MULTI-DISCIPLINARY DESIGN AND FEASIBILITY STUDY OF DISTRIBUTED PROPULSION SYSTEMS

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Abstract

This paper discusses pre-design and integration considerations involved when implementing distributed propulsion for future aircraft concepts. In this context, distributed propulsion is achieved by utilization of multiple or a single (large) fan. The distributed integration of the propulsion system leads to strong coupling between airframe aerodynamics and motive power performance, which is addressed with high-end, low-fidelity and interlaced fidelity methods. As a first step, representative integrated and distributed propulsion system configurations were qualitatively evaluated in terms of power system integration, operational aspects, weight, noise, and efficiency. Selection of the distributed propulsion solution for further investigation was based upon identification of the greatest potential to realize quantitatively benefits of boundary layer ingestion at aircraft system level. With regards to the multi-disciplinary aircraft-level analysis, input from all relevant technical sub-spaces were examined, and the chosen configuration then compared to an advanced reference aircraft reflecting evolution in the state-of-the-art. Finally, comparative trade studies were performed in order to identify a best and balanced solution for the chosen configuration.

1 Introduction

The European Union (EU) unveiled an array of ambitious emission reduction goals for implementation by the year 2050 going far beyond near-term objectives such as those espoused by the Advisory Council for Aeronautics Research in Europe (ACARE) in 2001. Although near-term objectives declared by the ACARE Vision 2020 [1] with 80% and 50% reduction in nitrous oxide (NO_x) and carbon dioxide (CO_2) emissions, respectively, have been adopted by the European research community at large for over a decade now, the EU “Flightpath 2050” agenda [2] stipulates a reduction of 90% in NO_x-emissions, and of 75% in CO_2 emissions. All quoted values are relative to the capabilities of typical aircraft in-service during year 2000.

With the expressed intent of realizing these ambitious goals, technical solutions beyond those of innovative aircraft configurations, flow control devices and adaptive systems need to be offered. One such idea is to break up the classical separation of airframe and engine and fully exploit possible synergy effects by closely coupling the propulsors with the airframe. Possible synergy effects may cover aerodynamics (reduction of wetted area, reduction of flow dissipation by wake filling), propulsion system aspects (realization of optimum fan pressure ratios, boundary layer ingestion), and structural improvements. Recognition of the shift in the typical aircraft design paradigm is depicted in Fig. 1. Simultaneously, enhanced flexibility with respect to power system source and transmission by treating the power system as a modular part during aircraft design (or even during operations) is seen as key enabler for reaching Flightpath 2050 goals. This development is further motivated by the currently foreseen performance increase of electric components, which may enable net benefits on aircraft system level for power system hybridization or complete electrification.

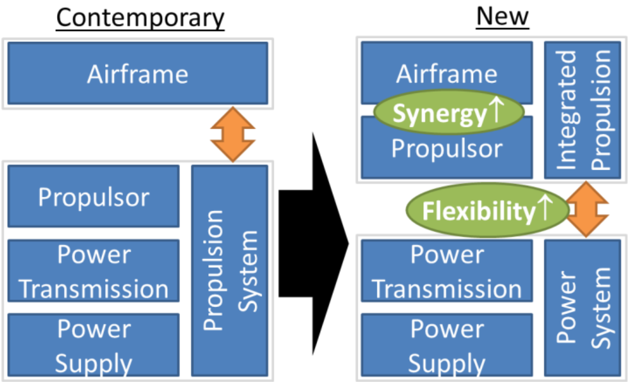


Fig. 1. Shift in aircraft design paradigm motivating integrated [distributed] propulsion.

1.1 Overview of Distributed Propulsion

The investigation of aircraft concepts with distributed propulsion is gaining increased attention. An overview of the different types of distributed propulsion vehicles has been given by Kim [3] using the following classification:

- Jet flaps (blowing engine exhaust out of the wing trailing edge) [4],[5]
- Cross-flow fan (2D propulsor integrated within the wing trailing edge) [6],[7]
- Multiple discrete engines (driven by their own power source) [8],[9],[10]
- Distributed multi-fans driven by a limited number of engine cores; transmission approaches include
  - Gas-driven (pneumatic)
  - Gear-driven (mechanic)
  - Electrically driven

Common to all of those concepts is the idea of distributing the thrust-producing jet stream in order to increase overall vehicle efficiency. In the context of this paper, a new type of concept will be added, which is justified by targeting the same goal. This configuration is characterized by a single-rotating or counter-rotating fan encircling the fuselage with intent to entrain the fuselage boundary layer and distribute the thrust along the viscous wake generated by the fuselage. The configuration, hereafter referred to as a "Propulsive Fuselage" is schematically depicted in Fig. 2. In this context, a propeller-type configuration has been investigated by Bolonkin [11], highlighting mainly the advantages in terms of low specific thrust.

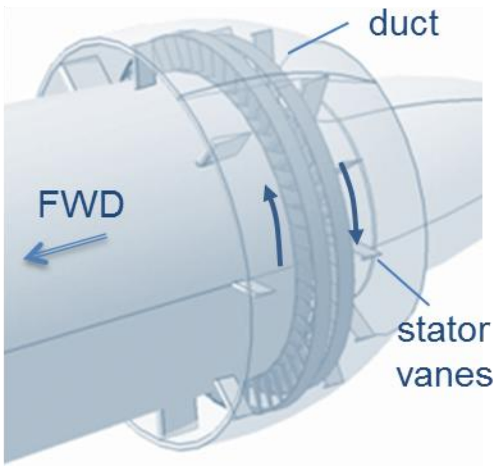


Fig. 2. Propulsive fuselage concept as an additional type of distributed propulsion.

