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CONCEPTUAL DESIGN STUDIES OF BOUNDARY LAYER ENGINE INTEGRATION CONCEPTS

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ABSTRACT

The potential of several innovative engine integration concepts including the Boundary Layer Ingestion (BLI) technology has been investigated in the scope of the European Clean Sky 2 AIRFRAME ITD platform and “NACOR” project (New Aircraft Concepts Research – Call for Core Partners Wave 1, consortium ONERA (lead) - DLR). The studies have been conducted at the conceptual aircraft design level using only fuel-based propulsion system and considering two design missions: a short medium range (SMR) mission based on an AIRBUS A320, and a business jet (BJ) mission. In the present paper, only the results on the SMR mission are described.

1. INTRODUCTION

Following the challenging targets defined in the Flightpath 2050 [1], DLR and ONERA have investigated several unconventional engine integration technologies that could significantly reduce the environmental impact of air transportation in a near future. A stepwise analysis process is applied in order to cover a wide design space on the one hand, and to allow for deep analyses of the most promising concepts on the other.

The process begins with the evaluation of a large number of potential engine integration concepts, covering a large design space. Subsequently, the configurations are ranked based on performance criteria (mainly fuel burned) and the most promising ones are selected for more detailed analyses in the next steps. In total, three downselections have been performed in the scope of the project. A generic overview of this process is provided in Figure 1.

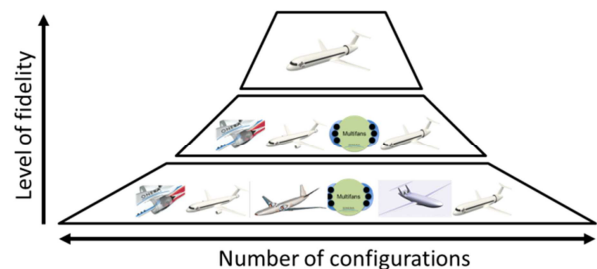


Figure 1 - Overview of the evaluation process.

2. OVERVIEW OF ENGINE INTEGRATION CONCEPTS

This section gives a brief overview of the different concepts assessed through this paper. For the two missions considered in this study the same four configurations have been investigated:

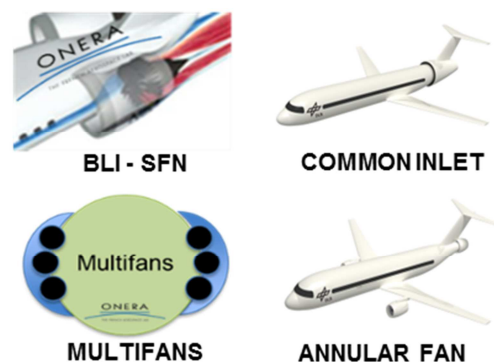


Figure 2 - Innovative engine integration concepts.

- the BLI-SFN (Boundary Layer Ingestion - Side Fuselage Nacelle): two turbofans with their classical inlet semi-buried in the rear part of the fuselage;
- the Common Inlet: two turbofans fed by a common circular inlet around the fuselage;
- the Multifans: several fans mechanically driven by two engine cores, and fed by two enlarged inlets at each side of the fuselage;

- the Annular Fan: a single fan driven by a core installed at the tail of the aircraft, complemented by two downsized underwing turbofans.

These concepts are shown in Figure 2.

3. DESCRIPTION OF TOOLS

In this section, the tools applied in the scope of this work are described.

3.1. ONERA - Aircraft Design Workflow in MYSTIC

To assess the performance of the four concepts for both missions, the MYSTIC OAD process has been used.

This tool incorporates physical modules for the classical disciplines of Overall Aircraft Design: Propulsion, Aerodynamics, Mass breakdown and balance, Handling qualities, Trajectory and Performance [2].

