Review of the Investigation of Innovative Propulsion System Architectures for Aircraft

Valencia E.*; Laskaridis P.*; Singh R.*; Aguinaga A.**; Cando E.**; Liu C.****; Hidalgo V.***

*, *Power and propulsion department, School of engineering,Cranfield University, MK430AL, United Kingdom*

***Facultad de Ingeniería Mecánica, Escuela Politécnica Nacional,Quito E11-253, Ecuador*

****State Key Laboratory of Hydroscience Engineering, Tsinghua University, Beijing 100084, China*

*****School of Aeronautics and Astronautics, Shanghai Jiao Tong University, 800 Dong Chuan Rd., Shanghai, 200240*

Resumen: Los beneficios potenciales que representa la aviación en los campos: económico, de seguridad y de desarrollo tecnológico de un país, han motivado a países como Ecuador a fomentar el crecimento de la aeronáutica en los últimos años. La manufactura de vehículos no tripulados y satélites, por ejemplo, han significado importantes pasos en la evolución de esta rama. En este ámbito, la presente investigación contribuye al estudio de sistemas de propulsión innovadores de alta eficiencia, que permitan la disminución del consumo de combustible, emisiones y ruido. El efecto de estas variables en el medio ambiente ha sido estudiado de una manera extensa. Por tal razón, es conocido que el crecimiento de la aviación llevará consigo a una alteracion a nivel global del ecosistema. Debido a ésto, grandes esfuerzos en investigación han sido enfocados a los sistemas de propulsión y fuselaje alternativos, que permitan el desarrollo sustentable de la aviación. El presente trabajo compila la investigación sobre nuevas arquitecturas de sistemas de propulsión, los cuales exhiben potenciales beneficios en las anteriormente mencionadas métricas. Uno de estos novedosos conceptos es el avión NASA N3-X, el cual en éste estudio ha sido considerado como estructura base de propulsión sobre la cual diferentes diseños conceptuales fueron analizados. En éste concepto resaltan dos aspectos importantes en el mejoramiento del rendimiento de las aeronaves: la re-energización de la capa limite (BLI) y la propulsión distribuida. Desde el punto de vista aerodinámico, éstas tecnologias presentan como problemas principales, la distorsión tridimensional inducida por BLI y las pérdidas de presión producidas en los conductos de admisión de los propulsores. Referente a estos problemas, la metodología desarrollada permite la implementación de estos en el análisis del sistema, utilizando diferentes niveles de fidelidad y diseños de propulsión. En resumen, éste trabajo pretende dar una idea de la labor llevada a cabo en el ámbito de los diseños innovadores de propulsión para aviones. Lo cual ha sido considerado especialmente para brindar una idea global de la problemática y el enfoque seleccionado para estudiar este complejo sistema. En éste sentido, tambien se destacan los principales desafíos, que se deben abordar con el fin de hacer viables estos conceptos.

Abstract: The potential benefits of aviation in the economics, safety and technological development of a country, have motivated countries like Ecuador to create incentives that enable the development of the research in the aerospace field. Some examples are the built in house UAV's and satellites, which represented important steps in the development of the Ecuadorian aerospace research. In this context, the present work contributes with the study of innovative propulsion architectures, which present high overall efficiency and therefore contribute to the reduction of fuel burn and emissions. These metrics have been chosen because previous studies have shown that the growing of aviation in future years may dramatically increase their impact over the environment. For this reason, novel airframe and propulsion layouts as the N3-X concept has been developed in the recent years. Two special features highlight from this concept, which are boundary layer ingestion and distributed propulsion. Although the benfits produced by these features is large, they present numerous challenges. From the aerodynamic perspective, BLI induced distortion and intake losses have shown dramatically mitigate the benefits. Therefore, this aspects have been included in the method developed to assess the propulsion system performance. This method enables to broad the spectrum of concepts studied, whilst using different architectures and approaches with different levels of fidelity. To summarize, this paper intends to give an insight of the work carried out in the area of innovative propulsion designs for aircraft. This is to give a global idea of the framework utilized, whilst emphasize major issues which need to be addressed in order to make feasible these concepts.

Keywords: Distributed propulsion, Aerodynamic integration effects, Propulsion architectures, Distortion, Rotational machinery, Alternative propulsor designs, Performance design

---

1. INTRODUCTION

The importance of aviation in the development of a country has motivated the Ecuadorian government to incentive projects in the aerospace field. In this context, built in house UAV's, which at the moment have drug tracking and military purposes can be cited. Furthermore, these drones are expected to be sold at Latin America scale [1]. Another example is the domestically made satellites such as Pegaso and Kryasor [**?**], which have been sent to space to promote the space investigation and include Ecuador in the selected group of countries which present aerospace research programs. This increasing interest in the aerospace field has motivated to carry out the present investigation, where innovative designs and methodologies have been developed to enhance the state of the art and hence contribute to the development of the Ecuadorian aviation. In this context, the present work proposes a methodology to assess innovative propulsion systems, whilst accounting for aerodynamic integration issues. This method enables to broad the spectrum of systems analysed and hence optimum and suitable architectures based on different variables can be defined. The figure of merit in this study is the fuel consumption, as this can be related to the environmental impact which is a a major future problem due to increase in oil prices, population growth and increasing globalization. These three aspects are expected to increase the aviation sector (UAV's and civil aviation). For instance, air traffic in the Asian Pacific region has been growing annually by 5.7 % in the last 20 years [1], which is expected to increase to 33 % by 2030. Regarding UAV's, the actual development in systems and control has enabled the development of self controlled drones, which in the coming years are expected to broad the scope of applications. For instance, there are plans to use drones for non-military purposes, private surveillance and delivery services [**?**], among others. These figures imply that the aviation environmental impact will increase as well. To overcome this problem, ambitious performance targets for future aircraft concepts have been set by different organizations such as: NASA, ACARE; at determined time spans [2, 3]. These targets progressively set limits for emissions, noise and fuel burning. Regarding this latter NASA has set for the N+3 timeframe (2030) an ambitious target of 70 % reduction [3] with respect to today's civil aircraft.