Current research in the field of distributed propulsion system integration has focused on distributed multi-fans driven by a limited number of engine cores. Investigations based on Blended Wing Bodies (BWB) have been performed by NASA [12], the Silent Aircraft Initiative [13], Stanford University [14], the Massachusetts Institute of Technology [15], and within the European FP6 project NACRE [16]. Also, conventional aircraft layouts with ingesting engines on the upper wing side or inside a split wing have been investigated, e.g. by Empirical Systems Aerospace and Advanced Magnet Lab for turbo-electric aircraft [17].

In the present paper, the focus is set on those distributed propulsion concepts that are realized by utilizing multiple or a single (large) fan. The fans are assumed to be driven by two turbo-shaft core engines, either mechanically or electrically, to allow comparison. The aircraft concepts investigated in this study will be, thus, characterized by a high level of propulsion system close-coupling with the airframe. One main driver for the investigation of such systems is to achieve a very low specific thrust, namely, low fan pressure ratios (FPR), without suffering from the same increase in nacelle drag as conventional podded propulsion systems [18]. This is beneficial in terms of propulsive efficiency and external noise. Additionally, such propulsive devices could be partially immersed in the boundary layer of the wing or the fuselage. Several studies, dating back to Betz [19] and Smith [20], as well as recent studies by

Felder [21], indicate an increase of propulsive efficiency for propulsors utilizing boundary layer ingestion (BLI). Also, recent investigations conducted by Sato [15] seem to confirm the benefit of BLI, which was found to be primarily due to the reduction of jet and wake dissipation, and increases with the amount of boundary layer ingested into the propulsor.

This paper contributes to the research on distributed propulsion aircraft by proposing methods and models for estimating aerodynamic, propulsive, and structural aspects necessary for a pre-design, multi-disciplinary assessment of integrated propulsion systems. Notably, the study aims to investigate the possible benefit of BLI at aircraft system level by selecting a "best suited" aircraft configuration for realizing BLI-borne benefits. This configuration is to be subsequently analyzed using higher order methods as part of future research activities, and thus, may act as an established upper bound case for BLI applications.

1.2 Approach of this Study

The content of the presented paper is divided in two main parts. The first part (Section 2) presents the documentation of the down-selection process, which has been carried out to determine the best suited distributed propulsion configuration for the specified requirements. It has to be noted that the individual weighting of these requirements reflects rather the scientific goals of this study, as opposed to offering a realistic economic evaluation. Preceding the down-selection the basic principles of BLI are described, which allow for an estimation of the performance of distributed propulsion systems. The second part (Section 3) consists of a multi-disciplinary analysis of the selected propulsion concept, showing the design trade-off between the involved disciplines, and a comparison of the design result against that of an advanced reference aircraft.

2 Qualitative Concept Down-Selection

The following section describes the formal down-selection process that was carried out in order to identify the most promising concept, i.e. one that can realize maximum efficiency benefits associated with distributed propulsion. The first two sub-sections are dedicated to the estimation of the potential efficiency benefit related to BLI, since this has been declared as one of the main motivators for distributed propulsion concepts. It is pointed out that using the Power Saving Coefficient (*PSC*, as introduced by Smith [20] in earlier work) as a metric allows for a suitable quantification of BLI benefits even at a pre-design stage. The results are shown and discussed in Section 2.2.

2.1 Boundary Layer Ingestion - Overview

The potential for increasing the efficiency of an integrated propulsion system by ingesting slow boundary layer flow can be illustrated by the application of basic zero-dimensional actuator disk theory. Neglecting pressure contributions (assuming a fully expanded nozzle), the ideal propulsive efficiency η_P (ratio of usable power $T \cdot V_\infty$ compared to the kinetic power P added to the flow) of a propulsor with inlet velocity V_1, outlet velocity V_2, and flight (freestream) velocity V_∞ is given by

$$\eta_P = \frac{T \cdot V_\infty}{P} = \frac{\dot{m}(V_2 - V_1) \cdot V_\infty}{\frac{\dot{m}}{2}\left(V_2^2 - V_1^2\right)} = \frac{V_\infty}{V_1 + \Delta V/2} \qquad (1)$$

As Equation (1) indicates, possibilities to enhance the propulsive efficiency are on the one hand the reduction of specific thrust, i.e. the reduction of $\Delta V = V_2 - V_1$, or a reduction of V_1. The first option implies an increase of mass flow $\dot{m}$ for a required thrust T and correlates to an increase of bypass ratio for turbofan engines. The second option equals a reduction in ram drag as achieved through BLI.

A physical explanation for this efficiency increase is given by the consideration of energy losses in the flow field, as described by Drela [22]. In general, propulsive efficiency loss is a consequence of any net kinetic energy left in the wake (characterized by non-uniformities in the velocity profile) compared to that of a uniform velocity profile [23]. These non-uniformities are the reason for fluid friction, and hence, for dissipation of energy in the trailing wake until the velocity field is uniform again. These energy losses due to friction can be reduced by designing an integrated propulsion system such that velocity profile non-uniformities are minimized by filling the wake. Fig. 3 illustrates the basic principle of wake filling for different levels of propulsion system integration.