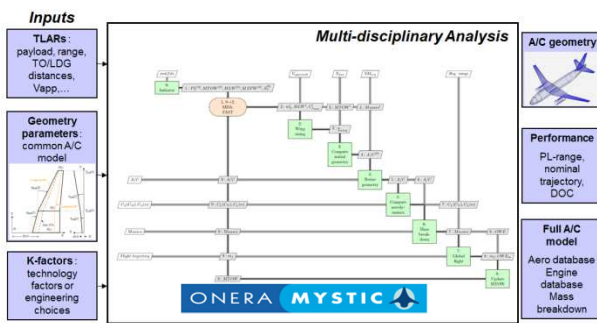


Figure 3 - inputs and outputs of the MYSTIC tool.

In the process, three sizing loops are implemented, allowing designing an aircraft upon its TLARs with iterations on the disciplinary modules.

As the logic of the study is to progressively increase the level of fidelity of the different modules while decreasing the number of selected configurations, 3 levels of BLI modules have been defined. Only results with the first ones are detailed in this paper.

The starting point of both modules is the definition of a geometric parameterization of the BLI arrangement. Two main parameters are necessary:

- The embedding ratio, defining which part of the nacelle is buried into the fuselage body (front view), and driving the average flow that will be seen by the engine inlet,

- The k-ingestion ratio defining the amount of BLI that will be ingested by the engine inlet (k=0 means the nacelle is considered as circular at the same size of the fan, k=1 means that 100% off the boundary layer of the fuselage is ingested).

Based on this simplified geometric parameterization enabling the evaluation of the amount of boundary layer ingested by the engine, the two first modules have been defined as follows:

Level 0: this module relies on an empirical relationship between ingested drag and power saving coefficient of the BLI arrangement. This relationship, extracted from the work of Plas [3], encompasses all the gains and penalties of the thermodynamic cycle, and can give a first idea of the possible fuel savings. Main parameters of the model are the inlet entrance position and the BLI captured length. As limitations, hypotheses are required on the BL shape, and engine performances is fully empirical and not related to any specific engine/geometry.

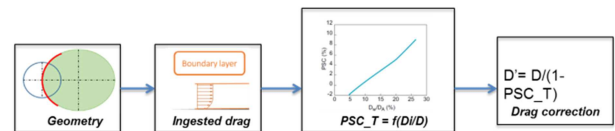


Figure 4 - Schematic of the BLI L0 module.

Level 1: in order to go deeper in the thermodynamic principles of BLI, a fan module is introduced to model the engine performance in the presence of a modified inflow. The computation of the average quantities enables to compute the right throttling for the engine and the necessary shaft power, and thus a more precise computation of the power saving coefficient. Main parameters of the model are the inlet capture streamtube and the engine characteristics (size and BPR/OPR/FPR). As limitations, the boundary layer is still modelled by a pre-defined profile, and simplified hypothesis are necessary regarding BLI impact on engine components efficiency.

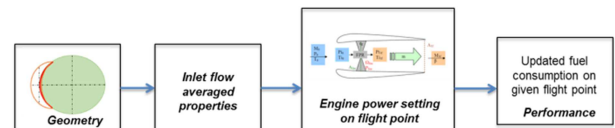


Figure 5 - Schematic of the BLI L1 module.

3.2. DLR - Aircraft Design Workflow in RCE

The overall aircraft design workflow embedded in the Remote Component Environment RCE [4] is

utilized for the analysis of the BLI-SFN and Multifans concepts at DLR for the SMR mission.

The total workflow consists of Level 0 and Level 1 tools which are communicating via the common language of aircraft design (CPACS) [8].

