through the blade passage, due to the higher amount of energy imparted to the flow when the FPR is high.

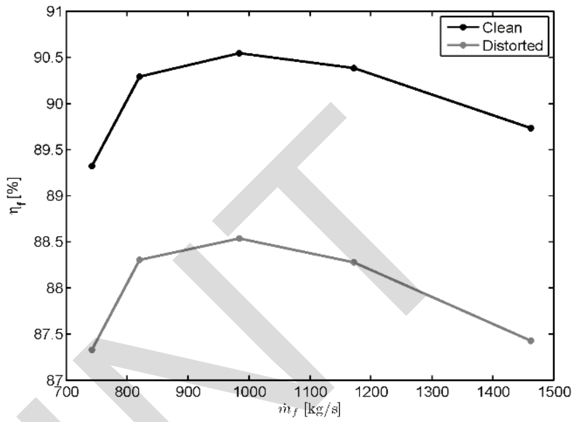


Fig. 10. Fan efficiency in function of the total mass flow of

III.1.3. Comparison of the Alternative (DM) Method with the Parametric and PC Performance Assessment Methods for BLI Systems

To compare the performance trends between the parametric and the DM approaches, the TSFC has been plotted in Fig. 11. In this case, it is observed that the implementation of the DM approach, in the propulsor performance model, predicts a larger power consumption for the propulsor unit, which can be attributed to the larger detriment in fan performance (lower fan efficiencies), predicted with this distortion tool, and the higher influence, that the intake losses have on the region working with the low velocity flow.

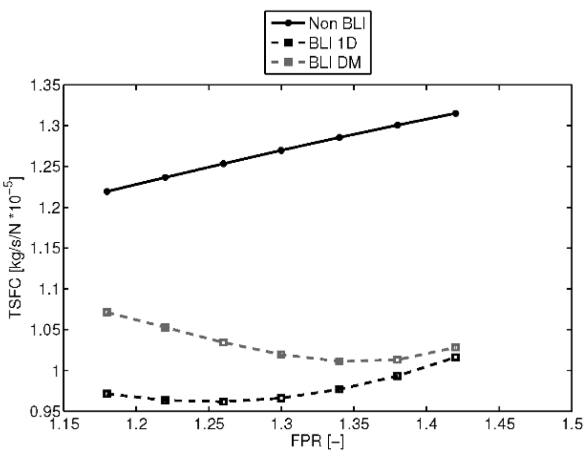
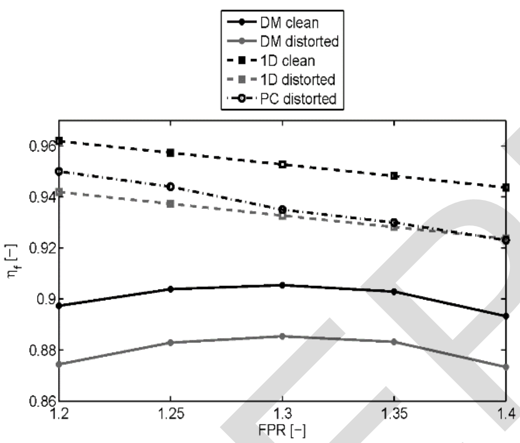


Fig. 11. TSFC predicted with the parametric and DM approaches

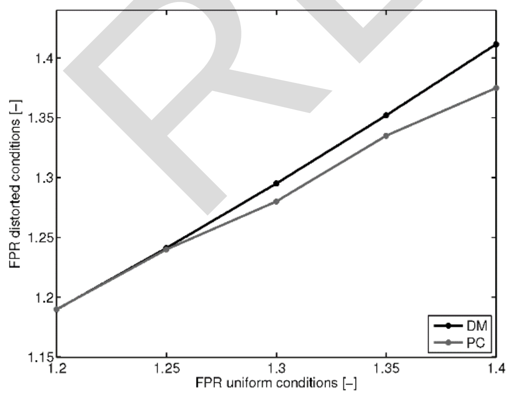
The analysis of the propulsor performance, operating under these boundary layer characteristics, highlights the importance of the duct design, and incoming flow rearrangement within the duct, to avoid a dramatic reduction of the BLI benefits at lower pressure ratios.

The low fan efficiencies for the DM approach are due to the use of the blade design module, which in this case determines the fan efficiency for clean conditions (DM clean), based on conventional designs.

