

Aerodynamic Design Space Exploration of a Fuselage Boundary Layer Ingesting Aircraft

van Sluis, M.; della Corte, B.; Gangoli Rao, A.

DOI

[10.2514/6.2023-4069](https://doi.org/10.2514/6.2023-4069)

Publication date

2023

Document Version

Final published version

Published in

AIAA AVIATION 2023 Forum

Citation (APA)

van Sluis, M., della Corte, B., & Gangoli Rao, A. (2023). Aerodynamic Design Space Exploration of a Fuselage Boundary Layer Ingesting Aircraft. In *AIAA AVIATION 2023 Forum Article AIAA 2023-4069* (AIAA Aviation and Aeronautics Forum and Exposition, AIAA AVIATION Forum 2023). American Institute of Aeronautics and Astronautics Inc. (AIAA). <https://doi.org/10.2514/6.2023-4069>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Aerodynamic Design Space Exploration of a Fuselage Boundary Layer Ingesting Aircraft

M. van Sluis^{*}, B. DellaCorte[†] and A. Gangoli Rao[‡]

Fuselage Boundary-Layer Ingestion (BLI) is a promising example of synergistic design and propulsion-airframe integration to reduce fuel burn. For a BLI configuration, the aerodynamic performance of the aircraft is a result of the complex aerodynamic interaction between the fuselage airframe and the BLI propulsor. This paper presents a design method for the aft fuselage including the propulsor shrouding to minimize the required shaft power of an aft-mounted propulsor in the conceptual design phase. First, a global aerodynamic design space exploration is carried out using Computational Fluid Dynamics (CFD) to identify the key design parameters and their influence to the aerodynamic performance of the propulsive fuselage. An optimization study is subsequently carried out to improve the aerodynamic performance of a baseline design. The optimization was performed for a turbo-electric BLI configuration and within representative design constraints. The optimization achieved a decrease of approximately 10% of the isentropic shaft power required for the aft-mounted propulsor for a constant net force acting on the propulsive fuselage. The presented methodology and the resulting design practices can be effectively applied to other advanced aircraft configurations.

I. Introduction

To make future civil aviation sustainable, ambitious goals regarding emissions and noise have been set by the Advisory Council for Aeronautics Research in Europe (ACARE), described in the FlightPath 2050 [1]. These goals, as part of the Strategic Research and Innovation Agenda (SRIA) [2], aim at a reduction of 60% CO₂ emission per passenger kilometre by 2035 relative to the year 2000. Evolution of current aircraft technology will fall short of these ambitions. A step-change in aircraft technology and design is required in order to meet the goals. Many different novel technologies are being investigated, such as full laminar flow wings [3] and hybrid electric propulsion [4]. However, in order to meet the emission targets for aviation, a multitude of novel technologies will have to be integrated in a synergistic manner, as no single technology in existence today appears to be able to fulfil the requirements alone. Boundary Layer Ingestion (BLI) is one such technology to reduce aircraft fuel burn by exploiting synergistic airframe-propulsion integration. In a BLI configuration, the propulsor is tightly integrated onto the airframe and operates on the boundary-layer flow. As a

^{*}Researcher, Flight Performance and Propulsion, Delft University of Technology, M.vansluis@tudelft.nl

[†]PhD candidate, Flight Performance and Propulsion, Delft University of Technology, B.DellaCorte@tudelft.nl

[‡]Associate professor, Flight Performance and Propulsion, A.GangoliRao@tudelft.nl

29 consequence, the BLI propulsor re-cuperates the momentum and energy deficit in the boundary layer, thereby reducing
30 the viscous dissipation in the wake [5] [6]. A conceptual-level study has shown that ingestion of the full fuselage boundary
31 layer by a single circumferential propulsor yields the largest potential aerodynamic saving [7]. In particular, it was found
32 that such a configuration, named the Propulsive Fuselage Concept (PFC), using a gas-turbine driven BLI propulsor,
33 could achieve a net fuel burn reduction of approximately 10% compared to a conventional baseline configuration [8]. A
34 similar order of magnitude fuel burn reduction was found by more recent NASA studies on the turbo-electric NASA
35 STARC-ABL aircraft [9] [10]. In order to improve the aerodynamic benefit of the fuselage annular (or Type II) boundary
36 layer ingestion, aerodynamic shape optimization of both the fuselage and its corresponding nacelle and boat tail is
37 required. Differently from a conventional aircraft design, the objective function for the optimization process of a tightly
38 coupled BLI system does not necessarily have to be drag minimization. The tight coupling of the propulsor and the
39 airframe requires a novel design approach where the combined performance of the system should be considered as a whole.

40
41 Recent studies attempt to optimize the fuselage and aft nacelle geometry to improve the different aspects of the aircraft
42 performance. For example, the fuselage-fan inlet distortions, induced by the wings and fuselage upsweep in the
43 STARC-ABL concept, were minimized through CFD-based shape optimization of the shroud and hub contours [11]. The
44 adjoint-based shape optimization yielded to noticeable lower distortion levels while the drag increase was constrained
45 to a single drag count. However, the improvements in the distortion levels were accompanied by modest increases in
46 the required power of the propulsor to match the thrust requirement. In a similar computational approach [10], it was
47 attempted to improve the aerodynamic propulsive efficiency by altering the shaping of the nacelle and aft fuselage contour.
48 Free-Form Deformation (FFD) was applied to the entire aft fuselage section, while a turbofan model was implemented to
49 emulate the BLI fan. The main finding of the work [10] is that, depending on the transmission efficiency of the electrical
50 power system, the propulsor size is altered to maximize the Power Saving Coefficient (PSC). Although the propulsor size
51 was clearly the dominant factor, the contour shaping of the fuselage and nacelle were also altered during the optimization
52 to improve the inflow to the propulsor. However, the paper is focussed on the PSC of the final optimized configuration
53 and does not distinguish between the various contributions of the design parameters. Although adjoint aerodynamic
54 shape optimization has shown to improve the performance of BLI aircraft designs [12], it does not give a comprehensive
55 insight into the various interactions of the individual components. In order to streamline the conceptual design phase
56 of a BLI configuration, it would be very useful to have a qualitative and quantitative understanding of the design
57 parameters. In a different study [13], the aft geometry on the STARC-ABL concept was optimized using OpenVSP
58 [14]. Rather than using mathematical control points to describe the geometry, design criteria such as ellipse radius and
59 tangent angles were prescribed. The geometry was optimized for various levels of FPR and net force coefficient, thereby
60 minimizing the shaft power. Although the work [13] discusses the performance of the optimized designs in detail, little
61 insight is provided regarding which geometric parameters have a higher influence the aerodynamic performance of a

62 fuselage BLI configuration. In another work [15], the duct and shrouding of a regional electric aircraft is optimized,
 63 using a parametrized representation of the nacelle and duct shaping. The optimization is performed for three different
 64 objective functions, namely maximum thrust, lowest flow mechanical power and maximum propulsive efficiency. Each
 65 objective yields a noticeably different geometry. However, only two parameters describing the inlet lip of the duct
 66 are included in the actual analysis, limiting the explored design space. As the paper focusses on multidisciplinary de-
 67 sign of the particular aircraft, the specific knowledge gained in terms of aft-body shaping for a BLI configuration is limited.

68
 69 In this paper, a systematic approach for the aerodynamic design space exploration and optimization of a (axisymmetric)
 70 bare PFC configuration (i.e.fuselage including BLI propulsive device) is described. The aerodynamic analysis was based
 71 on RANS CFD simulations and a body-force model for the fuselage propulsor. A comprehensive set of geometrical and
 72 operational parameters were considered to accurately and flexibly describe the PFC geometry and flow conditions. A
 73 sub-set of the most influencing parameters was obtained through a Design Space Exploration (DSE), after which a global
 74 optimization was performed to minimize the fuselage-fan isentropic power. The goal of the paper is to demonstrate
 75 which are the important sensible parameters driving the propulsive fuselage design in the conceptual design phase of the
 76 PFC. The methodology described in the present work has been used for aircraft level optimality studies, as described in
 77 [37].

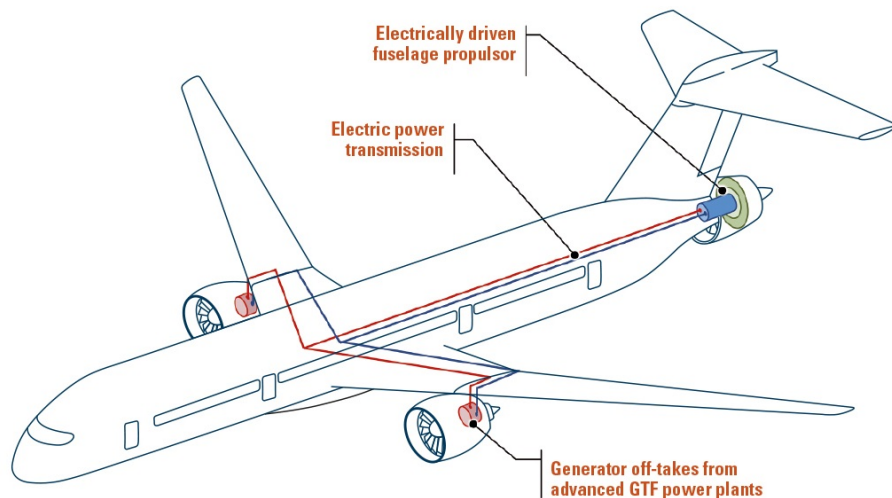


Fig. 1 Overview of aircraft layout and turbo-electric drivetrain (image: Bauhaus Luftfahrt)

78 A. Background

79 The aerodynamic design space exploration in this work is conducted for the PFC within the CENTRELINE project
 80 [16][17]. The design is focussed on an Airbus A330-300 class aircraft with an entry to service in 2035. The aircraft is
 81 being designed to carry 340 passengers over a range of 6500 nm. A turbo-electric drive-train is utilized, with power

82 off-take from the under-the-wing Geared Turbo-Fan (GTF) engines to supply an electric motor driving the BLI fan in
 83 the rear of the aircraft. The electric motor is rated for 8 MW design power and 95% efficiency. The FF is aimed to be
 84 able to provide 6% thrust at top-of-climb [18]. The main level requirements are listed in Table 1. A schematic of the
 85 concept is shown in Figure 1.

Table 1 Overview of CENTRELINE top-level requirements [18]

Parameter	Requirement
Range	6500 nmi
Passengers	340
Design cruise Mach	0.82
Cruise altitude	FL350
Maximum cruise altitude	FL410
Approach speed	140KCAS

86 II. Methodology

87 In order to conduct a thorough aerodynamics design space exploration, the design space needs to be well defined. The
 88 definition of the aerodynamic design space is important to ensure that no parts of the design space are excluded from the
 89 exploration. In general, one could divide the aerodynamic design space into two categories, as depicted in Figure 2,
 90 namely *operational* and *geometric* design parameters. The geometric parameters of the PFC can be divided into aircraft
 91 level and component level parameters. In case of the PFC, the Fuselage Slenderness Ratio (FSR) and the duct height of
 92 the Fuselage Fan (FF) are examples of aircraft level parameters. These parameters directly define the overall geometric
 93 shape of the aircraft. The same hold true for the operational parameters, which can be either dictated by the mission
 94 design or the system performance.