- Level 0:** The Level 0 multidisciplinary sizing process consists of the tool openAD [9] which is based on semi empirical models. It is a self-contained conceptual aircraft sizing tool which can be applied either as a standalone fast responding methodology or can be integrated into a bigger environment. Inside this bigger workflow it serves either as the initial interpretation of the TLARs (Top Level Aircraft Requirements) into a geometrical model and performance characteristics or as a synthetization at the end of a higher fidelity tool structure to merge the disciplinary results into a consistent aircraft. That implies that openAD is capable of handling a various set of inputs between the minimum required and the maximum available without over constraining the methodology.
- Level 1:** The Level 1 workflow consists of a series of disciplinary tools based on semi-empirical and physics based models. The integrated disciplines are described below:
- Aerodynamic:** The aerodynamic performance is calculated by the tool LIFTING_LINE [10] which is a vortex lattice method that calculates the lift, the induced drag and the pitching moment of the lifting surfaces. A second module called HANDBOOK_AERO is used to calculate the viscous drag of the aircraft.
- High Speed Performance:** The aircraft mission calculator (AMC) is a 2D stepwise high speed performance tool with trim drag calculation capabilities.
- Propulsion:** The turbofan engine performance is provided by DLR's gas turbine performance code GTlab (Gas Turbine Laboratory) [11][12].
- Wing Mass:** The structural mass of the wing is estimated by the tool CLA [13] which is a reduced order model of aero-elastic FEM calculations.
- BLI related Methodology:** The power saving coefficient (PSC) which takes only the positive effects due to the reduced momentum at the intake into account is calculated with the actuator disc theory. The boundary layer height as well as the momentum deficit flow captured by the intake is estimated by converting the drag which is produced by the

body in front of the propulsion unit. This method is also described in [14]. The reduced fan efficiency due to the disturbed inflow is extracted from a coupled high-fidelity 3D-CFD simulation with thermodynamic overall engine simulation.

3.3. DLR - Aircraft Design Environment MICADO

The aircraft design environment MICADO (Multidisciplinary Integrated Conceptual Aircraft Design and Optimization, that is a licensed product of the ILR of RWTH Aachen University) [5] is used for the design and analysis of the Annular fan and the Common Inlet concepts at DLR. MICADO consists of loosely coupled modules that represent the major disciplines in the conceptual aircraft design. It utilizes a combination of low level physics based and semi-empirical methods and uses thermodynamically calculated engine maps. MICADO also enables to perform automated parameter studies and optimization. Risse describes the detailed design methodology of MICADO (Figure 6) in [17].

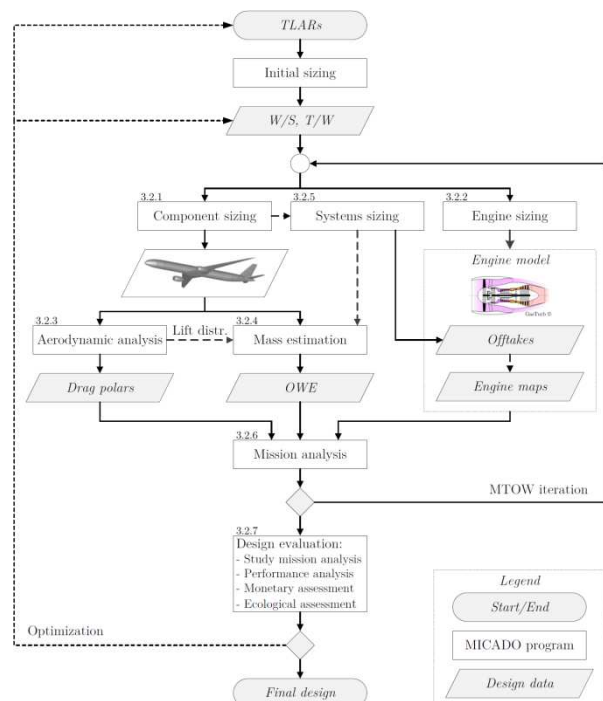


Figure 6: MICADO workflow [17].

For the assessment of configurations with BLI, modifications have been introduced to MICADO. The major adaptation is related to the consideration of the impact of the reduced inflow velocity for the BLI-engines. A convenient way to calculate this impact is the PSC as proposed by [6] for an actuator disc. The approach chosen for

these studies is similar, but the altered inflow Mach number is provided directly to the engine model. Instead of calculating the PSC, the impact of it is embedded in the SFC value. This means that the evaluation of the fuel flow is performed considering the reduced Mach number calculated at the intake plane. The thrust requirement for the engines on the other hand is calculated at the free stream Mach number for the complete airframe. As in [6], the BLI engine has to provide the same thrust as an engine without a BLI impact. But due to the lower inflow Mach number, the power required for the BLI engine to generate this thrust is reduced. The average Mach number at the intake is calculated based on the turbulent flat plate boundary layer theory [16].