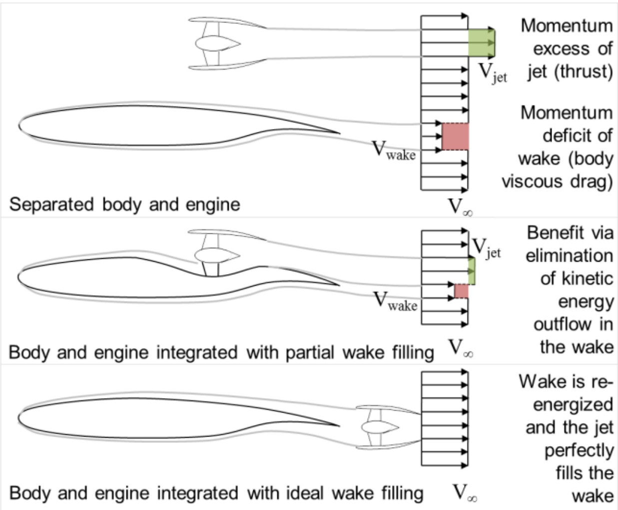


Fig. 3. Illustration of the basic principle for wake filling.

The classical case of separated body and engine is shown in the upper most portion of Fig. 3. For the simplification of a self-propelled case (no additional drag components like induced drag or wave drag) the momentum excess of the jet must equal the momentum deficit in the wake due to viscous body drag. The propulsive efficiency of the overall system is improved if the jet "fills in" the wake directly behind the body. This is shown with the two cases for integrated propulsion systems in the bottom portion of Fig. 3. In the ideal system, the jet perfectly fills in the wake, creating a uniform velocity profile. In this case, there are no losses due to dissipation occurring in the wake of the integrated system. However, the jet does not fully fill in the wake in practice, but rather creates smaller non-uniformities in the velocity profile, as illustrated in the middle part of Fig. 3. The resulting velocity profile contains a smaller net kinetic energy than that of the case where the body and engine are independent. However, for any closely coupled propulsion system it may become necessary to assess the overall system efficiency by evaluating the losses in the complete flowfield.

2.2 Boundary Layer Ingestion - Methods

A first detailed quantification of the concept of wake ingestion was investigated by Smith [20]. He applied an incompressible actuator disk model and described the wake by integral wake properties like wake displacement area. These wake parameters together with the ratio of ingested drag to total thrust can be used to calculate the propulsive efficiency and a *PSC* indicating the wake ingestion benefit. The *PSC* used in the following is defined as the reduction in power due to BLI relative to the total power requirement without BLI, viz.

$$PSC = \frac{P_{NoBLI} - P_{BLI}}{P_{NoBLI}} \tag{2}$$

The analysis of Smith shows that the main impact on *PSC* correlates well with the ratio of ingested drag to total thrust, D_{ing}/T. The D_{ing} parameter "Ingested drag" in this context describes the amount of viscous drag generated on that part of the airframe surface, which is wetted by the flow entering the propulsive device.

The following down-selection takes advantage of the fact that this property can be easily estimated for a given aircraft configuration. The *PSC* derived by Smith [20] is depicted in Fig. 4 assuming typical values of a turbulent boundary layer profile, a wake recovery factor of R = 0.90 (this describes the capability of the propulsor to flatten the wake), and a thrust coefficient of C_T = 0.70, which is a reasonable value for an integrated propulsion system and corresponds to a FPR = 1.35 at typical cruise conditions. C_T is defined as the specific thrust per propulsor area A_P, normalized by freestream dynamic pressure q_∞:

$$C_T = \frac{T}{A_P \cdot q_\infty} \tag{3}$$

Additionally, Fig. 4 shows results derived by Rodriguez [24] and Plas [25] that confirm the achievable ideal benefit determined by Smith [20]. Plas used a compressible parallel compressor model with FPR = 1.50. Even if he also calculated *PSC* values for non-ideal conditions (non-ideal fan, distortion transfer), only the results for ideal BLI benefit are depicted in Fig. 4 and used in the following to assess the different distributed propulsion configurations. The impact of not having ideal conditions was then assessed on a qualitative basis for the concepts. A final set of highlights of Fig. 4 are two points specially annotated on the chart. These points represent in-house analysis, the details of which are discussed in Section 3.3.

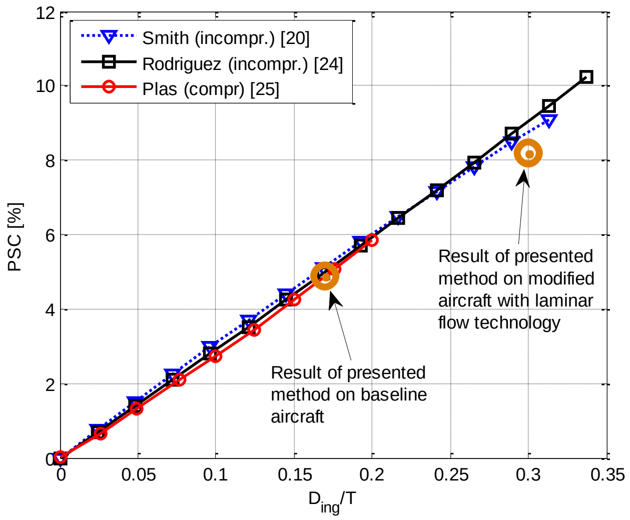


Fig. 4. Estimation of ideal power saving coefficient vs. ratio of ingested drag based on three methods derived from literature.

2.2 Down-Selection Process

The goal of this section is to describe the down-selection process carried out in order to assess different aircraft concepts using distributed propulsion. The assessment is only considering the integrated propulsion system, i.e. only the combination of airframe and propulsors without the power system (cf. Fig. 1). The considered concepts were all based on the idea of driving a number of propulsors – either axial or cross-flow fans - with a small number of turbo-shaft core engines. The selected concepts are listed in Table 1.

The qualitative down-selection process follows the method described in [26]. The concepts were assessed with respect to specified criteria, which were grouped into categories. The scores were given with respect to a baseline [reference] concept, which was selected to be a conventional under-wing mounted podded propulsion system. Criteria within a category were weighted amongst each other. Additional weighting of the categories is done by applying different scenarios. Scenario weightings are derived systematically as well as based on a chosen cost function. For the current application the method was modified to allow for integration of quantitatively derived properties like the *PSC* as a BLI efficiency indicator.