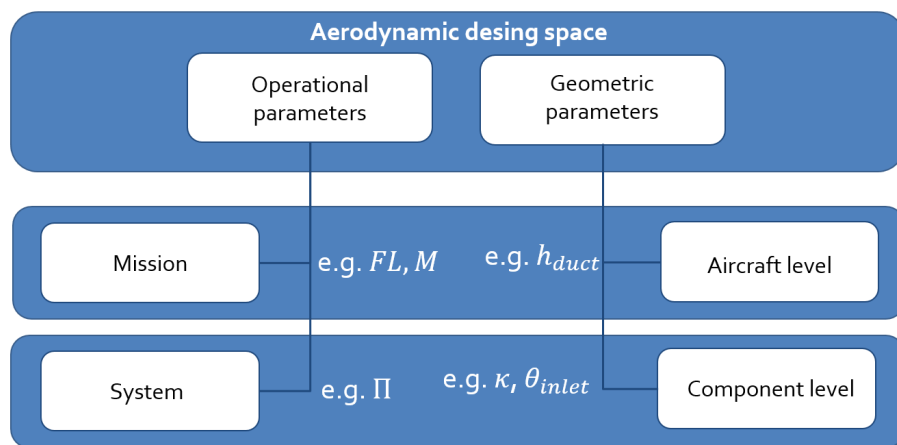


Fig. 2 Classification of the aerodynamic design space parameters

95 A MATLAB®-based framework has been set-up to analyse a very large number of PFC geometries. An overview of

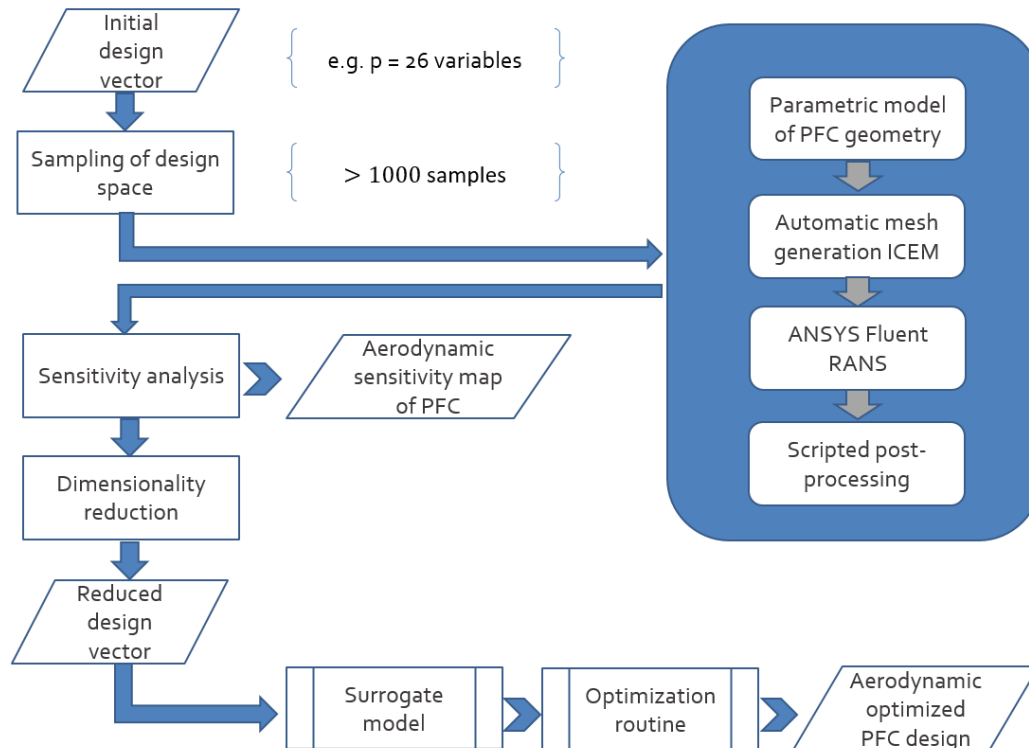


Fig. 3 Flow diagram of the aerodynamic design space exploration procedure

106 the workflow is presented in Figure 3. The principal step is to generate a parametric model of the PFC. The main
 107 requirements is that the model should be flexible enough to allow for a wide variety of fuselage and nacelle shapes, in
 108 order to have minimum restrictions of the design space. Next, the design space is surveyed using statistical methods
 109 for quasi-random sampling. Each sample reflects a unique geometry and operating condition. The sample space is
 110 consecutively fed into the main computational framework, where the design vector is translated into a geometry and a
 mesh. A mesh quality above a specified threshold was ensured to provide consistent and accurate results. Subsequently
 the Reynolds Averaged Navier-Stokes (RANS) analysis was carried out using ANSYS® Fluent 18.2 and the subsequent
 results were post-processed by a scripted routine. Based on the solution data of evaluated samples, a sensitivity study is
 carried out to identify the driving parameters. Using the knowledge from the sensitivity analysis, a surrogate model of
 the aerodynamic response can be constructed and be used in an optimization routine.

106 A. Parametrization of the Propulsive Fuselage Concept

107 In order to describe the bare PFC geometry by a limited set of design parameters, a parametric model of the ge-
 108 ometry has been developed. The parametrization of the geometry needs to be as flexible as possible, to be able to
 109 generate a wide variety of geometries. At the same time, it should be ensured that the geometries created by the
 110 parametric model are feasible and do not violate the basic constraints set beforehand. In order to combine these two op-

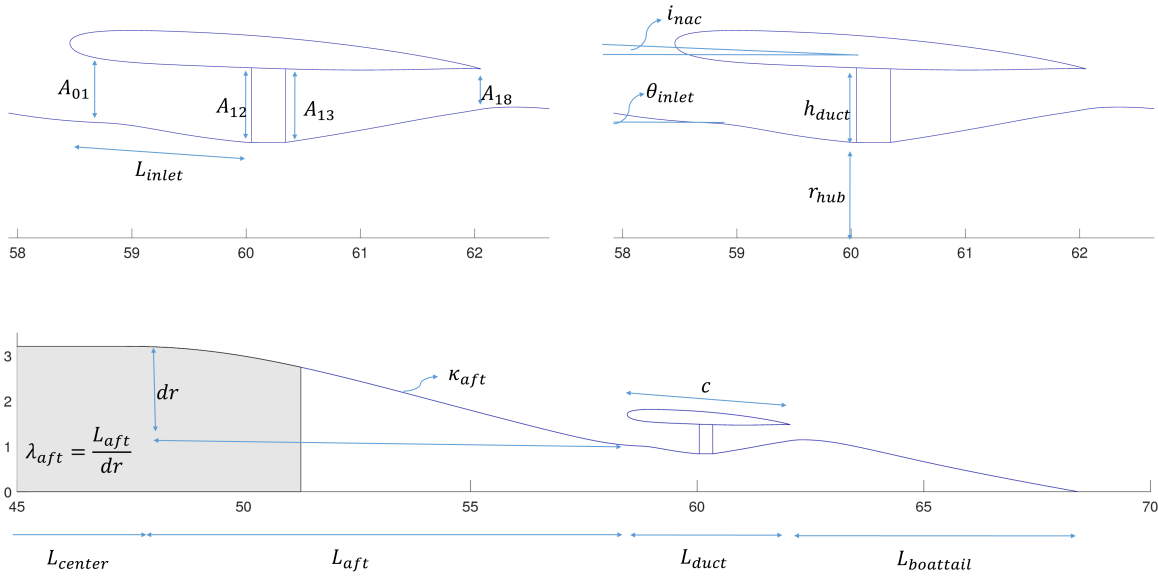


Fig. 4 Drawing with main length parameters of an example PFC fuselage geometry as described by the parametric model. Note that the cabin area is indicated by the highlighted area.

111 posing requirements, a parametric model has been developed that incorporates both flexibility and basic engineering rules.

112

113 Since the aft-fuselage is the main area of interest of the PFC, the parametric model is focussed on the aft section
 114 of the fuselage. Therefore it does not include the wings, empennage or main under-wing podded engines. A con-
 115 ventional fore-body shape is adopted from the Engineering Sciences Data Unit (ESDU) (fore-body 9 [19]). The
 116 slenderness of the nose section is kept constant, to ensure shape similarity with varying fuselage diameter. A second
 117 requirement for the PFC fuselage is that the effective floor area is kept constant, in order to compare the performance
 118 of the PFC to the R2035 reference aircraft [20]. Since a study into the cabin topology is beyond the scope of the
 119 current work, a minimal fuselage diameter was set to bound the useable floor area. For sizing of the main fuselage
 120 dimensions, the fuselage diameter is given as primary input, together with the slenderness ratio of the aft fuselage
 121 section up to highlight of the duct. An iteration loop is used to find the corresponding length of the fuselage centre
 122 section. Since the relative axial position of the FF is an important design parameter and the lengths of the upstream
 123 section are already determined, the length of the boat tail is derived from the total fuselage length. The position of the
 124 FF is used as the reference location for the aft geometry. An overview of the main fuselage dimensions is shown in Figure 4.

125

126 The curves of the fuselage geometry are constructed using Non-Uniform Rational B-Splines (NURBS) [21]. Widely
 127 used in CAD modelling, NURBS enable to make localized changes to the geometry without affecting the overall
 128 shape of the curve. This in an important property as it allows to study individual changes to geometry rather than

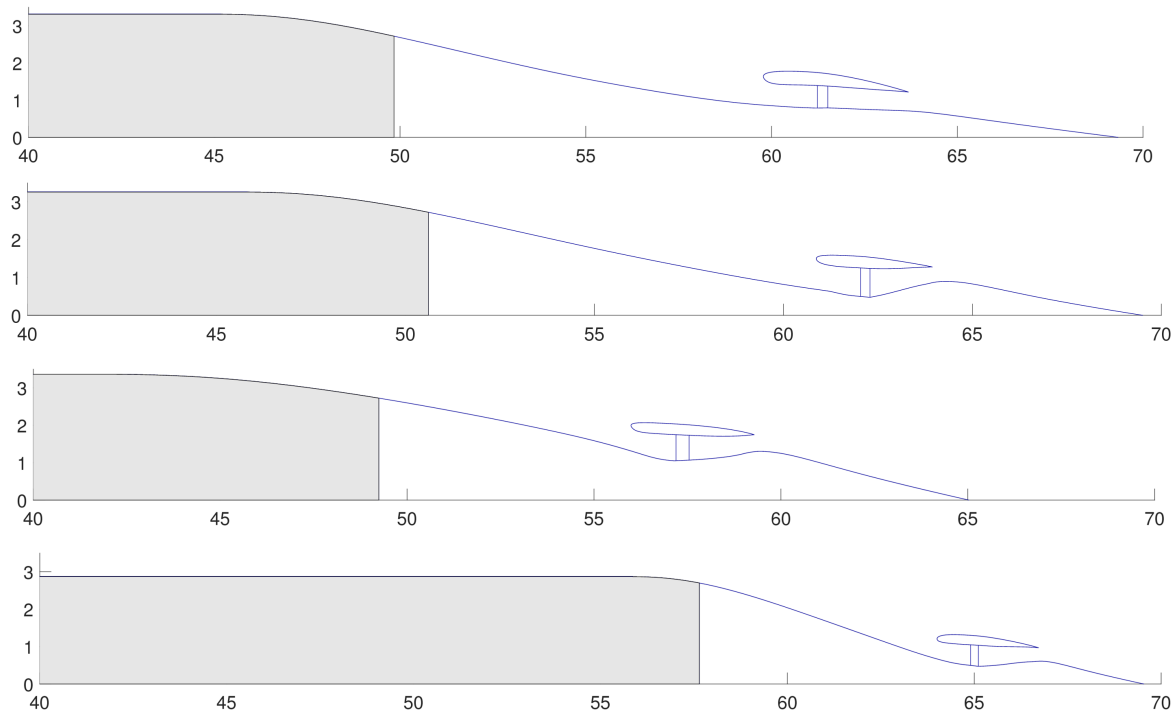


Fig. 5 Examples of aft-fuselage geometries initiated by the parametric mode using random design parameter samples. Dimensions are given in meters.