Since the engine deck used for the analyses is calculated assuming free stream conditions, this simplistic approach leads to an error regarding the total temperature in the flow. Also, the impact of the inflow distortion is not taken into account. The results regarding the BLI impact are hence considered optimistic.

4. ANALYSES AND RESULTS

In this chapter the analyses and the results related to the individual configurations are described.

4.1. Reference Configuration

The CERAS CSR-01 database [7] serves as the common conventional reference configuration. It is utilized for the validation and calibration of tools for ONERA and DLR.

On the ONERA side, the ability of the MYSTIC tool to reproduce the results of the CSR-01 upon the same TLAR has been documented in [15]. On the DLR side, the same tool as the one used to model CSR-01 (MICADO) was used for the design of novel configurations.

In order to account for the impact of advanced technologies, as utilized for the BLI configurations, an advanced reference is used by DLR. It was optimized w.r.t. the wing loading and the thrust to weight ratio. The advanced technologies applied are listed in [2].

In the following sections, the results obtained by ONERA and DLR for the four configurations are presented and analysed separately. All these results are compared to reference configurations described above, i.e. the CERAS CSR-01 for ONERA (with current technologies), and the advanced one for DLR (with advanced

technologies). Therefore, both comparisons capture the only effect of the BLI technology, and should give the same order of magnitude for DLR and ONERA.

It is also important to note that all ONERA results are based on the L1 BLI module described in §3.1.

4.2. SFN-BLI

4.2.1. ONERA

In order to have a first evaluation at aircraft level of the potential of this first configuration, several important assumptions have been made. First in terms of parameterization, an embedded ratio of 0.6 (60% of nacelle diameter buried) and a k-ingestion factor of 0.0 have been considered (only the flow directly in front of the nacelle is ingested, see §3.1). The aerodynamics performance have been evaluated taking into account the reduction of the wetted area due the absence of the pylon and the buried nacelles but for the mass breakdown, no specific mass penalty has been added compared to a classical rear fuselage engine integration. Indeed, it was supposed that the reduction of the mass due to the reduction of the size of the structural elements connecting both engines was compensated by additional masses required due to this new integration (shielding between both engines for instance). The impact of BLI was evaluated using the PSC (Power Saving Coefficient = $\frac{P_{NOBLI} - P_{BLI}}{P_{NOBLI}}$, where P is the Power provided by each engine to ensure the Thrust/Drag equilibrium in cruise) integrated in the overall performance evaluation through a correction on the lift-to-drag ratio (L/D). In terms of fan efficiency, a 1% penalty was assumed due to the incoming distortion upstream of the fan stage.

The final performances of this configuration are detailed in Figure 7. They are compared with the reference underwing CERAS-CSR01 configuration and with the performances of the three other BLI concepts. For this configuration, the ingestion of the boundary layer does not enable to improve the performance of the coefficient (PSC slightly negative). Indeed the increase of the propulsive efficiency (pure BLI effect) is counterbalanced by the decrease of the fan efficiency. The increase of L/D is due to the important reduction of the wetted area slightly compensated by the rear engine integration (small increase of the size of the Horizontal Tail Plane – HTP). A very small increase of the Maximum Take-off Mass (MTOM) is observed which leads at the end to a small reduction of the fuel burned

for the whole mission (-0.5% compared to the reference configuration with under wing mounted engine). It is important to remind that this rear engine integration is responsible for approximately a 2% increase of the fuel burned compared to an underwing integration. This means that compared to a rear fuselage mounted engine configuration, the gain of the SFN-BLI configuration would have been around 2.5% (decrease of the fuel burned).