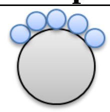
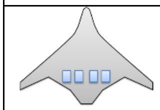
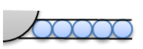
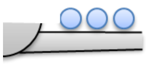
Concept	Description and Abbreviation
	Aft-mounted fans covering the upper part of a cylindrical fuselage (REVOLVE)
	BWB with embedded fans on top of the lifting body trailing edge (BWB)
	Tube and wing configuration with fans integrated within a split-wing (SPLIT)
	Tube and wing concept with fans mounted on the upper wing side (WING)
	Cylindrical fuselage with circum-ferential fan at the aft section (PROPFUS)
	Cross-flow fan embedded into the trailing edge of the wing (CROSS)

Table 1. Distributed propulsion concepts considered in the down-selection process.

The criteria used for assessing the distributed propulsion concepts were grouped into the following categories:

- Power system integration
  - Improve volume restrictions
  - Improve accessibility
  - Reduce thermal management effort
  - Improve transmission system flexibility
- Noise
  - Improve shielding
  - Reduce cabin noise
  - Decrease nozzle velocities
  - Improve frequency spectrum
- Weight
  - Reduce power system weight
  - Reduce transmission system weight
  - Reduce propulsive device weight
  - Reduce integration weight penalties

- Operability (technical)
  - Relax geometric constraints
  - Improve controllability
  - Improve operational robustness
  - Improve robustness against Foreign-Object-Damage
  - Reduce impact of propulsor failure
- Operability (non-technical)
  - Improve passenger attractiveness
  - Improve ramp safety
  - Improve loadability
  - Augment high-lift
  - Improve maintenance
- Efficiency potential
  - Maximize feasible intake area
  - Improve efficiency due to BLI (*PSC*)
  - Reduce integration drag
  - Improve propulsor pressure recovery
  - Reduce propulsor inflow distortion

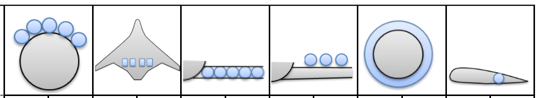
All criteria except the BLI benefit were qualitatively assessed with respect to the baseline configuration using scores out of -3, -1, 0 [parity with baseline], +1, and +3. The BLI benefit potential was estimated using the *PSC* as described in the next section.

2.3 Estimation of the BLI potential

The potential of the selected concepts to achieve an efficiency increase due to BLI was estimated based on Fig. 4 yielding the ideal *PSC*. The ratio of D_{ing}/T was estimated with the following equation

$$\frac{D_{ing}}{T} = \frac{C_{D0,ing}}{C_D} = \frac{C_{D0,ing}}{C_{D0}} \cdot \frac{C_{D0}}{C_D} \tag{4}$$

Minimum and maximum values for the proportion of viscous drag that is ingested by the propulsor are determined based on geometric considerations for each of the concepts depicted in Table 1. The ratio of viscous drag to total drag C_{D0}/C_D was assumed to be 55-65% for all concepts in order to reflect a reasonable aircraft design. The result of this *PSC* estimation together with the derivation of a scoring value used in the down-selection is shown in Fig. 5. The scoring value was derived from the nominal value of *PSC*, which is calculated as mean value of minimum and maximum achievable *PSC*.



	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
$C_{D0,ing}/C_{D0}$	0.12	0.18	0.20	0.30	0.00	0.00	0.08	0.12	0.35	0.55	0.10	0.25
C_{D0}/C_D	0.55	0.65	0.55	0.65	0.55	0.65	0.55	0.65	0.55	0.65	0.55	0.65
D_{ing}/T	0.06	0.12	0.11	0.20	0.00	0.00	0.04	0.08	0.19	0.36	0.06	0.16
PSC	1.86	3.46	3.19	5.66	0.00	0.00	1.28	2.26	5.58	10.37	1.60	4.71
Score	**1**		**2**		**0**		**1**		**3**		**1**	

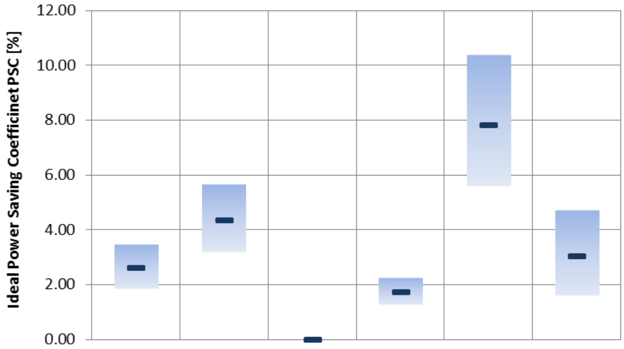


Fig. 5. Estimation of the ideal PSC for the different distributed propulsion concepts.

For the estimation of $C_{D0,ing}/C_{D0}$, the following assumptions were made: The PROPFUS concept was assumed to ingest approximately 80% of the total fuselage viscous drag in the optimum case, whereas, for the REVOLVE concept a maximum of one-third of the fuselage is covered with fans. Further, the maximum values of both concepts reflect an aircraft design with laminar lifting surfaces, which increases the fraction of fuselage viscous drag to total viscous drag up to a value of 70% [27], yielding a maximum ingested drag value of 36% for the PROPFUS concept. For the BWB, the complete center-body upper-side boundary layer is assumed to be ingested, for the CROSS concept the complete lower and upper wing boundary layer was assumed as being ingested in the best case.