129 combined effects. First order continuity is enforced between the NURBS segments, to ensure a curvature continuity.
 130 Since the aim of the work is to gain an understanding of the aerodynamic behaviour of the design, the control
 131 points of the NURBS are either related to a design parameter or embedded engineering rules. As such, there are
 132 no 'free floating' control points in the design vector. The nacelle geometry was treated in a similar manner, albeit
 133 not with NURBS. Instead, it was chosen to use a third order Bezier-Parsec approach [22], which was developed
 134 to describe airfoils using design parameters only. In total, 12 design variables are used to describe the airfoil
 135 geometry. The flow channel to the fuselage fan is dictated by the nacelle, whose chord length is a function of the
 136 diameter of the FF. The positioning of the nacelle is performed with the FF location as a reference. The length
 137 of the inlet and the incidence angle of the nacelle are both determined with respect to the FF. To promote a feasi-
 138 ble duct geometry, the cross-section area of the throat and the duct exit are prescribed as a function of the FF inlet face area.

139

140 The flexibility of the parametric model is shown in Figure 5, where a few examples of generated PFC designs are
 141 shown for a set of (bounded) random design parameters. As can be observed, the model is able to produce substantially
 142 different PFC designs. In order to ensure that the resulting designs from a random combination of the in total 26
 143 design variables are feasible designs, the bounds were chosen carefully. For example, the bounds for the nacelle are
 144 set such that the 3rd order Bezier-Parsec (BP3333)[22] parametrization always yields a feasible airfoil representation.

Table 2 Overview of the design parameters and their respective bounds

Parameter	x_{min}	x_{max}	unit	Parameter	x_{min}	x_{max}	unit
D_{fus}	5.50	6.90	m	y_c/c	-0.02	0.05	-
κ_{aft}	0.40	1.50	-	κ_c	-1.00	-0.10	-
λ_{aft}	3.5	8.00	-	x_t/c	0.25	0.40	-
x_{FF}	0.84	0.905	-	κ_t	-0.08	-0.01	-
l_{inlet}/c	0.25	0.50	-	δ_{TE}	8.0	12.0	deg
h_{duct}	0.30	1.00	m	β_{TE}	5.0	12.0	deg
r_{hub}/r_{tip}	0.369	0.625	-	i_{nac}	0.0	8.0	deg
θ_{inlet}	0.0	20.0	deg	A_1/A_{12}	0.90	1.05	-
c/D_{FF}	0.80	1.40	-	A_{13}/A_{12}	0.95	1.00	-
$(t/c)_{max}$	0.08	0.11	-	A_{18}/A_{12}	0.60	0.70	-
ϱ_{LE}	-0.50	-0.10	-	Π	1.20	1.50	-
γ_{LE}	10	30	deg	FL	310	390	100ft
x_c/c	0.30	0.50	-	M	0.75	0.85	-

145 Furthermore, it is made sure that no excessive long or short aft-fuselage section are created. Nevertheless, for some
146 specific combinations of parameters a non-feasible geometric design can still occur. These geometries are filtered out by
147 a set of engineering constraints, such as bounds on boat-tail cone angles, and are not included in the analysis.

148 B. Sampling of aerodynamic design space

149 In order to cover as much of the design space as possible, a suitable sampling strategy should be adopted. Ideally,
150 one would use permutations of all possible combinations of design parameters to ensure complete sampling of the
151 design space. However, such an approach is only feasible when the number of design variables is very small or the
152 computational cost of analysis is low. For the current application, a quasi-random sampling approach is better suited.
153 Many different algorithms and methods are in existence [23], such as the Latin Hypercube Sampling (LHS) method. A
154 multitude of different LHS derived methods exist today, each method trying to increase the space-filling capability of
155 the sampling and reducing the correlation between individual samples. For the current work, a novel method combining
156 both Latin Hypercube design and stratification [24] is selected. The partial stratification of the variables allows one to
157 group design variables which are expected to have a strong correlation. For example, it is expected that the FPR and
158 duct height h_{duct} will have a strong coupling on the required shaft power by the FF. Grouping the parameters together
159 will ensure the optimal spacing of the samples in the design space with respect to each other. In case the anticipated
160 interaction is not present, the quality of the sampling would not be penalized. A three-fold stratification plan was used,
161 meaning that groups of three design parameters were made for stratification, prior to the hypercube sampling. In total
162 9261 samples were generated and used as input for the analysis framework.

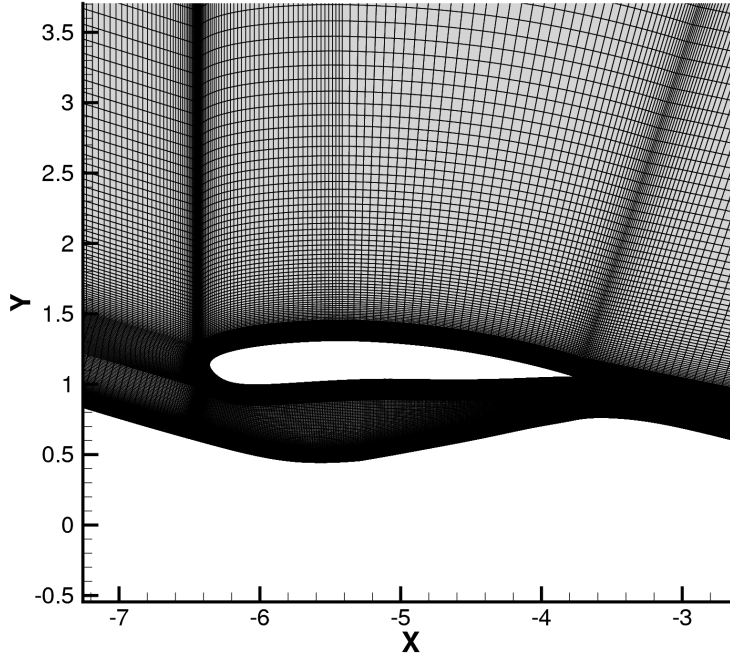


Fig. 6 Example of a mesh, generated by the framework, for an arbitrary sample PFC geometry. Coordinates are in meters and measured from the trailing edge

C. Grid generation

To prepare the generated bare PFC geometries for analysis, a Matlab® routine has been developed that generates the topology of the mesh and writes the required input files for Ansys®ICEM. The latter program is used for the computation of the actual mesh. For the core of the Matlab tool to prepare the geometry, modified open-source Matlab® routines [25] have been used. A structured C-grid is created for the main domain and two embedded O-grids wrap the fuselage body and the FF nacelle. Since the turbulence will be resolved up to the wall, the mesh complies with the $Y^+ \leq 1$ requirement. The latter is crucial to capture the development of the boundary layer in the best possible way using RANS models. In total, a typical 2D axis-symmetric mesh contains about 360,000 to 400,000 cells. For every generated mesh, the mesh quality statistics were analysed automatically by ANSYS® ICEM to assess the mesh quality. The quality criterion used in ICEM is a weighted combination of cell warpage, orthogonal quality and the determinant. The statistical mesh properties are shown in Table 3. As can be observed, the average of the minimum and mean quality index of the mesh are high. However, the standard deviation of the average minimum quality index is relatively high as well, indicating a wider variation in cell quality. Due to an imperfect conversion in the interface between Matlab® and ICEM, the total success rate of the mesh routine was approximately 51%

III. Setup of CFD simulation

The computational analysis of the flow field using RANS was carried out using the commercial software ANSYS® Fluent (version 18.2). The pressure-coupled, axis-symmetric solver was used. The fluid was modelled as an ideal

Table 3 Statistics of mesh quality criterion by ICEM for meshes of converged simulations (N = 3560). The quality index for hexa elements is a weighted diagnostic between the determinant, orthogonal quality and cell warpage.

Quality Index	\bar{x}	σ
Minimum quality	0.8915	0.1486
Average quality	0.9883	0.0146

180 compressible gas, with the fluid viscosity being modelled by the three-coefficient method of Sutherland [26]. Since
 181 the flow is assumed compressible, the energy equation is enabled. Turbulence is modelled by the $k - \omega$ Shear Stress
 182 Transport (SST) developed by Menter [27]. Compressibility corrections and Kato-Lauder production limiter were
 183 enabled. Spatial discretization of the turbulence transport equation was done through a second-order accurate scheme
 184 (QUICK) [28]. The discretization of the momentum and energy equation are in turn taken care of by a third-order
 185 MUSCL [29] scheme.

186 A. Fan modelling

187 An important aspect for the analysis of the PFC is the modelling of the fuselage fan in CFD. A through-flow nacelle
 188 approach (i.e.no inflow or outflow domain boundaries) was used to preserve the boundary layer over the fan stage.
 189 In order to accomplish this, a simple body-force was developed and implemented using a User-defined Function
 190 (UDF). In the mesh, a separate fluid domain is defined which represent the box volume around the fan. The UDF
 191 adds an axial momentum density S_m (N/m^3) source term to all cells within the domain containing the fan. Note that
 192 momentum is only added in axial direction, assuming zero swirl or radial changes in momentum. This is acceptable
 193 as the stator vanes behind a fan should recover most of the swirl [30]. Shown in Figure 7 is the change in total
 194 momentum mass-averaged over the duct area. The volume of the FF is hi-lighted in grey. As can be seen, the
 195 axial velocity is decreased over the fan, whereas the static pressure is increased. Since the fluid is assumed to be
 196 compressible, additional source terms for the energy equation S_e are added. The energy is computed as the local
 197 work done by the external force of the momentum density source. As such, the total enthalpy of the fluid is increased
 198 as shown in Figure 8. Since the fan total pressure ratio is the main design parameter for the FF, the momentum
 199 source term is adjusted iteratively by the UDF until the mass-averaged FPR is equal to the specified target fan pressure ratio.