As observed in Figs. 12, the efficiencies predicted with this module were lower than the assumed for the parametric approach [11], which were based on an advanced fan design (1D clean) [4]). This detriment in the fan efficiency increases the amount of power consumed when the DM approach is used. Fig. 12(a) also highlights the detriment in fan efficiency predicted with the DM approach and the PC method. As observed, the detriment (comparing clean and distorted cases with the DM approach) predicted by the DM approach is larger, by around 0.5%, than the predicted by the PC. The PC method does not use a fan design module [36] and it assumes at clean conditions the same fan efficiencies than the advanced fan design [4].



(a) Isentropic fan efficiency



(b) Pressure ratio

Figs. 12. Fan performance characteristics predicted with the DM, PC and parametric approaches for a 95 % thrust split configuration. The PC distorted and 1D clean data is taken form [36] and [4] respectively

The larger detriment predicted, by the DM approach, could be attributed to the inclusion of the radial distortion patterns in the analysis. Fig. 12(b) illustrates the fan pressure ratio for the distorted cases, when using the DM, and PC approaches.

In the case of the DM approach, these data correspond to the mass averaged values, when the propulsor unit is delivering 95% of the net thrust (95% T_S) at cruise condition. Fig. 12(a) also shows, that for the DM approach the detriment in fan performance is the same at low or high fan pressure ratio, whilst the PC method describes a better performance at low fan pressure ratio.

This comparison illustrates that when using the DM approach, the reduction in capture sheet height (ingestion of more distorted flow) when pressure ratio is increased can be beneficial.

This can be attributed to the reduction in the momentum drag which, in this case, offsets the higher level of distortion for configurations with small capture sheet height. This benefit could not be observed when using PC, as only two streams were used to model the flow, and therefore, for smaller capture sheet heights, the difference in velocity between clean and distorted streams, increase largely offsetting the benefit of momentum of the drag reduction [36].

III.2. Propulsion System Performance

The various propulsor array configurations described in Table IV were used in the optimization subroutine depicted in the flow chart in Fig. 7. Various configurations were simulated in this work to establish the optimal thrust split.

The various cases of T_S assessed were 50%, 65%, 75% and 95%. Fig. 13 indicates the OC cases found in terms of least TSFC observed, assuming pressure losses of 1% and 2%. The study enables establishing the optimal levels of thrust split, and the benefit in TSFC, that may be accrued from it. As observed, and expected, from the parametric studies, as the pressure losses in the flow ingested by the propulsors, increase the optimal solution shifts, towards the requirement of generating greater thrust from the core engines. Fig. 13 also depicts a TSFC curve, for the SC cases described in Table IV. In this case, the trend observed demonstrates the influence of the electric motor design (rotational speed and power) on the propulsor arrangement, which influences over the height of the capture sheet. Since the SC cases have fewer propulsors, and therefore, higher capture sheet heights, the momentum drag is higher for these cases. The latter, in turn, increased the power requirement of the propulsor unit, and consequently the TSFC.

For the sake of clearness and that TeDP is only achievable if the electrical equipment attains certain level of performance, in the next paragraphs only the trends observed for the SC cases will be discussed. Therefore, the optimal configuration described in the following analysis will refer to the propulsion unit arrangement, which presents the lower TSFC within the SC cases.

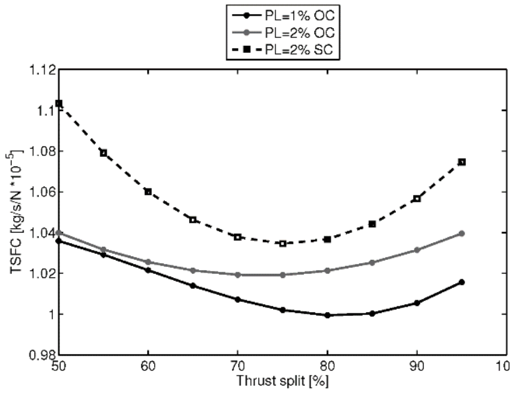


Fig. 13. Optimum (OC) and suitable (SC) propulsion architectures for different intake pressure losses

Furthermore, as the performance trends for the SC and the OC cases are affected by the same variables, it is enough to describe only one of them.

The SC cases indicate an optimal thrust split of 75%, when components' weight, were not considered. The performance benefit of increasing thrust split up to 75%, seen in Fig. 13 is related to BLI, due to the lower momentum drag perceived by the propulsion system, as the propulsors unit, which ingest the boundary layer is delivering more thrust than the main engines, which operate with freestream flow. In other words, the distributed propulsor unit enhance the system performance, as its implementation outweigh the transfer losses due to TeDP (electrical equipment and transmission losses) and the aerodynamic integration effects.