2.4 Discussion of Scenario-based Results

Only the scoring result for the efficiency category shall be presented in detail because the concept selection in this work was based on an efficiency scenario due to reasons that will be explained later. The result of the efficiency scoring including the *PSC* outcome given in Fig. 5 is shown in Table 2.

Efficiency Potential	Ref	REVOLVE	BWB	SPLIT	WING	PROPFUS	CROSS	Weight
Maximize feasible intake area	0	3	3	0	0	3	1	0.30
Improve BLI Efficiency (PSC)	0	1	2	0	1	3	1	0.35
Reduce integration drag	0	0	0	-1	-3	1	1	0.10
Improve propulsor pressure recovery	0	-3	-3	0	-1	-1	-1	0.20
Reduce propulsor inflow distortion	0	-3	-3	0	-3	-1	-1	0.05
Score	**0.00**	**0.50**	**0.85**	**-0.10**	**-0.30**	**1.80**	**0.50**	
Normalized Score	**0.50**	**0.58**	**0.64**	**0.48**	**0.45**	**0.80**	**0.58**	

Table 2. Scores of the category "Efficiency".

The first criterion reflects the possibility to shift the optimum value of the propulsor area to higher values by embedding the propulsors within the airframe, thereby reducing the specific thrust and increasing η_P [28]. The BLI efficiency was scored based on the *PSC* analysis discussed before. The possible reduction of integration drag includes nacelle drag as well as interference drag. Propulsor pressure recovery has a major impact on the efficiency of the integrated propulsion system. A degradation of pressure recovery is expected for all integrated propulsion concepts due to necessary ducting and mixing. Also the increased inflow distortion compared to the podded reference case has to be accounted for when assessing a concept.

The scoring and weighting as shown in Table 2 resulted in the PROPFUS being assessed as the most promising concept from an efficiency point of view due to the significant BLI benefit, combined with low losses due to pressure recovery and inflow distortion. The BWB ranked second due to lower *PSC* and higher losses accompanied with BLI. REVOLVE and CROSS concepts are third due to lower *PSC* potential.

The final result of the down-selection using a normalized score and applying different weighting scenarios is given in Fig. 6. The score of the reference case (2 podded wing-mounted engines) is 0.50 for all scenarios and not shown in the figure. The first scenario reflects a cost oriented scenario which aims at assessing the concepts with respect to operating costs. In this scenario the BWB yields the best result, followed by the PROPFUS and the REVOLVE concepts. The remaining scenarios are defined by a systematic variation of the category weights, such that one category is weighted with 0.50 and the remaining weights are equally distributed amongst the other categories. From this analysis it can be deduced that the PROPFUS concept is scoring best from an efficiency perspective. However, the concept is also showing a very high deviation amongst the different scenarios with less good scoring of the operational scenarios (including geometric constraints for tail-strike, high impact of propulsor failure, and Foreign Object Damage due to icing and debris).

Nonetheless, it was decided to further investigate the PROPFUS concept with the intention of quantitatively assessing the possible benefit of BLI at aircraft system level for an aircraft configuration that features the highest

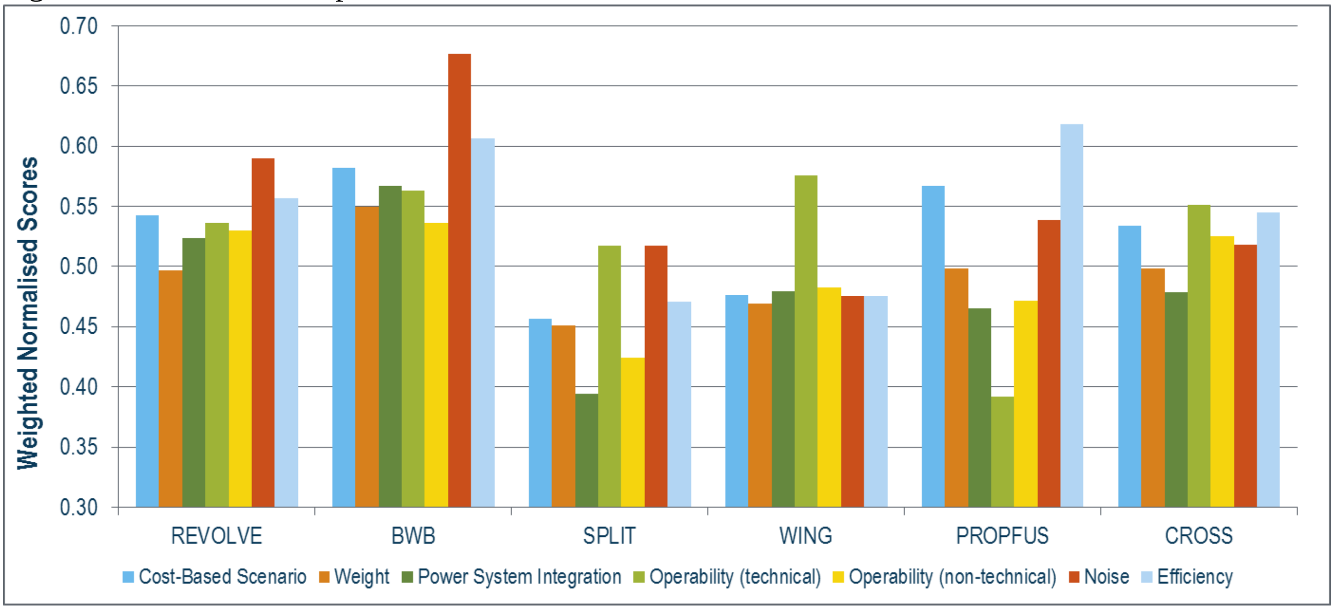


Fig. 6. Results of the down-selection of distributed propulsion concepts. Shown are normalized scores for different scenarios (score of the podded reference concept is 0.50).

potential to realize the BLI benefit. The identified issues with respect to the chosen PROPFUS concept emphasizes the need for delivering amenable engineering solutions during detailed integration and sizing activities (to be conducted at a later stage).