200

201 B. Drag-thrust bookkeeping

202 As a results of the high level of integration of the aft-mounted BLI propulsor, the conventional thrust-drag bookkeeping
 203 schemes are not suitable as the distinction between the propulsor and the airframe is ambiguous. However, a distinction
 204 between thrust and drag is desired from an aircraft conceptual design point-of-view. The simple fan model, as described

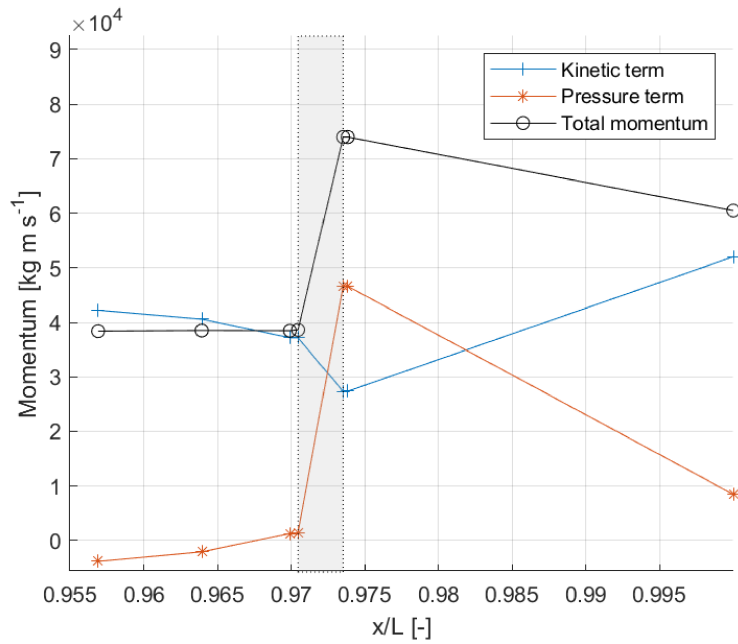


Fig. 7 Example of mass-averaged total momentum across the duct using the body force model.

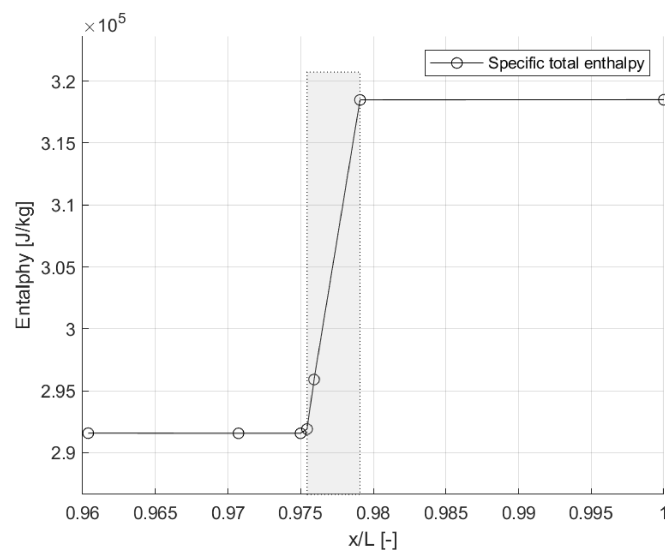


Fig. 8 Example of mass-averaged specific total enthalpy across the duct using the body force model.

205 in III.A, allows for a clear definition of the propulsive force by the actuator volume and drag. Integration of the
 206 momentum density source term (N/m^3) over the volume defining the FF directly yields the propulsive force. Note that
 207 the propulsive force by the actuator volume is (by definition) not identical to the FF thrust [31]. The drag is obtained by
 208 integration of the viscous and pressure normal forces over all the solid surfaces. As such, the force balance of the bare
 209 PFC can be reduced to:

$$F_{\text{NPF,bare}} = F_{\text{T,FF}} - D_{\text{bare}} = \iiint_V S_a dV - \iint_S \tau dS - \iint_S p \cdot \hat{n} dS \quad (1)$$

210 All quantities in the above equation are available in the numerical results. Similarly, the energy provided by the FF to
 211 the flow can be computed as:

$$P_{\text{shaft, id}} = \iiint_V S_e dV \quad (2)$$

212 Note that the integrated energy source terms yields the required power by the FF without including any losses. The
 213 efficiency of the fan is explicitly not included to reduce complexity and avoid additional assumptions. As such, $P_{\text{shaft,id}}$
 214 represents the minimum required power. Since NPF and ideal shaft power are dimensional quantities, a non-dimensional
 215 term called the BLI efficiency factor has been defined:

$$f_{\eta,\text{PFC,bare}} = \frac{F_{\text{NPF, bare}} \cdot V_{\infty}}{P_{\text{shaft,id}}} \quad (3)$$

216 The above equation expresses the ratio between the rate of work done by the NPF acting on the bare PFC and the ideal
 217 shaft power. Although the relation is very straightforward, it allows to directly asses the performance different PFC
 218 design. Since the relation is easy to evaluate and is sensitive to even small design changes, it is well suited to be used in
 219 the design space exploration.

220 IV. Results

221 With the computational framework in place, the aerodynamic design space exploration was carried out. The analysis
 222 has two objectives: first it is attempted to obtain insight in the sensitivity of the various design parameters on the
 223 aerodynamic performance of the PFC. The second objective is to use the knowledge gained from the design space
 224 exploration to optimize the axisymmetric bare PFC design.

225 A. Sensitivity analysis

226 The main aim of the aerodynamic design space exploration is to gain an understanding of how each of the design
 227 parameters is influencing the aerodynamic performance of the PFC. Ideally, one would look at both the influence of the

228 isolated design parameters as well as their combined effect on the aerodynamic performance. Statistical methods, such
229 as Principal Component Analysis (PCA) [32], can be used to determine the driving parameters in large design problems
230 with computational expensive analysis [33]. Such a statistical insight into the design parameter dependency is desired.
231 However, no convergence of the PCA result was obtained for the current dataset, as there remained a dependency on the
232 number of included results. The sensitivity of the various design parameters is found to be different in orders of magnitude.
233 It is believed that this, together with the interdependency of the parameters, caused too much scattering of the gradient data.

234
235 Nonetheless, to still be able to understand the main sensitivities of the aerodynamic design for the PFC, a one-dimensional
236 sensitivity study has been carried out. An initial design, representing the mean of the design vector, has been selected
237 as a baseline. Each design parameter was changed, one by one, within their respective limits. Results for the most
238 dominant design parameters with respect to $f_{\eta, \text{PFC, bare}}$ of the baseline design are shown in Figure 9. The data points are
239 fitted with a second order polynomial function. As can be observed, the FPR together with the height of the FF duct
240 appear to be the dominant design parameters for the aerodynamic performance of the PFC. This is to be expected, as
241 together these parameters dictate the required idealized power by the FF. Despite this, a few interesting observations
242 can still be made. First, it can be seen that for the baseline design, increasing the FPR is beneficial but the benefit is
243 diminishing towards the upper bounds of the FPR. On the other hand, the performance of the bare PFC is reducing
244 rapidly when the FPR is lowered. It should be noted that the geometry is not adapted with any change in design FPR.
245 Therefore, the area ratio of the duct inlet and exit are not adjusted to minimize spillage drag and facilitate optimal
246 mass-flow. Nevertheless, it does show that the drag penalty due to addition of the FF nacelle can be offset most by
247 increasing the propulsive force of the FF as much as possible. A similar observation can be made for the duct height. For
248 higher duct heights, the additional momentum deficit that is ingested by the fan is diminishing. Furthermore, the nacelle
249 is no longer embedded in the lower total pressure region of the boundary layer, thereby increasing its drag. The next set
250 of design parameters that play an important role, are the Mach number and the area ratio of the duct exit. Both effec-
251 tively determine the magnitude of the mass flow through the duct, which is again driving the power requirement of the fan.

252
253 The shaping of the rear fuselage section upstream of the FF appears to be of lesser importance, based on the sen-
254 sitivities of λ_{aft} and κ_{aft} . Nevertheless, a trend can be observed which suggest that for the baseline design, a
255 shorter rear section with a more convex aft body shape would be beneficial. In terms of fuselage diameter, the
256 trend suggests a slightly lower fuselage diameter, which would result into a longer fuselage centre section. Also
257 shown in Figure 9 is the relative axial position of the FF, which is favoured to be positioned at the aft. However,
258 as one can see from the last data point, there appears to be a drop towards the upper bounds. This could be ex-
259 plained by the fact that the length of the boat tail is reduced if the FF is positioned further aft. The pressure forces
260 acting on the boat tail have a force component in flight direction, reducing the drag. Shortening of the boat tail

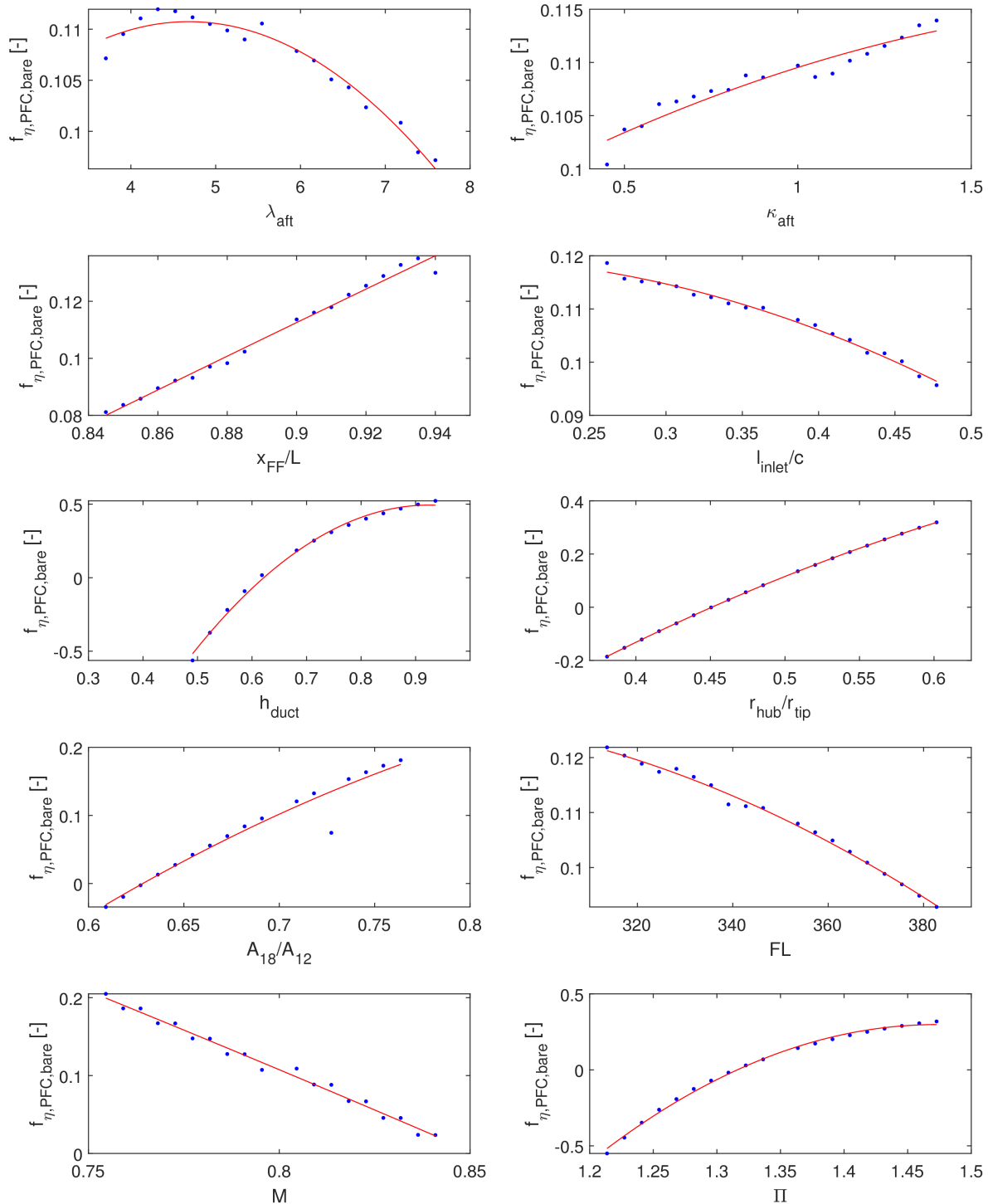


Fig. 9 Plots of 1-dimensional sensitivity of the design parameter w.r.t to the boundary layer ingestion efficiency factor in comparison with the baseline design. All other parameters are kept constant

261 reduces the exposed surface area and with that decreasing the drag reduction. At the same time, the integrated skin
 262 friction drag over the boat tail caused by the exhaust plume is diminishing as well. Moreover, the best theoretical

263 position of a BLI propulsor is at the trailing edge, since the entire momentum deficit in the boundary layer can be ingested.