As current conventional aircraft configurations are now reaching their design limits in terms of improvement in performance, the aviation industry is now in pursuit of innovative aircraft designs to achieve the ambitious targets. NASA's CESTOL [4] and N2 [5] aircraft designs and the Cambridge /MIT SAX-40 concept [6, 7] are typical examples of these technological innovations. All these designs have been developed for the N+2 timeframe and incorporate blended wing body (BWB) [8] airframes with variants of distributed propulsion system.

For the N+3 timeframe, however, one of the most promising and challenging concepts is the NASA N3-X aircraft concept. This concept adds three innovative features to its predecessor concept, the N+2 version : turboelectric distributed propulsion (TeDP), boundary layer ingestion (BLI) and High Temperature Superconducting (HTS) equipment. Studies carried out have shown that implementing distributed propulsion and BLI could reduce fuel burn by 8 % and 7-8 % relative to today's aircraft respectively [9, 10], whilst using superconductivity and HTS electrical equipment to enable improved electrical transmission efficiency. A schematic representation of this aircraft concept is shown in fig. 1. Although each feature of the N3-X aircraft concept present potential benefits, they also bring new challenges. For instance, the implementation of HTS equipment requires of cryogenic temperatures and hence cooling systems. From the propulsion performance perspective, the aerodynamic integration between airframe and distributed propulsors emerge as main limitation. In order to keep these losses to minimal levels, one of the greater challenges of implementation is therefore the integration of the distributed propulsors with the airframe. Previous studies on the subject define various layouts and further optimise it based on a set geometry [11].

Regarding distributed propulsion, the use of several fans, which are driven by few engines has been found as the most suitable option for future distributed propulsion. The reasons behind this selection are its better performance, less weight contribution to the system , similar functioning to conventional systems, potential opportunities for the implementation of other improvements (noise sheltering, BLI). In ref. [12] a comparison of the performance of two distributed propulsion configurations (one with 16 small engines and the other with 16 fans driven by two turbogenerators using superconductivity for the electrical transmission) with a baseline case using two high by-pass ratio turbofans is carried out. In this study is shown that the 16 fans case weighs more than the comparable 16 engine case, however it has a 9 % lower TSFC (translated to 7 % cruise fuel burn). Furthermore, the fuel burn reduces by 9 % if hydrogen replaces the refrigerator used in cooling.

The work undertaken in this study aims to broaden the spectrum of concepts studied. The study introduces a methodology that uncouples the airframe and the propulsion systems, such that it enables the preliminary de-

---

Artículo recibido el 22 de Abril, 2014; revisado 22 de Abril de 2014. Esta obra fue financiada en parte por la SENESCYT. Autor para correspondencia: e.valencia@cranfield.ac.uk

[1] The Ecuadorian drones (Fenix and Gavilan) are expected to cost $1/7^{th}$ the cost of the Israeli's concept.This information has been found available in

sign of different propulsion arrangements. As TeDP systems with BLI comprise several systems, which in turn depend on many variables, the present analysis selects a group of main variables (design space variables), which enable definition of the basic structure and further allow assessment of their performance. Figure 2 indicates the methodology used to undertake system analysis.

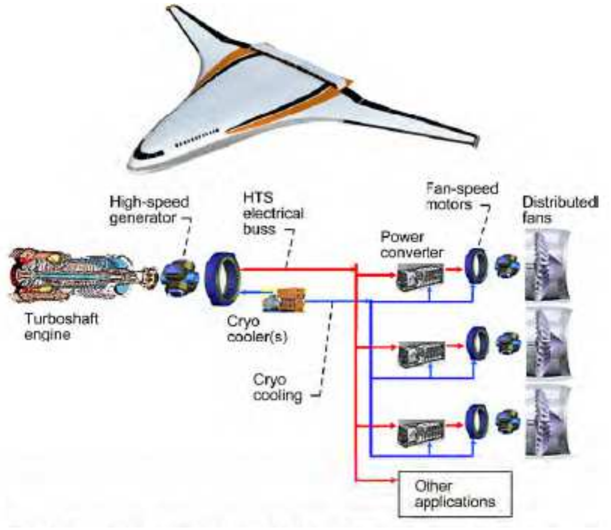


Figura 1. N3-X vehicle and a schematic of its TeDP system [12]

In this methodology the systems, variables and parameters involved in the future aircraft concept are identified and then different propulsion architectures are assessed. For this purpose, the propulsor and main engine systems are built in modules that enable the assessment of BLI induced distortion, intake losses, propulsor array configuration and propulsor design. In this framework, the predictions about electrical and cooling systems are used to assess the feasibility of the concepts. The suitability of the configurations is defined by calculating fuel savings and the related benefits in terms of emissions and noise that each concept could bring [13, 14].