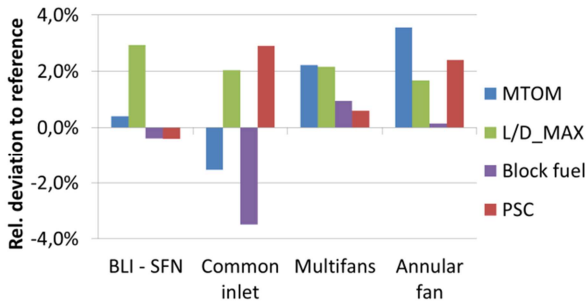


Figure 7: ONERA - Overall performances of the four BLI concepts.

4.2.2. DLR

The Side Fuselage Nacelle (SFN) concept of DLR is equipped with two conventional turbofan engines partially integrated into the rear part of the fuselage together with a T-tail empennage. It has the same aircraft technology assumptions as the reference with the same design mission and a redesigned wing and tail.

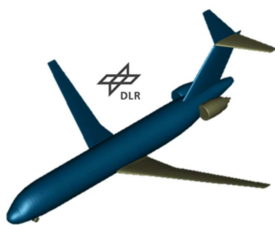


Figure 8: DLR BLI-SFN configuration.

The advantages of this configuration are: the BLI effect due to reduced intake momentum (PSC), the reduced pylon mass due to better transmission of forces, the reduced nacelle mass, the reduced wetted area of the pylons, nacelles, and the fuselage.

The main disadvantages are the fan efficiency loss, that is common for all BLI configurations and the configurational effects because of the engines shifted further to the rear in order to maintain the cabin space.

In Figure 9, the comparison between the DLR's SFN configuration and the corresponding

reference aircraft is drawn. The analysis shows that the SFN concept offers a reduction in MTOM by 1.5%, an improvement in L/D by 3%. The SFC in cruise is reduced by 0.5%. The final block fuel saving is 2.4%.

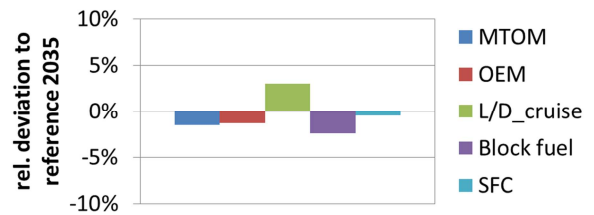


Figure 9: DLR BLI SFN configuration - Overall performances.

4.3. Common Inlet

4.3.1. ONERA

For the common inlet configuration, different values for both BLI parameters (see §3.1) have been considered. Both embedded and k-ingestion ratios have been fixed at 1.0, which means that the engine is fully embedded within the external shape, and the BL of the whole fuselage is ingested.

For the evaluation of the overall performance, similar assumptions, compared to the SFN-BLI concept, have been done. The reduction of the wetted area has been accounted for aerodynamics, no mass penalty has been considered and the PSC has been integrated in the performance evaluation process through a correction of L/D. Furthermore, the distortion upstream of the fan stage has been considered as more severe than for the first configuration, a penalty of 3% on the fan efficiency has been applied (value linked to the embedding ratio).

The results are depicted in Figure 7. As expected, the PSC is higher than on the previous configuration (3.5%) as 100% of the fuselage boundary layer is ingested by both engines even if a strong fan efficiency penalty is applied. The increase of L/D is very slightly lower than on the SFN-BLI concept. Overall, it leads to a small reduction of the MTOM (1.5%) and an important reduction of the fuel burned compared to the reference underwing configuration (3.5%).

4.3.2. DLR

The "Common Inlet" configuration offers several advantages. The wetted area is reduced due to the engines embedded in the fuselage. The circumferential common inlet captures a large

amount of boundary layer at the fuselage (only upfront the intake). The small lateral spacing of the engines reduces the yaw moment in case of engine failure. Therefore, the vertical tailplane area can be reduced. The highly integrated engines are also beneficial in terms of noise.