Specifically, for lower Ts, there is a lower effect of distortion on the propulsor array performance. This latter effect can be related with two causes. The first is the reduction in distortion, due to the ingestion of a higher amount of mass flow, and therefore, higher capture sheet, which reduces the level of distortion in the flow. This effect, however, could not be captured by the DM approach in its current form, as the velocity profiles generated at the fan face change, by small amount, and therefore, the drop in fan efficiency is small and could not be captured by the DM tool. In addition, the margin of convergences used in the code for capture sheet height (10^3m) and fan efficiency (10^4) at clean conditions, reduce the accuracy prediction for the DM case. The second effect is related with the reduction in distortion, due to an increment in Ts, caused by the shifting of the SC cases, to higher FPR's. At higher FPR's, the distortion effect reduces, due to the lower sensitivity of the propulsor unit, to intake losses, as previously explained.

For the SC cases, at thrust splits higher than 75% (optimal), the increment in thrust split, increases the influence of intake losses, due to the higher mass flow going through the distributed propulsor unit. This also, contributes to increase the amount of energy required by the propulsor unit, which increases the effect of the transfer losses (inefficiencies of the electrical and cooling equipment). On the other hand, there is an increment in propulsive efficiency, as the main engines do not present the benefit of BLI.

The characteristics of the optimal propulsion arrangement for the suitable configuration cases are summarized in Table V. In this table can be observed the large bypass ratio turbofan engines required for this configuration, which could cause installation, and weight losses in the system and therefore, limit the benefits predicted when using propulsion systems with T_s. This optimal propulsion arrangement, however, could be observed as a transitional configuration, between today's aircraft and the N3-X concept, wherein all the thrust is produced by the distributed propulsors. This is attributed to the fact that the recommended optimal configuration is better suited to deal with the aerodynamic integration issues and transfer losses than the N3-X concept. Additionally, the lower power setting for the distributed propulsor array, to operate, will reduce the demand for cooling, and HTS electrical equipment. This will further enable a reduction in weight and size, thereby, resulting in an overall improved performance of the concept. Furthermore, for the timeframe, where this design is implemented, high bypass ratios may be achieved by reduction in main engine core sizes, such that the installation drag, and weight losses added with this concept could be minimized. When comparing the configuration with 75% thrust split in the optimum case, with the one obtained in the parametric studies [11], it can be observed that the fan performance method with the DM approach predicts an increment of around 2% in TSFC. This would mean that the 5% benefit in TSFC predicted with the parametric model could be reduced to a 3%.

TABLE V
OPTIMUM CONFIGURATION FOR THE SC RATES

Parameter	DM	1D [11]
Main engine fan pressure ratio	1.25	1.2
Main engine by pass ratio	12	12
Thrust split	75%	75%
Distributed propulsor power †[MW]	14.7	14.1
Number of propulsors	19	15
Propulsor FPR	1.25	1.25
Propulsors diameter [m]	1.13	1.294
Torque [N.m]	2058.95	3461.1
Rotational speed [rpm]	3579.31	2687.93

† Power consumed by the propulsor array

IV. Conclusion

An alternative propulsor performance tool has been developed, and used to assess optimum, and suitable distributed propulsor arrangements for the N+3 timeframe aircraft concept, whilst considering the concept of thrust split, and using TSFC and electric motor capabilities (rotational speed and power), as figures of merit. This alternative method incorporates a previously developed method for BLI induced distortion assessment, which is based on semi-empirical correlations, and has been denominated the DM approach. This distortion tool enables to introduce the inlet flow properties in the propulsor performance assessment, as it assesses the effects of circumferential, and the radial distortion patterns on the fan performance. The results and trends obtained through the application of the parametric approach, have been verified and refined using the alternative performance model. Furthermore, the DM distortion tool has been compared against the PC approach, and it was observed that the inclusion of the radial distortion patterns in the analysis increases the drop in fan efficiency by around 0.5%, at low fan pressure ratios. The study indicates that to obtain the expected performance benefits, from the distributed propulsion system, there is a requirement of reducing aerodynamic integration losses (intake losses and distortion).

In this regard, an optimum configuration was found at 75% thrust split when installation and weight penalties were not included. This study emphasizes the importance of accounting for drag, and weight during preliminary design, to improve, and refine the prediction of the optimal configuration. Finally, the contribution of this work is the implementation of the DM approach, for the assessment of the BLI induced distortion, and therefore, the inclusion of the flow inlet characteristics in the propulsion system analysis, which is important in BLI systems, as it enables to determine the BLI benefits, whilst accounting for the detriment, in fan performance due to BLI.

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Valencia, Esteban

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