As the present investigation focus on the preliminary design stage, the incorporation of BLI induced distortion in the propulsion system analysis requires a tool with good enough accuracy for this design level and able to assess the combined distortion patterns whilst keeping low consumption of computer resources. For this purpose, an alternative method based on blade design and semi-empirical correlations has been developed and incorporated into the system analysis [15].

The method used in the present investigation enabled the assessment of thrust split between main engine and propulsor array in the system analysis. The propulsion designs assessed demonstrated that reducing the thrust delivered by the propulsors and changing the main engines configuration from turboshaft to turbofan could be favourable and contribute to reduce the effects of the aerodynamic integration issues [14]. In the context of reducing BLI induced distortion, the present work has explored the performance of an alternative propulsor design, which ingest indirectly the boundary layer [13].

2. METHODOLOGY

2.1 *Overall methodology*

Fig. 2 shows a diagrammatic representation of the overall methodology used for the propulsion system performance assessment. As observed the analysis is divided in four main systems, which are: propulsors, main engine, electrical and cooling systems. The first two systems are connected by the thrust split and propulsor's power requirement. The other two systems are used to check the suitability of the propulsion configurations. For this purpose, the HTS electrical motors are sized in function of power and rotational speed [16–18]. The electrical motor diameter is an important parameter, as in this design is assumed that they are mounted in the propulsor shafts (fig. 4) and that the space to allocate fans/propulsors over the BWB airframe is defined. For the purposes of this analysis the N3-X NASA [10] aircraft concept was selected as the baseline architecture, due to its turbo-electric distributed propulsion system (TeDP) that incorporates boundary layer ingestion. As this work focuses on the assessment of propulsion system designs, the N3-X flight conditions at cruise (12.19 km /Mach 0.84) and airframe configuration have been maintained. At this stage of the study, the cooling system is assumed to implement cryocoolers.

2.2 *Propulsor performance*

The performance of the propulsor with BLI is carried out using a parametric and a quasi-two dimensional approaches. In the case of the one dimensional model the inlet properties are calculated based on a mass flow average of the BL ingested. In the case of the quasi-two dimensional approach the three dimensional BL profiles are used with the discretized semi-empirical approach [15]. These BL profiles correspond to the flow Mach and total pressure , which have been defined for the N3-X airframe [10] at a distance of 0.85 x=c at the centerline. To simplify the analysis the propulsor inlet array (station 1) is located at this position before compression or diffusion effects have occurred. This assumption implies that the height of the intake is equal to the height of the boundary layer capture sheet. The cruise intrinsic thrust (F_N=73.952 kN) then is utilized to define the propulsor's mass flow [14]. For the performance calculation a momentum based method using the internal control volume shown in fig. 3 is utilized. The implementation of these assumptions simplify

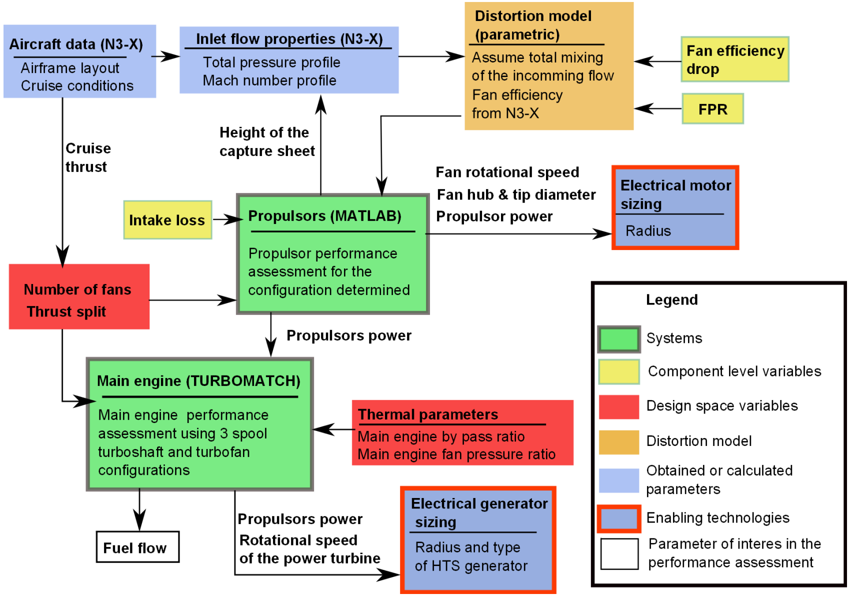


Figura 2. Methodology for the propulsion performance study of TeDP systems with BLI.

the intrinsic thrust as follows

$$F_N = NF\left(\dot{m}_f\left(V_4 - V_1\right) + \left(p_4 - p_\infty\right)A_4 - \left(p_1 - p_\infty\right)A_1\right) \quad (1)$$

where NF corresponds to the number of fans.
To account for the reduction in momentum drag due to BLI, the control volume inlet properties are assumed equal to the BL properties mass averaged values. These values are calculated based on the BL profiles provided in ref. [10], which are assumed to exist at a distance of 0.85 x=c over the N3-X airframe centerline. To simplify the analysis the inlet control volume (station 1) is located at this position and is assumed that the ingested BL has not been either diffused or compressed within the streamtube entering the intake [19] . In other words, it is assumed that at design point the height of the intake is equal to the height of the capture sheet.
The BL profiles for total pressure and Mach are calculated with equations 3 and 2 respectively. Otherwise stated, the values of the correction factors (CF) for Mach number and total pressure equations are 0.2 and 0.105 respectively and correspond to the BL properties at the 0.85 x=c location according to ref. [10].