264

265 The design parameters that describe the shaping of the nacelle appear to be of lesser importance. As discussed previously,
266 the gradients for the parameters describing the aerodynamic shape of the nacelle are one or two orders of magnitude
267 lower as compared to the other parameters. This is because the shape of the nacelle influence mostly the local drag
268 production and have limited effect on the main flow field. Therefore, the optimization of the nacelle shape is most
269 meaningful when the main design parameters have been fixed, provided that a feasible baseline nacelle geometry is
270 provided.

271

272 The aforementioned trends and sensitivities are useful to perform design trade-off studies in the early design phase.
273 Nevertheless, it should be kept in mind that the sensitivities could change if multiple design parameter are changed
274 simultaneously. Furthermore, the presented trends are valid only for the baseline design. It is expected that the direction
275 of the trends will remain similar for different designs, but the gradients and locations of apparent optima will shift, as
276 these are design specific.

277 **B. Optimization**

278 Although the 1D sensitivities, discussed in the previous Section, are very useful for gaining an understanding of the
279 design, it remains a challenging task to optimize the bare PFC by manual iteration. Therefore it is attempted to find the
280 optimal design vector for the bare PFC using surrogate model gradient-based optimization. In the end, the optimized
281 design will be compared to a previous bare PFC design.

282 *1. Reduced design vector*

283 To reduce the complexity of the optimization problem and enhance the fit of the surrogate model, the number of design
284 variables could be reduced. However, elimination of design variables from the design vector will impact the accuracy of
285 the model. A much reduced design vector could fail to capture the true global optimum. Depending on the quality and
286 size of the sampling and the choice of surrogate model, the workable number of design variables that can be used is
287 generally between 5-10 variables. Only the design variables that have a significant impact on the overall aerodynamic
288 performance of the bare PFC are selected. This includes the FPR, duct height h_{duct} nozzle area ratio A_{18}/A_{12} , axial fan
289 location x_{FF} and hub-to-tip-ratio $r_{\text{hub}}/r_{\text{tip}}$. Therefore, the reduced design vector becomes:

$$X = [\Pi, M, FL, h_{\text{duct}}, (A_{18}/A_2), (r_{\text{hub}}/r_{\text{tip}}), (x_{\text{FF}}/L)] \quad (4)$$

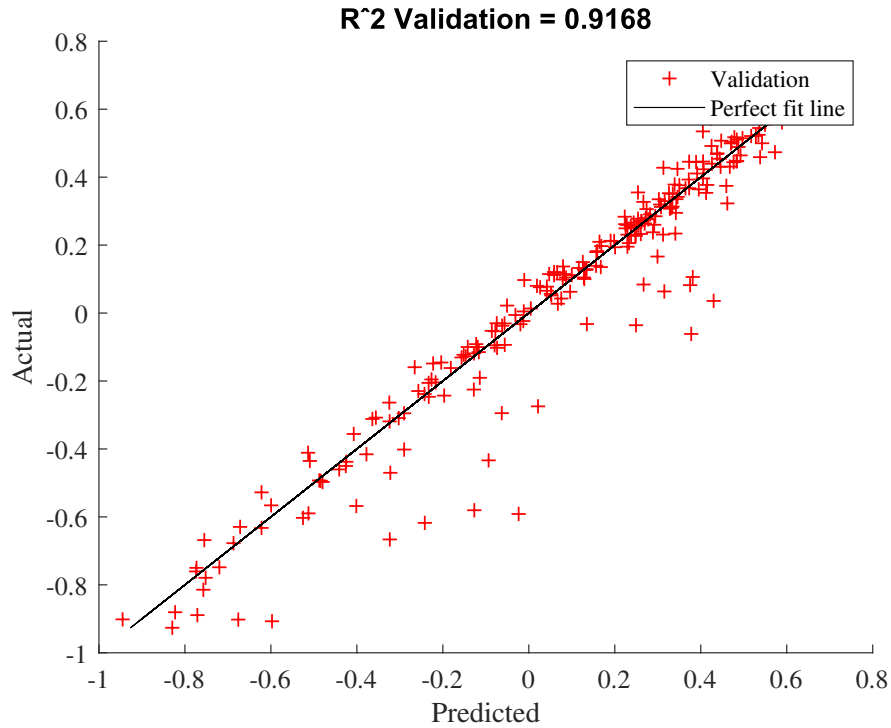


Fig. 10 Plot of predictions of $f_{\eta,PFC,bare}$ by the surrogate model and actual validation data

290 2. Surrogate model

291 Many different methods and models are in existence for application to aerodynamic optimization and design space
 292 exploration engineering problems [23]. Of the various methods under consideration, the Support Vector Regression
 293 (SVR) [34] was selected to be used in the optimization. The principle of SVR is to fit a kernel function with an
 294 acceptable error margin (ϵ) and tolerance (C) to the data. Optimization of the aforementioned hyper parameters
 295 ensures that the mean absolute error of the regression curve with respect to the data is minimized. For multi-
 296 dimensional data, the parameters ϵ and C are tuned to ensure an optimal fit of a hyper-surface to the data. In
 297 order to implement the method in the Matlab® framework, the software library LIBSVM [35] was used. Before
 298 fitting the data, the data was standardized to avoid numerical bias. To validate whether the fit of the model is
 299 good enough, a new set of samples was evaluated in the CFD framework. The samples were again generated using
 300 LPSS and distributed over the design space. In total 625 samples were generated, which resulted in 221 additional
 301 converged CFD results. The ϵ -SVR algorithm with a Radial Basis Function (RBF) kernel is used, as this resulted in the
 302 best fit of the model to the data. The quality of the fit of the surrogate model with the validation data is shown in Figure 10.

303

304 As can be observed, the fit is acceptable, with a coefficient of determination $R^2 = 0.9168$. In general the points of
 305 positive response ($f_{\eta,PFC,bare}$) are represented to a good extent by the surrogate model, with a few exceptions of

306 outliers. In the negative domain of the response, the validation data is sparser and the variation in the predictions with
 307 respect to the actual values is larger. This means that the model could give a reasonable fit for most combinations of
 308 parameters, but could also significantly under- or over-predict the response. To see how well the model is capable of
 309 capturing the trends, the model is verified with the 1D sensitivity data. The comparison is shown in Figure 11. As can
 310 be observed, the fit is reasonable in case the change in the response is large, such as is the case for the FPR for example.
 311 In case that the parameter is less sensitive, the error of the fit becomes too significant to provide an accurate prediction.
 312 This can be observed to be the case for the altitude and the axial FF position. Despite the fact that the error of the fit is
 313 too large to predict the response in all cases with sufficient accuracy, the qualitative behaviour of the model is acceptable.
 314 Only towards the boundaries of the domain, the accuracy of the model predictions appears to be decreasing. However,
 315 in general, the model should be sufficient to fine-tune the main design parameters of the PFC.

316

317 In order to estimate the required power by the FF during the optimization, a separate model is required. The necessity
 318 stems from the fact that the maximum power by the FF needs to be set by a constraint, to avoid a design with a too large
 319 power requirement. The auxiliary model is trained for the following parameters:

$$P_{\text{shaft,id}} = f(\Pi, M, (r_{\text{hub}}/r_{\text{tip}}), h_{\text{duct}}, (A_{18}/A_2)) \quad (5)$$

320 The model with 5 parameters is again fitted with the ϵ -SVR model with a RBF kernel. The data is compared with the
 321 same verification data set as used for the main surrogate model. Shown in Figure 12 is the validation plot, presenting the
 322 predictions of the model against the validation data. The coefficient of determination is relatively good with $R^2 = 0.9609$.
 323 Especially in the lower power spectrum up to about 8.0 MW, the model appears to predict the required output power
 324 quite well. The increased level of scatter in the predictions towards the higher power regime should not pose a problem
 325 for the current objective. Although the number of parameters that are included in the model for $P_{\text{shaft,id}}$ is less than
 326 the model to fit $f_{\eta,\text{PFC,bare}}$, the model for ideal shaft power appears to have less scatter in the data. As such, the data
 327 suggest that the scatter of the $f_{\eta,\text{PFC,bare}}$ parameter is due to the interactions of the various design parameters and their
 328 combined effect on the drag. The non-linear behaviour of the drag, for example, due to flow separations or shock waves,
 329 make it more difficult to fit the surrogate model with sufficient accuracy.

330 3. Optimization formulation

331 To optimize the geometry of the bare PFC, a Matlab® gradient-based solver (*fmincon*) is used in conjunction with the
 332 aforementioned surrogate models for $f_{\eta,\text{PFC,bare}}$ and $P_{\text{shaft,id}}$. Multiple starting points for the optimization process are
 333 selected to enhance the chance of finding a true optimum bare PFC design. To enhance the chance of finding an optimal
 334 design, three of the most promising designs are selected from the cloud of design points. The objective function for the