3 Propulsive Fuselage Design Study

The Propulsive Fuselage concept consists of a single-rotating or counter-rotating ducted fan encircling the rear part of a cylindrical fuselage section (cf. Fig. 2). A large share of the fuselage boundary layer flow can be ingested into the propulsor without encountering severe circumferential flow distortion. The share of BLI depends on the position of the propulsor relative to the fuselage length.

The goal of this pre-design study was to set up a multi-disciplinary model allowing for a first estimate of the potential benefit compared to a reference podded configuration. This involved the execution of sensitivity analyses with purpose to quantify the influence of main aircraft and propulsion system design parameters, such as fuselage type (narrow-body, wide-body, short wide-body) and FPR, on the achievable benefit to vehicular efficiency.

3.1 Estimation of Propulsor Efficiency and Power Saving Coefficient

A zero-dimensional performance model of a ducted fan with the ability to predict design and off-design performance was created in order to estimate the propulsive device efficiency η_{Prop}. Propulsive device efficiency is defined as the ratio of usable propulsion power (net thrust times flight speed, $T{\cdot}V_\infty$) to fan shaft power, hence covering propulsive efficiency η_p, fan polytropic efficiency, as well as intake, ducting and nozzle losses. The model is based on basic gas-dynamic relationships and standard compressor theory [29]. The fan model is coupled with a numerically achieved boundary layer representation to estimate the BLI benefit by applying a simple equivalent intake velocity model.

The equivalent mean velocity as well as the equivalent total pressure at the propulsor intake is derived from the local boundary layer properties, which are measured from numerical CFD simulations performed for the clean fuselage [30]. The equivalent value is dependent upon the height of the propulsor intake, *h*, and is calculated as a mass flow averaged mean value.

In Fig. 7 the equivalent velocity is shown for three different investigated fuselage types: typical narrow-body (L = 43.0 m, D = 4.00 m); typical wide-body (L = 56.0 m, D = 5.50 m); and, a short wide-body (L = 43.0 m, D = 5.50 m). In all cases the propulsor intake is located at 75% of the fuselage length, representative of the point at which the constant cross-section due to cabin requirements terminates.

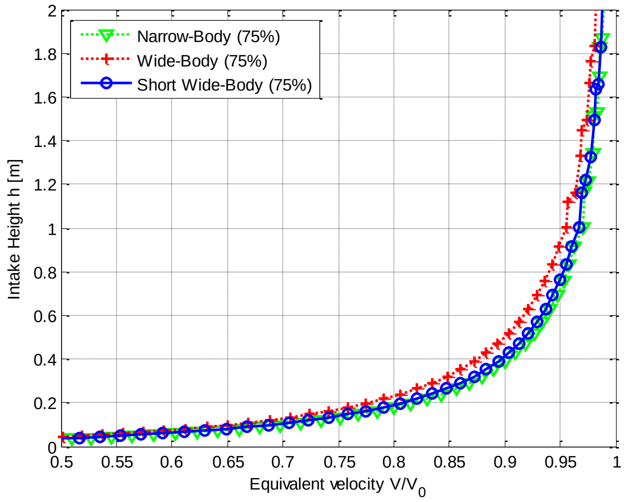


Fig. 7. Equivalent velocity as a function of propulsor intake height for three different fuselage types (numerical CFD results [30]).

3.2 Estimation of Weight and Drag

In Fig. 8, a simplified cross-sectional side view of a possible integrated propulsive fuselage concept is shown. The fan rotor is considered to be a shrouded BLaded rING (BLING), powered by a quasi-linear electric motor arrangement analogous to the design described in Reference [31]. The electromagnetic fields induced by the indicated levitation coils offer a convenient rotor bearing solution since friction losses can be minimized. It should be noted that the feasibility of the rotor BLING as a single piece design requires a more detailed evaluation in terms of manufacturing, maintenance as well as assembly and disassembly procedures.

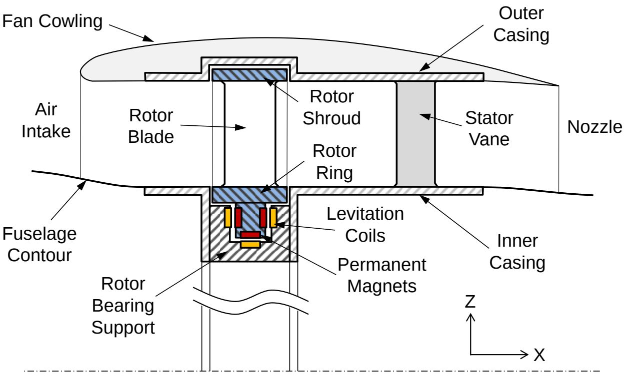


Fig. 8. Principal arrangement of propulsive fuselage concept in cross-sectional side view.

A classical metric for the mechanical sizing of turbo component rotor parts is the so-called An^2 figure-of-merit defined as the local annulus cross-sectional area A multiplied by the rotational rotor speed n squared. The An^2 figure-of-merit, thus, describes the centrifugal stresses in blade roots and inter-linked disks. The intrinsically high hub-to-tip ratio of the propulsive fuselage fan rotor (0.8-0.9) yields greatly reduced An^2 values for typical rotor circumferential velocities, compared to existing conventional fans. Hence, the critical sizing cases for the rotor structure are considered to occur due to the bending and torsional loads induced by the rotor blades in reaction to the driving torque by the electric motor. An accurate prediction of the masses of the PROPFUS propulsion system necessitates in-depth analysis of the relevant load scenarios.