$$M_{BL} = M_1 = M_\infty\left(\left(\frac{y}{0.371c_{cl}/Re_{cl}^{1/5}}\right)^{1/11} - CF\right) \quad (2)$$

$$P_{BL} = P_1 = P_\infty\left(\left(\frac{y}{0.371c_{cl}/Re_{cl}^{1/5}}\right)^{1/15} - CF\right) \quad (3)$$

where based on the previously assumed N3-X airframe dimensions, c_{cl} is the length based on the intake location $(0.85x = c)$ and Re_{cl} is the Reynolds number based on this length. For the parametric analysis the mass averaged values have been calculated with the following expressions

$$M_1 = \frac{1}{\dot{m}_f}\int_0^{H_{CS}} M_{BL}(y)\dot{m}_f(y)dy \quad (4)$$

$$P_1 = \frac{1}{\dot{m}_f}\int_0^{H_{CS}} P_{BL}(y)\dot{m}_f(y)dy \quad (5)$$

To determine the three dimensional velocity profile for high fidelity distortion approaches the total pressure and Mach number are utilized to define the velocity profile assuming negligible total temperature distortion.
The fan face flow properties are determined assuming the intake pressure loss, which is calculated using equation 6.

$$\Delta P_{in} = \frac{\Delta P_{1-2}}{P_1} \quad (6)$$

In order to define the height of the boundary layer ingested, the capture sheet height (H_{CS}) is utilized as handle in an iterative calculation. The capture sheet height is calculated using continuity and assuming a mailbox intake of width equal to the fan diameter. The capture sheet height is calculated assuming a mailbox intake of width equal to the fan diameter and using continuity. Figure 4 depicts a schematic diagram of the intake configuration. In the parametric analysis the fan pressure ratio and fan efficiency drop are input variables in the propulsor performance subroutine and they are used to calculate the flow properties downstream the fan . For the quasi- two dimensional

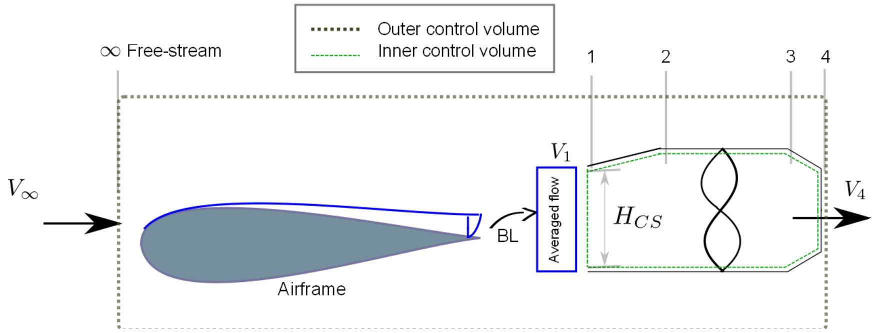


Figura 3. Control volumes used for propulsor performance analysis

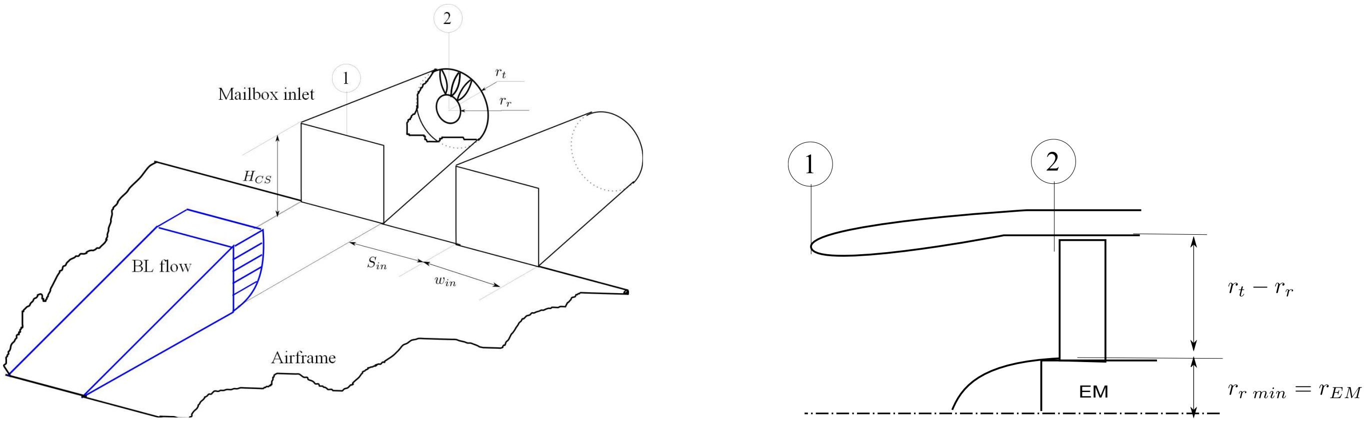
approach a discretized empirical method is used to define the fan pressure ratio and fan efficiency in function of the blade design and fan face BL. As the optimum configurations are found at low fan pressure ratios (propulsor array) [20] a range between 1.15-1.45 is selected. An appropriate intake loss range is difficult to predict for this sort of intakes, therefore the range studied (1-2.5 %) is based on values that make viable the use of BLI [21]. Finally, to calculate the flow properties at the exit station, a nozzle pressure loss of 1 % is assumed.