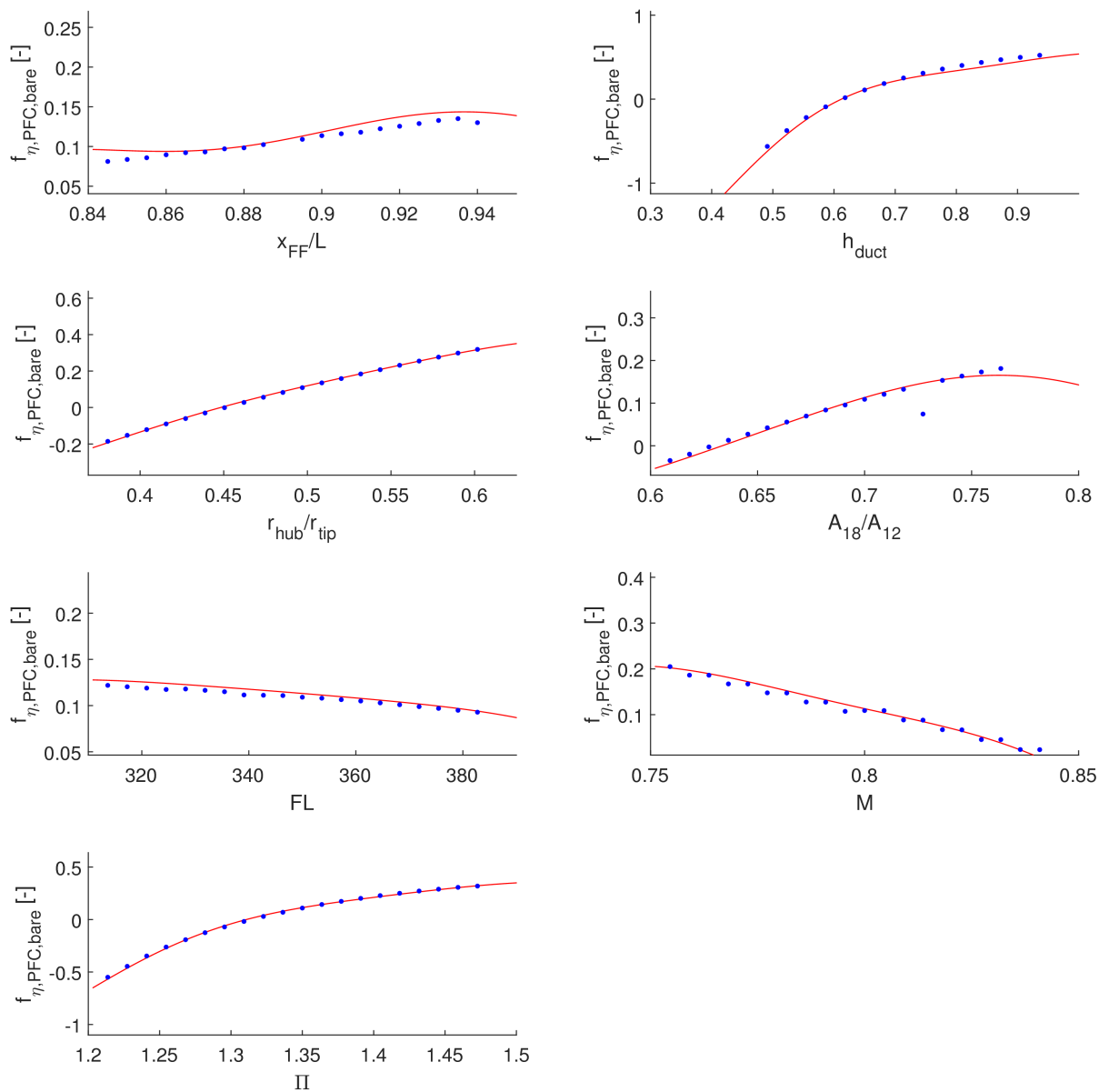


Fig. 11 Verification of surrogate model with 1-D sensitivity results obtained with CFD

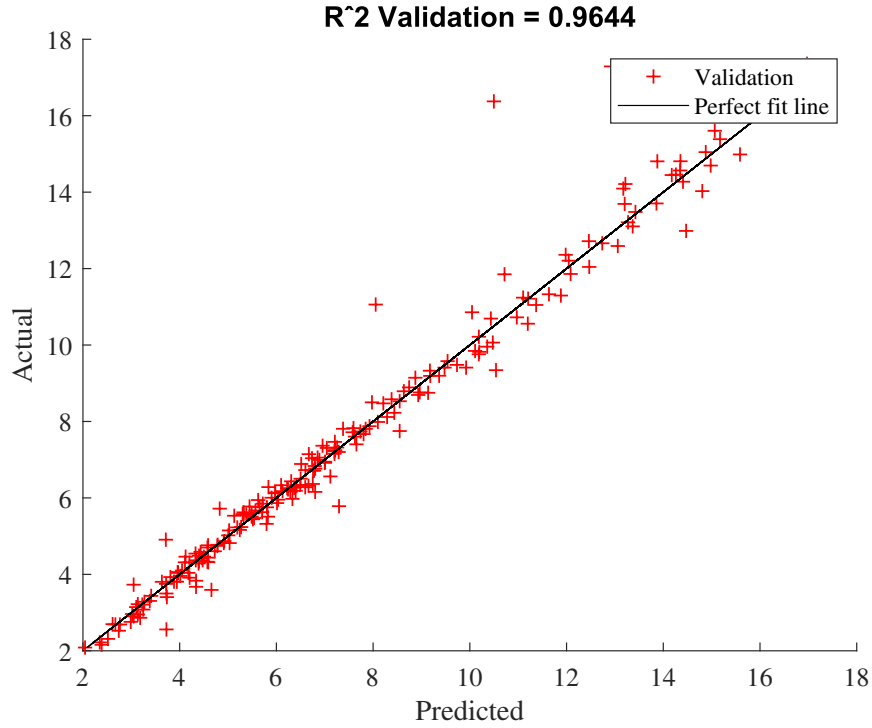


Fig. 12 Plot of predictions by the surrogate model for $P_{\text{shaft,id}}$ with actual validation data.

335 optimization is formulated as follows:

$$\text{Find: } x^* = \arg \min f(x) = \frac{1}{f_{\eta,\text{PFC,bare}} + C} \quad (6)$$

In the above formulation, a constant is added to ensure that the objective value is always positive. To comply with the requirements for the PFC overall aircraft design [36] the optimization is constraint:

$$x_L < x < x_U \quad (7a)$$

$$FL - FL_{\text{ref}} = 0 \quad (7b)$$

$$M - M_{\text{ref}} = 0 \quad (7c)$$

$$P_{\text{shaft,id}} - P_{\text{shaft,max}} \leq 0 \quad (7d)$$

$$L_{\text{fus}} - L_{\text{fus,max}} \leq 0 \quad (7e)$$

336 The equality constraints enforce that the optimizer finds an optimum solution for the operational conditions of the
 337 reference mission ($FL= 350$, $M= 0.82$). Furthermore, the maximum ideal power for the FF is limited to 5.5 MW, as the
 338 turbo-electric power-train of the CENTRELINE configuration is designed for this power output during cruise. Finally, a
 339 constraint is placed on the maximum fuselage length, not to exceed $L_{\text{fus,max}} = 70\text{m}$.

340 *4. Results and verification*

341 As a starting point for the optimization process, the cloud of available CFD results was surveyed for promising designs.
 342 Within margins of the operational conditions and upper limit for the ideal shaft power, the best-performing designs were
 343 picked and analysed. After assessment of the designs by engineering judgement, the best performing designs were
 344 selected. An overview of the 3 initial design vectors and the optimization results is shown in Table 4.

Table 4 Result of optimization using the 7 parameter surrogate model. Note that the performance parameters for the optimized result is a prediction by the model, in contrast to the CFD result of the initial configuration.

Optimum No.	Design vector	$f_{\eta, \text{PFC, bare}}$	$P_{\text{shaft, id}}$
1	$x_0 = [1.35 \ 0.80 \ 350 \ 0.65 \ 0.70 \ 0.50 \ 0.90]$	0.1090	6.20
	$x^* = [1.32 \ 0.82 \ 350 \ 0.73 \ 0.68 \ 0.43 \ 0.92]$	0.0334	5.50
2	$x_0 = [1.35 \ 0.81 \ 352 \ 0.89 \ 0.65 \ 0.43 \ 0.85]$	0.2511	16.91
	$x^* = [1.32 \ 0.82 \ 350 \ 0.73 \ 0.68 \ 0.43 \ 0.92]$	0.0325	5.50
3	$x_0 = [1.46 \ 0.81 \ 358 \ 0.63 \ 0.63 \ 0.43 \ 0.89]$	0.3886	11.80
	$x^* = [1.32 \ 0.82 \ 350 \ 0.73 \ 0.68 \ 0.43 \ 0.92]$	0.0334	5.50

x_0 initial design vector x^* optimum design vector

345 As can be observed from Table 4, the optimization algorithm finds the same optimum for three different initial points.
 346 The obtained optimum features a positive NPF compared to the bare PFC while not exceeding the limit on the ideal
 347 shaft power, constrained to a maximum of 5.50 MW. Since the surrogate model only provides an estimation of the
 348 aerodynamic performance, the selected designs are analysed separately by CFD simulation. The results are shown in
 349 Table 5.

350
 351 As can be observed, the results are not satisfactory, since the required power appears to be under-estimated while the
 352 $f_{\eta, \text{PFC, bare}}$ is over-predicted. Moreover, the influence of the other design parameters, which are excluded from the
 353 surrogate model, can still have a significant impact on the aerodynamic performance. Nevertheless, the prediction for
 354 the second candidate design is within a 10% error margin, which is acceptable for initial design. Regardless of the
 355 quality of the fit, it can be observed from Table 5 that the 3rd candidate design has the best aerodynamic performance
 356 out of the three candidate designs. The $f_{\eta, \text{PFC, bare}}$ is positive, at the cost of a power requirement by the FF that is
 357 higher than what is considered to be the maximum power for the FF. By fine-tuning of the design parameters, the most

Table 5 Verification of prediction of the surrogate model for three different candidate designs with CFD results.

Optimum no.	Surrogate model		RANS CFD	
	$f_{\eta, \text{BLI}}$	$P_{\text{shaft, id}}$	$f_{\eta, \text{PFC, bare}}$	$P_{\text{shaft, id}}$
1	0.0334	5.50	0.0028	6.13
2	0.0325	5.50	0.0278	5.90
3	0.0334	5.50	0.0416	6.03

Table 6 Effect of successive design changes to the optimized design on $f_{\eta,\text{PFC,bare}}$ and $P_{\text{shaft,id}}$

Iteration No.	Description	$f_{\eta,\text{PFC,bare}}$ [–]	$P_{\text{shaft,id}}$ [MW]	$\Delta P_{\text{shaft,id}}$ [%]
0	Optimized design with $\Pi = 1.30$	–0.0365	5.52	–
1	As above with $\kappa_{\text{aft}} = 1.20$	–0.0339	5.51	–0.2%
2	As above with $\lambda_{\text{aft}} = 4.50$	–0.0281	5.50	–0.5%
3	As above with $D_{\text{fus}} = 5.80$	–0.0273	5.47	–0.9%

358 promising candidate design can be improved further and made compliant with the constraints. Since the ideal shaft
359 power is very sensitive to the changes in FPR, the FPR is reduced slightly to bring down the required shaft power for the
360 third design. This comes at the cost of the NPF, which just becomes negative. With the knowledge gained from the
361 sensitivity analysis, one can adjust some of the other design parameters, which have not been taken into account in the
362 optimization. For example, the slenderness of the aft section can be reduced while the shape of the aft section is made
363 more convex. Similarly, the fuselage diameter is reduced effectively increasing the Fuselage Slenderness Ratio. The
364 effect of the successive design changes is shown in Table 6.

365 As can be seen in the table above, the changes have been effective in increasing the $f_{\eta,\text{PFC,bare}}$. Equally important, the
366 ideal shaft power $P_{\text{shaft,id}}$ of the FF was reduced by almost 1%. At the same time the BLI efficiency factor was improved.
367 A comparison of the PFC geometry before and after the aforementioned modifications is shown in Figure 13. As can be
368 seen, the modified design features a slightly shorter fuselage as a result of the reduced fuselage diameter. Furthermore,
369 the curvature of the aft body is more convex, resulting in a steeper curvature of the aft-body ahead of the FF. The latter
370 means that the boundary layer is facing a steeper adverse pressure gradient. Despite the small increase of the wetted
371 surface area, the drag is found to be reduced by $\Delta D_{\text{PFC,bare}} = -0.7\%$.

372
373 To understand the aerodynamic behaviour of the improved PFC design better, the contour plots of the Mach number and
374 total pressure (Figure 15) are included. As can be observed from the Mach number contours, the flow field does not show
375 any regions of separated flow or shock waves. The flow over the nacelle remains subsonic, an indication that there is no
376 excessive spillage drag. At the duct exit, the flow is expanded to atmospheric conditions. Due to the curvature at the
377 start of the boat-tail, the flow is locally accelerated. Inspection of the total pressure contours shows that the FF ingests a
378 majority of the momentum deficit of the fuselage boundary layer. The momentum added to the flow by the FF is more
379 than what is required for just filling the wake, as was found to be necessary to offset the additional drag of the nacelle.