For an initial estimate of the propulsion system component masses, here, a simplistic parametric model based on geometric primitives is used for material volume evaluation. Therefore, rotor blades and stator vanes are approximated through cuboid bodies. The ring and shroud of the fan rotor as well as the fan inner and outer casings as assumed to be bodies of revolution featuring rectangular cross sections. Component masses, subsequently, result from the product of displaced material volume and corresponding density.

For the studies presented in this paper, the PROPFUS fan rotor is assumed to consist of 70% Carbon Fiber Reinforced Polymers (CFRP) and 30% titanium. The stator is constituted of 80% CFRP and 20% titanium, while the casings are considered to be of solely CFRP. For the rotor blades, mean thickness-to-chord ratios of 0.08, and 0.12 for the stator vanes were assumed. Material thicknesses for rotor ring, shroud and fan casings were treated as parametric inputs to the model in order to cover a range of potential loading and associated sizing scenarios.

For the estimation of fan cowling mass, an empirically derived area specific mass coefficient was scaled linearly with cowling external area. The mass of bearing and support was assumed to be covered integrally by the linear electric motor using specific power values given in the literature [32].

Nacelle drag is estimated as the skin friction drag acting on the outer nacelle surface. The covering of the affected fuselage section has not been taken into account as a possible means of drag reduction. This is intended to counteract a potential rise in duct losses within the propulsive device due to the increased internal wetted area per intake mass flow.

3.3 Multidisciplinary Integration and Design Trade-Offs

The previously discussed models for the estimation of propulsive device efficiency, weight, and nacelle drag were integrated into a multi-disciplinary system model to assess the achievable net benefit at aircraft system level. The integration is based on the study of a short-range passenger transport aircraft employing a universally-electric systems architecture, and targeting an entry-into-service of 2035+ [33]. The reference aircraft features a novel, non-planar, continuous, multi-orientated C-Wing lifting surface system with a “short wide-body” fuselage. It is propelled by two podded ducted fans installed at the rear fuselage each with a diameter of 2.70 m, design FPR = 1.30 at top-of-climb (TOC), an inlet pressure recovery (IPR) of 0.997 and a fan design polytropic efficiency of 0.940. In order to meet the Max PAX design range of 900 nm with cruise at M0.75 and 33000 ft the aircraft has a Maximum Take-Off Weight (MTOW) of 109300 kg.

Prior to showing the integrated results, a discussion of the isolated propulsor characteristics is worthwhile. The propulsor device efficiency η_{Prop} as a function of design FPR and IPR is shown in Fig. 9.

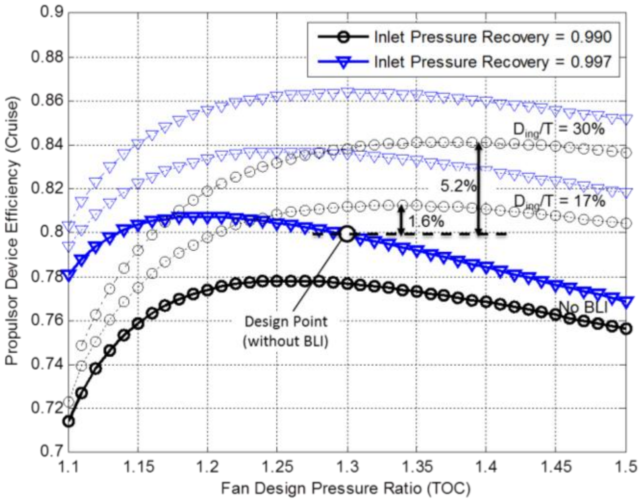


Fig. 9. Propulsor device efficiency vs design FPR for different IPR (no BLI, 17% and 30% ingested drag ratio).

The depicted design point in Fig. 9 shows that the podded fans of the reference aircraft without BLI are designed for a higher FPR than the optimum due to the counteracting influence of propulsor weight and drag at aircraft level. The efficiency for the BLI case is shown for D_{ing}/T ratios of 17% and 30%. For a baseline PROPFUS configuration directly derived from the reference aircraft by replacing the propulsion system (with a relative propulsor position at 75% fuselage length) a D_{ing}/T = 17% was calculated, yielding an increase of 1.6% in η_{Prop}. Here, an IPR = 0.990 was assumed for the BLI case, i.e. three times higher intake pressure loss compared to the podded reference case. The low D_{ing}/T for this aircraft is due to a high wing loading (leading to a high induced drag ratio) and a low fuselage viscous drag fraction due to the complex wing system with high sweep angle featuring no laminar flow. However, for an aircraft design with laminar wing technology and lower wing loading, an ingested drag ratio of 30% could be achieved (based on [27]), increasing the possible η_{Prop} benefit to 5.2%. The corresponding *PSC* values of the results achieved with the presented method are plotted in Fig. 4 for comparison with existing methods (using a constant FPR of 1.35). It can be seen that the results agree with literature with a gradually widening extent of under-prediction for higher D_{ing}/T.

Referring again to Fig. 9, it should also be noted that the optimum FPR for the BLI case shifts to higher values and exhibits a lower slope towards higher FPR. This results from the beneficial reduction of propulsor inlet velocity if the propulsor height is reduced, and hence, the boundary layer constitutes a larger fraction of the inflow (cf. Fig. 7). In addition, the expected larger inlet pressure losses for BLI shift the optimum to higher FPR.