2.2.1 *Distortion modelling*

Parallel compressor To improve the level of fidelity of the system performance analysis , a well known method denominated the parallel compressor [22, 23] has been implemented in the methodology presented in figure 2. The advantage of this method is that the fan performance characteristics can be defined based on the fan face flow properties. In other words, depending on the incoming flow the deterioration in fan performance can be determined. This method has been widely used to asses BLI systems [24], due to its simplicity, good enough accuracy and low computational resources. However, some of its drawbacks are the use of only two streams to model the incoming flow, the dependence in a default compressor map and the assessment of only circumferential distortion.

The parallel compressor method considers the circumference of the compressor to be divided into two flow regions: one of the relatively low velocities, such as would exit behind a distortion inducing screen and one of relatively high velocity. The compressor performance in each region is assumed to be that obtained from uniform flow operation at the local value of inlet velocity. It is further assumed that circumferential cross flow within the compressor is negligible, no inlet total temperature distortion, and that the exit static pressure is uniform.

Alternative method to assess radial and circumferential distortion The performance deterioration of axial fans/compressors working with distorted flow has been studied extensively in the past. Different approaches and tools such as: through flow methods [25] , semi-empirical correlations [26], and fan map based methods (parallel compressor [24]) have been utilized to assess their performance. It has been found that even though through flow methods such as streamline curvature [27, 28] and CFD can predict fan performance with higher accuracy than the other methods; they also require larger resources in terms of computational power and time. At the preliminary design stage, where the detailed geometry of a system/component is still undefined and several configurations have to be tested, reducing requirements of computational resources becomes imperative. Due to excessive simulation times these methods have also been found unsuitable in cases where full annular simulation is required and circumferential distortion is present (such as in boundary layer ingesting systems [12, 14]).These reasons, therefore, render methods such as the parallel compressor [24] more attractive for preliminary design at design point. However this method has its limitations, as it only enables to assess circumferential distortion. Hence it may be considered to have limited accuracy in the case of BLI systems, where a combination of circumferential and radial distortion of flow is observed. These limitations have motivated the search of an alternative distortion assessment method for preliminary design. This method consists on defining a basic blade design and then using empirical correlations to determine the fan performance characteristics. The novelty of the proposed method is that instead of using a one stream to model the flow through



(a) Propulsor airframe integration (b) Electric motor and fan configuration

Figura 4. Propulsor integration and fan configuration

the fan, it discretizes the inlet region in circumferential and radial directions, such that the performance characteristics of each segment can be deduced. This method also assumes that circumferential cross flow within the compressor is negligible, no inlet total temperature distortion and similar (<5 %) meanline static back pressure between the maximum and minimum distorted radial regions. Some of the advantages presented by this method include: assessment of combined distortion patterns, fan map independence, low consumption of computer resources and adequate accuracy for preliminary design. In order to verify the approach and ensure that the set of empirical correlations predicted the fan performance accurately, a series of validation test cases are undertaken. From the validation studies a combination of correlations developed by Miller [29, 30] were found to match more accurately the experimental results. For this reason, this approach has been denominated as as discretized Miller. Further information regarding this method is given in ref. [15].

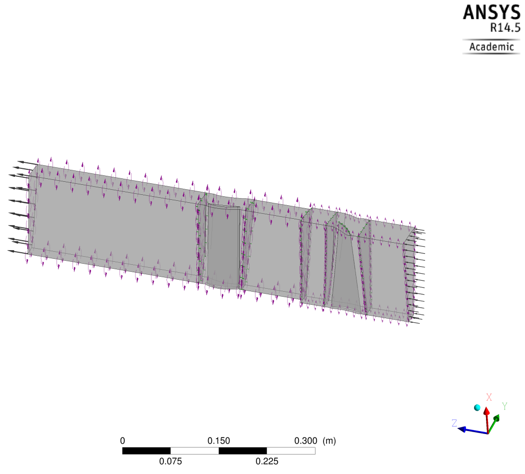


Figura 5. CFD domain for uniform case

2.3 *Alternative propulsor configuration*

In order to reduce the effect of BLI induced distortion and intake pressure losses, an alternative propulsor design which uses the ejector pump effect to re-energize the BL has been studied. In this design the propulsor comprises two regions; the free-stream region, which uses a fan to accelerate the flow, and the boundary layer region where the induced flow is re-energized by the ejector pump effect. The performance analysis of the free-stream duct is carried out as in the case of the direct BLI modelling, with two differences, firstly the inlet properties are at free-stream conditions and not affected by the fan pressure ratio and secondly, the flow does not expand to atmospheric conditions but it enters into the mixer, as shown in fig. 6 . The Mach number at this station is a variable utilized in the assessment of this configuration. At this preliminary design stage this value was varied as a function of fan pressure ratio to avoid choking the free stream duct and the formation of reverse flow at the secondary duct. For the BLI duct the properties of the induced boundary layer are once again calculated at the same position as for the aforementioned case (x=c=0.85 airframe location) and the precompression effects are again neglected. The flow properties are calculated using NASA's inlet profiles which are divided along the height of the secondary duct. The percentage of BLI is used as input variable and this determines the height of the BLI. Fig. 6 shows the parameters and variables involved in the propulsor performance calculation.