380 C. Comparison with reference design

381 Having achieved an improved design, it is interesting to compare the new design with the previous (Rev05) PFC
382 design within the CENTRELINE project. The latter was obtained by subsequent manual design iterations based on

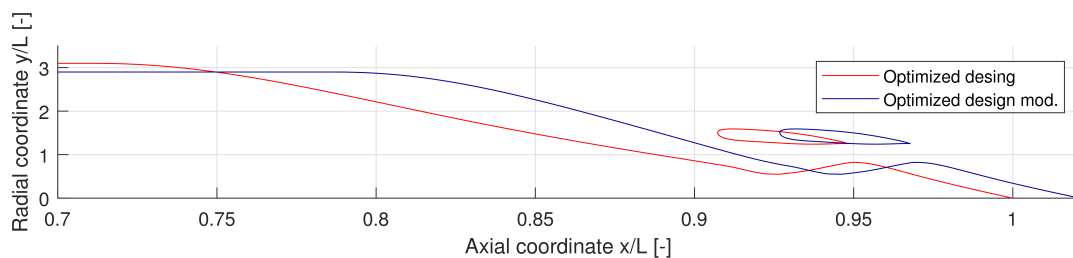


Fig. 13 Comparison of initial optimized bare PFC geometry and subsequent modified design of the PFC

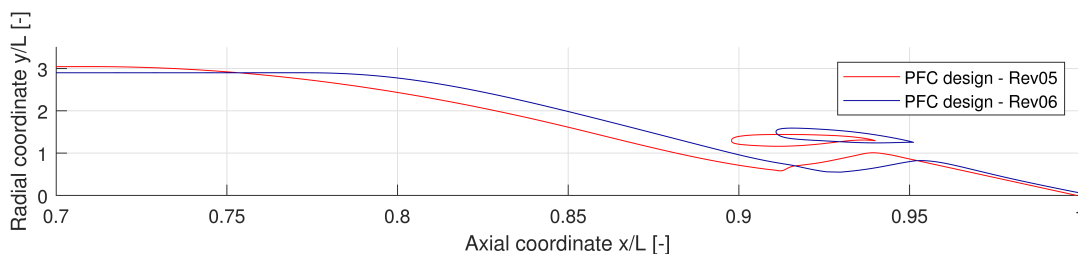


Fig. 14 Comparison of the geometry of the Rev06 design with the previous (Rev05) PFC design

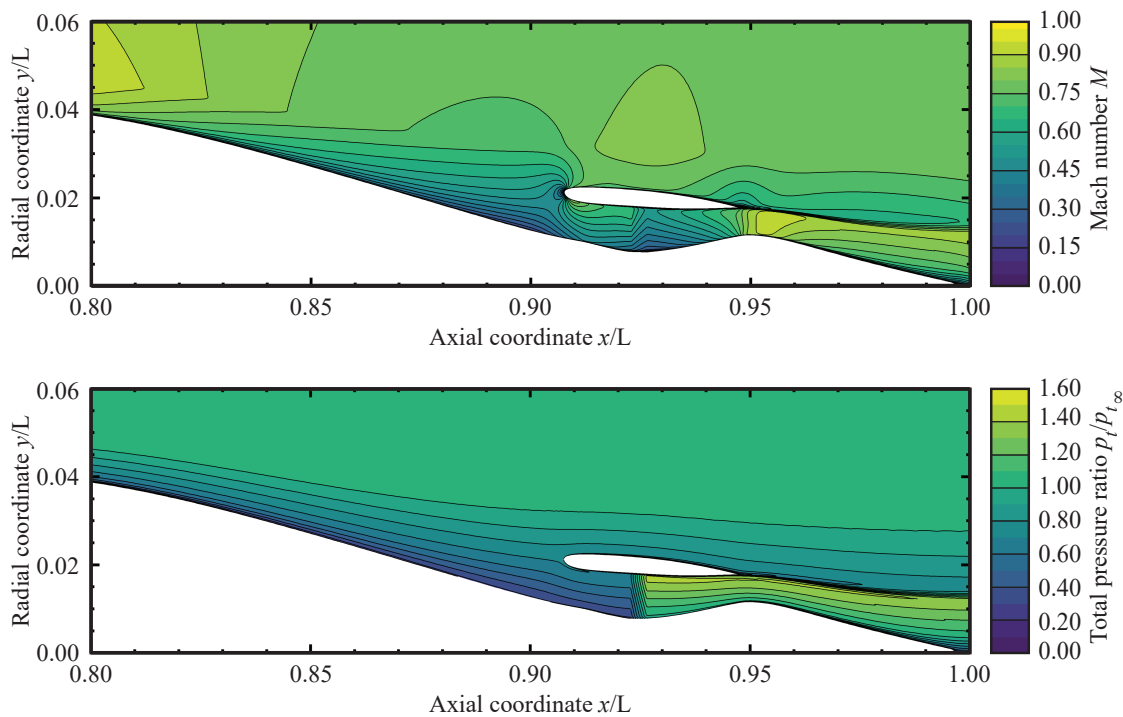


Fig. 15 Contours of normalized Mach number (top) and total pressure (bottom) for the Rev06 PFC geometry (M=0.82, FL=350, ISA +10 K)

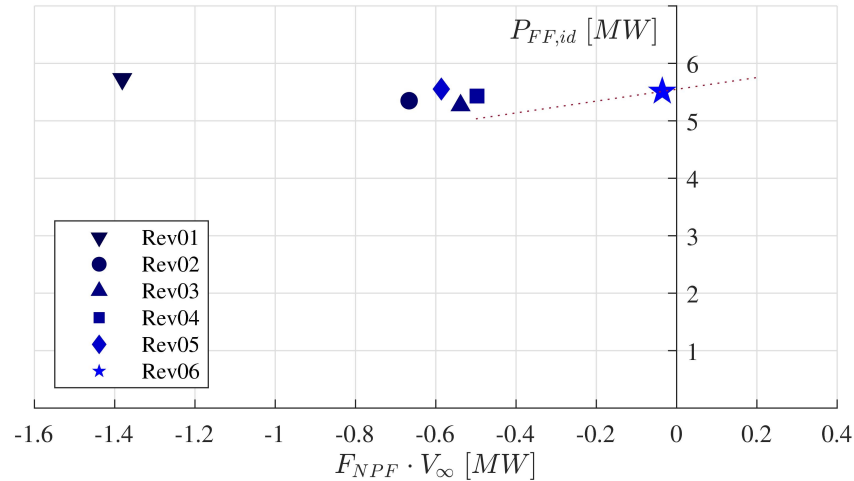


Fig. 16 Comparison of the Fuselage Fan idealized power versus the F_{NPF} times flight velocity for the improved design with previous revisions of the PFC design. (M=0.82, FL=350, ISA + 10 K) [37]

383 engineering judgement. Note that the Rev05 PFC design features a design FPR= 1.40 [16]. Shown in Figure 16 is the
 384 FF shaft power versus the product of the NPF and flight velocity. As can be observed, the improved design (called
 385 Rev06) is a significant improvement in terms of $f_{\eta,PFC,bare}$ over the previous revisions of the PFC design. Even though
 386 the NPF is still negative at this given power, the difference in the net balance of the propulsive force and the drag is
 387 $\Delta F_{NPF} \approx 1.50kN$. This corresponds to about 4% of the bare (i.e. no wings and empennage) PFC drag. A study on the
 388 aircraft level should be conducted to evaluate how much the relative reduction of total net force of the complete aircraft
 389 is and how the total system efficiency is affected. At the current design point, the FPR= 1.30, which is on the lower side
 390 of the spectrum. Further increasing the FPR is beneficial for the aerodynamic performance, as found already by the data
 391 presented in Figure 9. However, this would require an increased power output by the hybrid-electric drivetrain, adding
 392 additional weight and cooling complexity. To compare Rev05 and Rev06 directly, one should evaluate both designs
 393 for equal level of F_{NPF} . In case the FPR of Rev06 is lowered such that it matches the F_{NPF} of Rev05, it can be shown
 394 that the Rev06 design requires close to $\Delta P_{shaft,id} \approx 10\%$ less power. This is shown graphically by the dotted line in 16.
 395 The latter was obtained from a curve-fit from RANS CFD simulations for the optimized design with varying values for FPR.

396
 397 To see how the design is actually different from the previous PFC design (Rev05), the geometries are compared with each
 398 other. This is presented in Figure 14. As can be observed the fuselage length of both designs is comparable, despite the
 399 fact that the fuselage diameter of the Rev06 design is lower. However, this is compensated for by the increased internal
 400 volume in the aft section, which is less slender and has a more convex shaping of the fuselage contour. Furthermore, it
 401 can be seen that the incidence angle of the nacelle is much larger for the Rev06 design, compared to the Rev05 PFC
 402 geometry. Although both nacelles are approximately equal in size, the duct height of the Rev06 is higher due to the

403 lower hub-to-tip ratio. The minimum radius at the hub is $r_{\text{hub}} = 0.56\text{m}$, which is sufficient space to allocate the electric
404 motor [38].

405 V. Conclusion

406 The Propulsive Fuselage Concept (PFC) is a tube-and-wing aircraft architecture which uses an additional propulsor,
407 integrated in the aft-cone of the fuselage, to maximize the aerodynamic efficiency by exploiting Boundary Layer
408 Ingestion (BLI). To understand and maximize the aerodynamic performance of the PFC, a systematic survey of the
409 aerodynamic design space has been performed. A methodology based on the novel Design of Experiments techniques
410 has been implemented. The methodology comprises of the following elements:

- 411
412 1) A parametric model has been constructed to describe the geometry of the bare PFC (i.e. fuselage body with
413 integrated BLI propulsor). In total 23 design variables were used for the representation of the geometry, including
414 the aerodynamic shape of the nacelle.
- 415 2) A quasi-random sampling strategy was employed to span the entire aerodynamic design space. In total 9,600
416 samples were used as input for CFD frame-work. Approximately one-third of the samples resulted in a converged
417 CFD simulation
- 418 3) The development of a fully automated CFD pre- and post-processing MATLAB® framework has enabled the
419 analysis of several thousand unique samples of the design vector using CFD simulations.
- 420 4) Axisymmetric 2D RANS simulations were performed for the aerodynamic analysis of the PFC, representing the
421 best compromise between fidelity of the modelled flow field and computational effort. A simple body-force
422 model was implemented to model the BLI propulsor. The propulsor model was robust and did not compromise
423 the computational cost. Moreover, it allowed for a direct control of the imposed FPR and an effective calculation
424 of the propulsive force and power.
- 425 5) In order to enhance the physical understanding of the aerodynamics of the PFC, a one-dimensional sensitivity
426 study has been conducted to map the relative influence of each individual design parameter on the aerodynamic
427 performance of the PFC.
- 428 6) A surrogate model using a reduced number of design variables was constructed and successfully verified. Of the
429 initial 26 design variables, 7 of the most influential parameters, as selected through the sensitivity analysis, were
430 used to construct the surrogate model.
- 431 7) A gradient-based optimization with the reduced design parameters was performed to find an optimum set of
432 parameters. By selection of the most promising designs of the data set and application of the optimization results,
433 a local optimum design was found The objective function was the so-called BLI efficiency factor, defined as
434 $f_{\eta, \text{PFC, bare}} = F_{\text{NPF}} \cdot V_{\text{inf}} / P_{\text{shaft, id}}$. This scalar parameter represents a measure of the useful work done by the Net

435 Propulsive Force (NPF) and the idealized shaft power.

436
437 Verification of the aerodynamic performance in RANS CFD showed that the prediction of the surrogate model was
438 satisfactory, despite an apparent offset of the prediction compared to the CFD data. Successive adjustment of the
439 non-optimized design parameters, on the basis of the sensitivity study, further improved the aerodynamic performance
440 of the design. The optimized design, compared to previous PFC designs, features:

- 441
- 442 • Increased duct height h_{duct}
- 443 • Reduced Fan Pressure Ratio (FPR) from $\Pi = 1.40$ to $\Pi = 1.30$
- 444 • 10% reduction in ideal shaft power $P_{FF,id}$ at equal net force
- 445

446 The increased height of the duct of the Fuselage Fan (FF) ensures that a larger portion of the momentum deficit of
447 the boundary layer is ingested by the FF. To account for the increased mass-flow in the duct, the FPR of the fan is
448 reduced to meet the imposed limit on the ideal shaft power by the FF. Other modifications include an increased incidence
449 angle of the nacelle for better alignment with the incoming flow and reduced fuselage diameter. At a similar NPF, the
450 improved design would require approximately 10% less power, which is a significant improvement. CFD analysis of the
451 improved design shows that the aerodynamic design is feasible, without any signs of major flow defects. Both the initial
452 and optimized design increase the momentum and energy in the wake than would be required for pure wake-filling design.