The net benefit at aircraft system level is predicted using a linearized equation for the design range R derived from the reference aircraft at constant MTOW, viz.

$$R = R_0 + \frac{\partial R}{\partial m_{Prop}} \Delta m_{Prop} + \frac{\partial R}{\partial \eta_{Prop}} \Delta \eta_{Prop} + \frac{\partial R}{\partial (C_D S)_{Nac}} \Delta (C_D S)_{Nac} \tag{5}$$

where R_0 is the reference aircraft range, m_{Prop} is the propulsor device mass, "Nac" denotes nacelle, and S is the reference wing area. If this is normalized by the total mission energy demand E, which is derived accordingly, a figure-of-merit referred to as the energy specific air range R/E can be estimated. The possible relative increase of R/E is shown in Fig. 10.

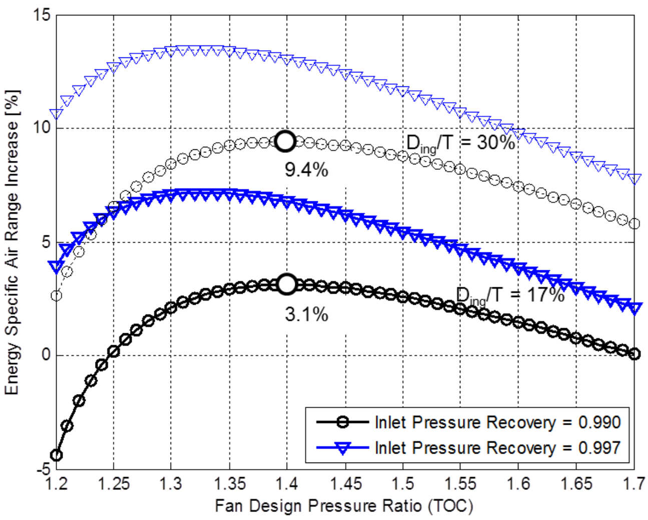


Fig. 10. Energy specific air range increase as a function of design FPR and IPR.

It can be seen that the derived optimum FPR values at aircraft level are considerably higher than for the non-BLI case. With D_{ing}/T = 17% a FPR of 1.4 yields the most efficient design with a 3.1% benefit over the reference [non-BLI] configuration. Assuming D_{ing}/T = 30%, an improvement over the baseline of up to 9.4% was predicted. Here, nominal values for the weight estimation model were assumed.

The calculated relative increase in range compared to the reference aircraft is shown in Fig. 11. In order to maximize range, the analysis indicates higher FPRs in the range of 1.45-1.50 are necessary. This is due to the direct impact of weight on the available battery mass for the specified condition of constant MTOW. Aircraft range can be increased by 2.9% assuming a D_{ing}/T of 17%. If design modifications can be implemented for an optimized aircraft design with D_{ing}/T = 30% a possible relative range increase of up to 10.6% is predicted.

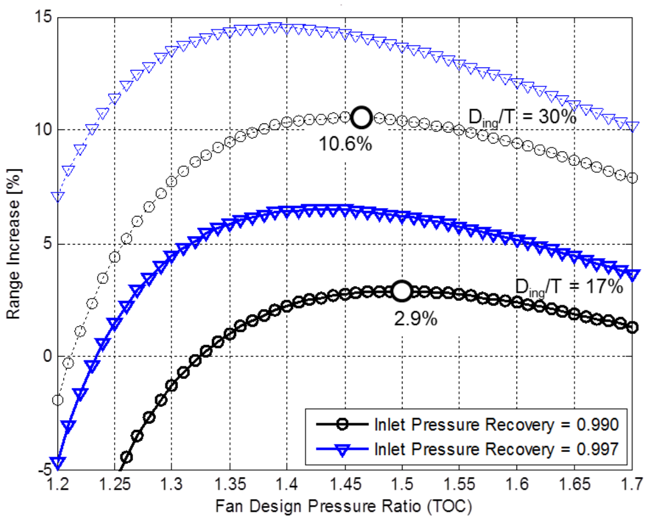


Fig. 11. Range increase as a function of design FPR and IPR.

4 Summary and Outlook

The purpose of this technical paper was to investigate the merits of distributed propulsion for future aircraft concepts. Initially, from a pool of five different integration approaches, whether involving single or multiple rotating fans, a relatively comprehensive qualitative evaluation was performed in order to down-select the best candidate. Categories included power system integration, operational aspects, weight, noise and efficiency. The greatest weighting in the selection procedure was assigned to a quantitatively analyzed category that addressed greatest potential to realize the benefits of boundary layer ingestion (BLI). The exercise showed that although the so-called “Propulsive Fuselage” did exhibit shortcomings regarding a number of operational attributes, the significant potential for efficiency gains compared to the other candidates was the deciding factor in its choice. Utilizing a set of high-end, low-fidelity and interlaced fidelity numerical tools a series of engineering trade-studies took place in order to identify an upper limit of vehicle efficiency and range improvement compared to an advanced reference passenger transport aircraft not employing BLI. One major finding of this study was that BLI is able to increase aircraft efficiency not just simply by increasing the propulsive efficiency of the fans, but also by shifting the optimum fan pressure ratio to higher values, hence allowing for a smaller propulsor size, and thus, lower weight and drag of the propulsion system. Results showed that integration emphasizing a BLI-focused approach could yield as much as 10.6% improvement in range. Less emphasis on a BLI-centric design philosophy produced a range improvement of 2.9%. Looking ahead, based upon the pre-design work discussed above, next steps will involve design and integration at a more detailed level. The implementation of an advanced toolset will be done in order to capture functional sensitivities between primary design variables associated with closely coupled systems found in the Propulsive Fuselage.

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