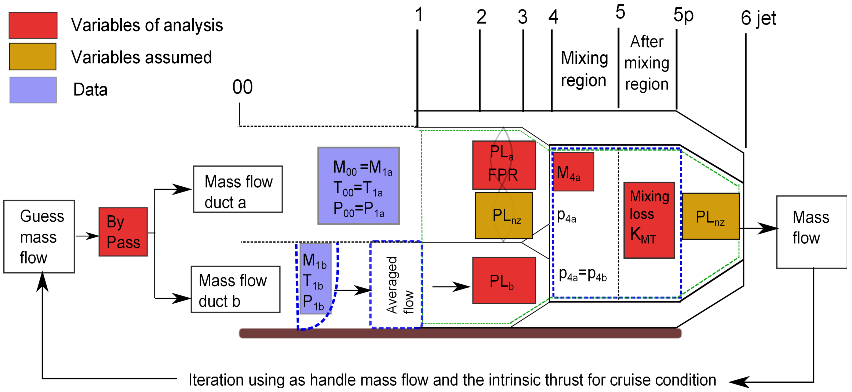


Figura 6. Control volume and variables used for the alternative propulsor design

2.4 *Main engine performance*

The main-engine is modelled using TURBOMATCH platform, which is a gas turbine performance tool developed in Cranfield University. As observed in fig. 2 the design space variables used in the main engine analysis are fan pressure ratio and by pass ratio. Turbine entry temperature (TET) has not been include in the analysis, as this is mainly related with material development and level of technology, which for the present study is set for the N+3 timeframe. It is also assumed that for this futuristic scenario the development in materials will enable the reduction of the core size , such that high by pass ratios can be achieved without the need of considerable increase in fan diameter as in current turbofan designs. In this way, the increase in size and therefore installation drag losses and weight increment can be neglected.

The characteristics of the main engine model used in this investigation are based on the futuristic design presented in ref. [10]. In order to optimize the performance of the main engine for low thrust split configurations (propulsor array producing less thrust), the main engine has been modelled as a 3-spool turbofan engine with a power turbine mounted in the low spool shaft. In the case of high thrust splits (>95 %) it was found that the 3 spool turbo-shaft configuration with a free power turbine was the optimum, as in those cases the main engine thrust was negligible. The layout of the main engines utilized are shown in fig. 7

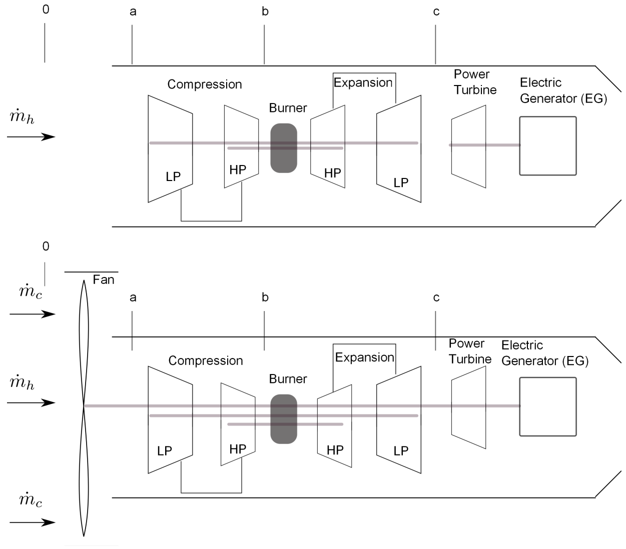


Figura 7. Main engine configurations

3. RESULTS AND DISCUSSIONS

3.1 *Propulsor performance*

In order to assess the effects of intake losses and BLI induced distortion the propulsor performance has been assessed using different distortion tools, such as:through flow methods [25] , semi-empirical correlations [26], fan map based methods parallel compressor [24]), one dimensional approach [14] and the discretized miller approach (DM) [15]. In this occasion, fig. 8 collects the results obtained with the parallel compressor approach for the propulsor depicted in fig. 3 together with the results for the alternative propulsor configuration (fig. 6) for different intake losses. For all the cases examined cruise conditions are assumed. The TSFC benefit in this figure is calculated with respect to a similar propulsion configuration without BLI. This parameter is preferred, as it highlights major trends in the propulsor performance. The cases presented correspond to configurations with thrust delivered mainly by the propulsor array. In these cases the a parallel compressor (PC) approach predicted approximately 2 % drop in fan efficiency [13, 20], which is lower than the 3 % predicted with the DM approach [15]. Depending on the pressure ratio analysed the propulsion system present a high sensitivity to intake losses, especially at low pressure ratios due to the higher influence of losses. This

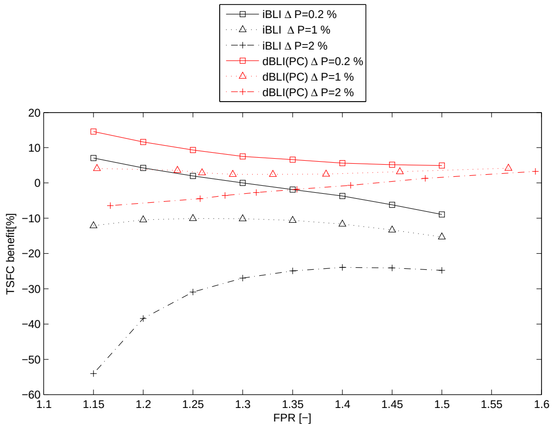


Figura 8. Propulsor performance sensitivity to intake losses [13]

high sensitivity becomes an issue, especially because optimum power configurations were found at low pressure ratios. As observed in fig. 8 pressure losses in the order of 2 % dramatically mitigate the expected benefits. This evidence the necessity of optimizing current intake designs, which is a challenge due to the complexity of the ducts required for these systems [**?**]. As pressure losses are dependent on the propulsor's mass flow the influence over the propulsion system can be reduced by using lower thrust splits (more thrust delivered by the main engines), which is explained further in the system analysis section.