453
454 Although a full optimization resulting in a global optimum has not been the outcome of the current study, the methodology
455 applied has been successful to make a significant improvement to the aerodynamic design. Moreover, further insight has
456 been gained into the sensitivity of the design parameters to the aerodynamic performance of the PFC.

457 Acknowledgements

458 This work was conducted within the CENTRELINE project, which has received funding from the European Union's
459 Horizon 2020 research and innovation programme under Grant Agreement No. 723242. The authors would like to
460 thank Dr. M. Pini for the discussions about Design of Experiments (DoE) and surrogate modelling.

461 References

- 462 [1] *Flightpath 2050: Europe's Vision for Aviation*, ACARE, 2011.
- 463 [2] *Strategic Research and Innovation Agenda*, ACARE, 2011.

- 464 [3] Beck, N., Landa, T., Seitz, A., Boermans, L., and Y. Liu, R. R., "Drag Reduction by Laminar Flow Control," *Energies*, Vol. 11,
465 No. 1, 2018.
- 466 [4] Pornet, C., and A.T.Isikveren, "Conceptual design of hybrid-electric transport aircraft," *Progress in Aerospace Sciences*, Vol. 79,
467 2015, pp. 114–135.
- 468 [5] Drela, M., "Power Balance in Aerodynamic Flows," *AIAA Journal*, Vol. 47, No. 7, 2009.
- 469 [6] Peijian, L., Ragni, D., Hartuc, T., and Veldhuis, L., "Experimental Investigation of the Flow Mechanisms Associated with a
470 Wake-Ingesting Propulsor," *AIAA Journal*, Vol. 55, No. 4, 2016.
- 471 [7] Steiner, H., Seitz, A., Wiczorek, K., and Plotner, K., "Multi-Disciplinary Design and Feasibility Study of Distributed Propulsion
472 Systems," *28th International Congress of the Aeronautical Sciences*, edited by ICAS, 2012.
- 473 [8] Isikveren, A., Seitz, A., Bijewitz, J., Hornung, M., Mirzoyan, A., and Isyanov, A., "Recent Advances in Airframe-Propulsion
474 Concepts with Distributed Propulsion," *29th International Congress of the Aeronautical Sciences*, edited by ICAS, 2014.
- 475 [9] Welstead, J., and Felder, J., "Conceptual Design of a Single-Aisle Turbo-electric Commercial Transport with Fuselage Boundary
476 Layer Ingestion," *54th AIAA Aerospace Sciences Meeting*, edited by Sci-Tech, 2016.
- 477 [10] Gray, J., and Martins, J., "Coupled Aeropropulsive Design Optimization of a Boundary Layer Ingestion Propulsor," *The
478 Aeronautical Journal*, Vol. 123, No. 1259, 2019, pp. 121–137.
- 479 [11] Kenway, G., and Kiris, C., "Aerodynamic Shape Optimization of the STARC-ABL Concept for Minimal Inlet Distortion,"
480 *Structures, Structural Dynamics and Materials Conference*, edited by Sci-Tech, 2018.
- 481 [12] Ordaz, I., Nielsen, E., and Rallabhandi, S., "Adjoint-Based Design of a Distributed Propulsion Concept with a Power Objective,"
482 *AIAA Aviation Forum*, edited by AIAA, 2019.
- 483 [13] Yildirim, A., J., G., Mader, C., and Martins, J., "Aeropropulsive Design Optimization of a Boundary Layer Ingestion System,"
484 *AIAA AVIATION Forum*, edited by AIAA, 2019.
- 485 [14] Hahn, A., "Vehicle Sketch Pad: A Parametric Geometry Modeler for Conceptual Aircraft Design," *48th AIAA Aerospace
486 Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, edited by AIAA, 2010.
- 487 [15] Brown, K., Fleming, J., Langford, M., and Ng, W., "Development of a Ducted Propulsor for BLI Electric Regional Aircraft -
488 Part I: Aerodynamic Design and Analysis," *AIAA Propulsion and Energy 2019 Forum*, edited by AIAA, 2019.
- 489 [16] Seitz, A., Peter, F., Bijewitz, J., Habermann, A., Goraj, Z., Kowalski, M., Pardo, A. C., Hall, C., Meller, F., Merkler, R., Petit, O.,
490 Samuelsson, S., Corte, B. D., van Sluis, M., Wortmann, G., and Dietz, M., "Concept Validation Study for Fuselage Wake-Filling
491 Propulsion Integration," *31st Congress the International Council of the Aeronautical Sciences*, edited by ICAS, 2018.
- 492 [17] CENTRELINE, "Project Public Website," <http://www.centreline.eu>, 2020.

- 493 [18] Seitz, A., Habermann, A., Peter, F., F.Troeltsch, Pardo, A. C., Corte, B. D., van Sluis, M., Goraj, Z., Kowalski, M., Zhao, X.,
494 Grönstedt, T., Bijewitz, J., and Wortmann, G., “Proof of Concept Study for Fuselage Boundary Layer Ingesting Propulsion,”
495 *Aerospace*, Vol. 8, 2021.
- 496 [19] Chappell, P. D., Clarke, A., Porter, R., and Wood, S., *ESDU 77028: Geometrical characteristics of typical bodies*, ESDU,
497 November 1977.
- 498 [20] Peter, F., Bijewitz, J., Habermann, A., Ludemann, M., Plotner, K., Seitz, A., and Troelsch, F., “Definition of the CENTRELINE
499 reference aircraft and power plant systems,” *69th Deutscher Luft- und Raumfahrtkongress (DLRKs)*, edited by D. G. für Luft-und
500 Raumfahrt (DGLR), 2020.
- 501 [21] Piegl, L., “On NURBS: A Survey,” *IEEE Computer Graphics and Applications*, Vol. 11, 1991.
- 502 [22] Derksen, R., and Rogalsky, T., “Optimum Airfoil Parameterization for Aerodynamic Design,” *Computer Aided Optimum Design
503 in Engineering*, Vol. 106, 2009.
- 504 [23] Yondo, R., Andres, E., and Valero, E., “A review on design Of Experiments and Surrogate Models in Real-Time and many-query
505 Aerodynamic Analysis,” *Progress in Aerospace Science*, Vol. 96, 2018.
- 506 [24] Shields, M., and Zhang, J., “The Generalization of Latin Hypercube Sampling,” *Reliability Engineering and System Safety*, Vol.
507 148, 2016.
- 508 [25] Hofer, D., “Matlab to Ansys ICEM/Fluent and Spline Drawing Toolbox,” , July 2019. URL [https://www.mathworks.com/
509 matlabcentral/fileexchange/66215-matlab-to-ansys-icem-fluent-and-spline-drawing-toolbox](https://www.mathworks.com/matlabcentral/fileexchange/66215-matlab-to-ansys-icem-fluent-and-spline-drawing-toolbox).
- 510 [26] Sutherland, W., “The viscosity of gases and molecular force,” *Philosophical Magazine Series 5*, Vol. 36:223, 1893.
- 511 [27] Menter, F., “Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications,” *AIAA Journal*, Vol. 32, 1994, p.
512 1598–1605.
- 513 [28] Leonard, B., “A stable and accurate convective modelling procedure based on quadratic upstream interpolation,” *Computer
514 Methods in Applied Mechanics and Engineering*, Vol. 19, 1979, p. 59–98.
- 515 [29] van Leer, B., “Towards the Ultimate Conservative Difference Scheme, V. A Second-Order Sequel to Godunov’s Method,”
516 *Journal of Computational Physics*, Vol. 32, 1979, p. 101–136.
- 517 [30] Pardo, A. C., and Hall, C., “Aerodynamics of boundary layer ingesting fuselage fans,” *ASME Journal of Turbomachinery*, Vol.
518 143, 2021.
- 519 [31] Habermann, A., Zahn, R., Seitz, A., and Hornung, M., “Multidimensional Parametric Study of a Propulsive Fuselage Concept
520 Using OpenFOAM,” *AIAA AVIATION 2020 (virtual conference)*, edited by AIAA, 2020.
- 521 [32] Pearson, K., “On Lines and Planes of Closet Fit to Systems of Points in Space,” *Philosophical Magazine*, Vol. 11, 1901, pp.
522 559–572.

- 523 [33] Berguin, S., “A Method for Reducing Dimensionality in Large Design Problems with Computationally Expensive Analysis,”
524 Ph.D. thesis, Georgia Institute of Technology, <http://hdl.handle.net/1853/53504>, 2 2015.
- 525 [34] Awad, M., and Khanna, R., “Support Vector Regression,” *Efficient Learning Machines: Theories, Concepts, and Applications*
526 *for Engineers and System Designers*, Apres, 2015, pp. 67–80.
- 527 [35] Chang, C., and Lin, C., “LIBSVM: a Library for Support Vector Machines,” *ACM Transactions on Intelligent Systems and*
528 *Technology*, Vol. 2, 2011, pp. 1–27. Software available at <http://www.csie.ntu.edu.tw/~cjlin/libsvm>.
- 529 [36] Habermann, A., Troelsch, F., Peter, F., Maas, P., van Sluis, M., Kowalski, M., Wortmann, G., Bijewitz, J., and Seitz, A.,
530 “Summary Report on Multi-Disciplinary Design Results,” Tech. Rep. CENTRELINE Project Deliverable D2.11, Bauhaus
531 Luftfahrt, November 2020.
- 532 [37] Seitz, A., Habermann, A., and van Sluis, M., “Optimality considerations for propulsive fuselage power savings,” *Proceedings of*
533 *the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 235, 2021.
- 534 [38] Wortmann, G., “Electric Machinery Preliminary Design Report,” Tech. Rep. CENTRELINE Project Deliverable D4.04,
535 SIEMENS, October 2018.