3.2 *Alternative propulsor analysis*

The performance results for the most optimistic case of the alternative propulsor configuration, which uses the ejector pump (EP) effect, are shown in fig. 8. As observed high levels of fan efficiency penalties associated with BLI and intake loses can make that the indirect BLI or ejector pump configuration can have a better performance. However it needs to be emphasized that the performance of the indirect BLI configuration is highly affected by the pressure losses at the mixing station and is very likely that the presence of these losses can outweigh any predicted savings.

3.3 *Weight analysis*

This study emphasises the importance of accounting for drag and weight during preliminary design in order to improve and refine the prediction of the optimal configuration. In ref. [31] the effects of weight are included in the system analysis and as observed they reduce the optimal thrust split for the optimal configurations.
The methodology developed in in this work can be adapted to optimize in function of other figures of merit as weight. In this study it has been preferred do not consider drag installation losses and weight issues of the propulsors array, main-engines, cooling and electrical systems. Even though installation and weight effects are critical, it is opined that, while predicting future characteristics for these components/ systems is still a significant challenge, using current standards for the application may prevent achieving any feasible solutions in the design search space being considered. Studies have recently been conducted for some of these components and references [16, 32] discuss various models and sensitivity analysis of various relevant design parameters. For these reasons, it has been preferred to assess the method developed based only on fuel consumption.

4. CONCLUSIONS

The growing interest of Ecuador in the aviation field and the potential benefits in various aspects such as: economical, technological development and safety, motivate the research of innovative designs which enable to reduce fuel consumption, pollutant emissions and noise levels. By addressing these issues, more environmentally friendly and operating cost effective aircraft can be developed. For the UAV field these competitive advantages may contribute to make it an attractive concept for commercialization. In this context, the present paper compiled the work carried out on the development of innovative propulsion architectures for aircraft. In order to achieve this, a methodology, which enable the assessment of different propulsion architectures, whilst accounting for important aerodynamic integration issues, has been presented. Furthermore, an alternative distortion method which accounts for radial and circumferential distortion, and an alternative propulsor design have been presented. As the present work primarily focuses on preliminary design and to also simplify the analysis, some fundamental assumptions and basic models have been selected to assess the performance of propulsors, main engines and electric system. It is also pertinent to note that as the present study focuses mainly on the propulsion system designs and its performance advantages, aircraft performance implications such as drag installation losses and weight increment have not been considered.

ACKNOWLDGMENT

The present investigation has been partially funded by SENESCYT.

REFERENCIAS

[1] Airbus. Delivering the future, global market forecast 2011-2030 full book. Web Pa-

ge Visited in March 2012, none 2011. URL

[2] ACARE. Aeronautics and air transport: Beyond vision 2020 (towards 2050). Accessed in March 2012, none 2010. URL .

[3] E. Greitzer, P. Bonnefoy, E de la Rosa Blanco, and et al. N+3 aircraft concept designs and trade studies, final report. Cr2010216794 vol1, NASA, Cleveland, Ohio, 9 2010. NASA/CR-2010-216794/VOL2.

[4] H. Kim, J. Berton, and S. Jones. Low noise cruise efficient short take-off and landing transport vehicle study. In *6th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, page none, Wichita, Kansas, 9 2006. AIAA. AIAA 2006 7738.

[5] Meng-Sing L. Hyoungjin K. Flow simulation of n2b hybrid wing body configuration. In *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, page none. AIAA, 2012. AIAA 2012-0838.

[6] Alexis Manneville. *Propulsion system concepts for silent aircraft*. 2004. URL .

Thesis (S.M.)–Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, 2004.

[7] E. de la Rosa, C. Hall, and D.l Crichton. Challenges in the silent aircraft engine design. In *45th AIAA Aerospace Sciences Meeting and Exhibit*, page none, Reno, Nevada, 1 2007. AIAA. AIAA 2007 454.

[8] R Liebeck. Design of the blended wing body subsonic transport. *Journal of Aircraft*, 41 (1):10–25, 2004. doi: 10.2514/1.42409. URL .

[9] G. Brown. Weights and efficiencies of electric components of a turboelectric aircraft propulsion system. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, page none, Orlando, Florida, 2011. AIAA.

[10] J. Felder, H. Kim, G. Brown, and et al. An examination of the effect of boundary layer ingestion on turboelectric distributed propulsion systems. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, page none, Orlando, Florida, 1 2011. AIAA. AIAA 2011 300.

[11] D. Rodriguez. A multidisciplinary optimization method for designing boundary layer ingesting inlets. In *Symposium on Multidisciplinary Analysis and Optimization*, page .none, Atlanta, 2002. AIAA/ISSMO.

[12] J. Felder, H. Kim, and G. Brown. Turboelectric distributed propulsion engine cycle analysis for hybrid-wing-body aircraft. In *47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, page none, Orlando, Florida, 1 2009. AIAA. URL .

AIAA 2009-1132.

[13] E. Valencia, L. Chengyuan, P. Laskaridis, and et al. An alternative configuration for distributed propulsion with boundary layer ingestion on a hybrid wing body airframe. In *21st ISABE Conference*, pages 1822–1829, Busan, Korea, september 2013. ISABE.

[14] E. Valencia, D. Nalianda, P. Laskaridis, and et al. Methodology to assess the performance of an aircraft concept with distributed propulsion and boundary layer ingestion using a parametric approach. *Part G:Journal of Aerospace*, June 2014.

[15] E. Valencia, N. Devaiah, P. Laskaridis, and et al. Discretized semi-empirical approach to assess the effects of combined circumferential and radial distortion patterns for boundary layer ingestion systems. manuscript submitted for publication, 11 2014.

[16] C.A. Luongo, P.J. Masson, T. Nam, D. Mavris, H.D. Kim, G.V. Brown, M. Waters, and D. Hall. Next generation more-electric aircraft: A potential application for hts superconductors. *Applied Superconductivity, IEEE Transactions on*, 19(3):1055 –1068, june 2009. ISSN 1051-8223. doi: 10.1109/TASC.2009.2019021.

[17] P.J. Masson, J.E. Pienkos, and C.A. Luongo. Scaling up of hts motor based on trapped flux and flux concentration for large aircraft propulsion. *Applied Superconductivity, IEEE Transactions on*, 17(2):1579–1582, 2007. ISSN 1051-8223. doi: 10.1109/TASC.2007.898111.

[18] P.J. Masson and C.A. Luongo. Hts machines for applications in all-electric aircraft. *Power Engineering Society General Meeting, 2007. IEEE*, pages 1–6, 6 2007. doi: 10.1109/PES.2007.385622.

[19] H. Kim and J. Felder. Control volume analysis of boundary layer ingesting propulsion systems with or without shock wave ahead of the inlet. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, page none, Orlando, Florida, 1 2011. AIAA. AIAA 2011 222.

[20] Chengyuan Liu, Georgios Doulgeris, Panagiotis Laskaridis, and Riti Singh. Turboelectric distributed propulsion system modelling for hybrid-wing-body aircraft. 07 2012. URL . AIAA 2012-3700.

[21] D Rodriguez. Multidisciplinary optimization method for designing boundary-layer-ingesting inlets. *Journal of Aircraft AIAA*, (3):883–894, 2009. doi: 10.1109/TASC.2005.849616. AIAA 2002-5665.

[22] R.S. Mazzawy and G.A. Banks. *Modelling and analysis of the TF30-P-3 compressor system with inlet pressure distortion / by R.S. Mazzawy, and G.A. Banks.* NASA Contractor Report. Washington, D.C. : NASA, 1976., 1976. NASA CR - 134996, PWA-5302.

[23] R.S. Mazzawy, D.E. Hadded, and D.A. Fulkerson. *F100(3) parallel compressor computer code and user's manual*. NASA Contractor Report. Washington, D.C. : NASA, 1978., 1978. NASA CR - 135388, PWA-5549-8.

[24] Angelique Plas. *Performance of a boundary layer ingesting propulsion system*. 2006. URL . by Angelique Plas.; Thesis (S.M.)–Massachusetts Institute of Technology, Dept. of Aeronautics and Astronautics, 2006.; Includes bibliographical references (p. 111-114).

[25] V. Jerez, C. Hall, and Y. Colin. A study of fan-distortion interaction within the nasa rotor 67 transonic stage. 134(5):1–12, 2012.

[26] Radu Cirligeanu and Vassilios Pachidis. *IGV loss and deviation modelling*. Restricted Theses 2010. 2010. URL MSc theses in Cranfield University, Accessed 10 july 2014.

[27] G. Doulgeris. *Modelling and integration of advanced propulsion systems*. Theses 2008, Cranfield University. 2008. PhD theses in Cranfield University.

[28] Vassilios Pachidis, Pericles Pilidis, Ioannis Templalexis, and Luca Marinai. An iterative method for blade profile loss model adaptation using streamline curvature. *Journal of Engineering for Gas Turbines and Power*, 130(1):1 – 8, 2008. ISSN 07424795. doi: 10.1115/1.2747643. URL .

[29] P. I. Wright and D. C. Miller. *An improved compressor performance prediction model*. 1991. Turbomachinery latest development in a changing scene proceedings of the IME European ConferenceMarch 19-20, 1991, London, UK.; Turbomachinery.

[30] D.C. Miller and D.L. Wasdell. Off-design prediction of compressor blade losses. 1987. IMECHE C279/87, 1987.

[31] Rudi Kirner. *An investigation into the benefits of distributed propulsion on advanced aircraft configurations.* Theses 2013. Cranfield University, 2013. URL MSc theses in Cranfield University, Accessed july 2014.

[32] J. Felder, M. Tong, and J. Chu. Sensitivity of mission energy consumption to turboelectric distributed propulsion design assumptions on the N3-X hybrid wing body aircraft. In *48th AIAA Joint Propulsion Conference and Exhibit*, Atlanta, Georgia, 7 2012. AIAA. AIAA 2012-3701.