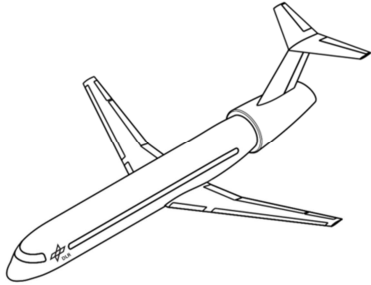


Figure 10: DLR Common Inlet configuration.

At the same time, there are disadvantages caused by this concept. The engines have to be integrated comparably far aft in the fuselage, thus shifting the center of gravity backward. The shift of the CG leads to a significant backward shift of the wing. This reduces the lever arm available for the empennage thus leading to an increased size of it. Also, the mass of the fuselage is increased due to the loads introduced by the engines. For buried engines, an air duct with a complex geometry is required. It increases drag and mass. Due to the location of the intake in the vicinity of the pressure bulkhead, a notable amount of flow at the rear fuselage cannot be captured. The proximity of the engines increases the probability to damage the second propulsor in case of uncontained engine failure.

For the design of the “Common Inlet” configuration of DLR, the following procedure is applied. The same static margin at cruise conditions as for the reference aircraft is required. The HTP volume coefficient as for the reference is used. The VTP volume coefficient is reduced by 10% due to the small yaw moment caused by an engine failure and the T-tail arrangement. The same field length requirements and approach speed as for the reference are applied. The same wing aspect ratio and the same high lift system as the reference configuration are used.

For the first analysis, several simplifying assumptions have been made. The mass penalty due to the complex fuselage structure and the shielding required to prevent an uncontained engine failure are neglected. The impact of the operating engine on the fuselage drag is not considered. The improvement of the aerodynamic performance of the wing due to fuselage mounted

engines is not taken into account. The growth of the boundary layer in the duct and the efficiency loss of the fan due to a distorted inflow are neglected. Parameter studies have been performed in order to evaluate the impact of the mass and the BLI.

In Figure 11, the analysis shows that compared to the advanced reference configuration the Common Inlet concept offers a reduction in MTOM by 4. The L/D is 4.2% smaller. The SFC in cruise is reduced by 4.6%. The final block fuel saving is 4.2%.



Figure 11: DLR Common Inlet configuration - Overall performances.

A detailed decomposition of effects in Figure 12 shows that the mass of the propulsion system is reduced by 20% due to the absence of pylons and nacelles. The mass of the fuselage is increased by 9% due to modified rear section and engine integration. The VTP is 7% heavier and the HTP is 26% heavier compared to the reference because of the reduced lever arm. The total viscous drag is the same as for the reference. The benefit related to the engine integration is alleviated by the increased size of the empennage. A high trim drag is responsible for further deterioration in L/D ratio. It is assumed, that an optimization of the wing location and the volume coefficient of the tailplane might reduce this penalty thus improving the performance of this concept.

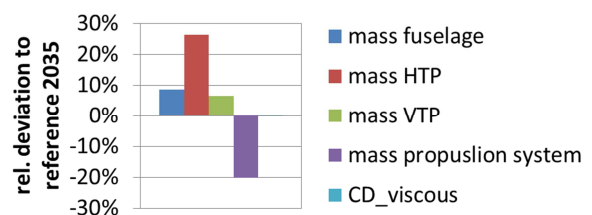


Figure 12: DLR Common Inlet configuration - Comparison of component masses and drag.

Additional parameter studies address the major uncertainties of this concept. They indicate that 5% increase in fuselage mass corresponds to 1% increase in block fuel consumption. An increase in

fuel flow by 1% leads to an increase in block fuel by 1.2%.

Finally, the impact of BLI as estimated by the aforementioned method is evaluated. This analysis is performed at overall AC level including the corresponding snowball effects. The consideration of the BLI effect leads to an improvement in SFC of about 5%. The impact on block fuel is 5.2%. The Impact on MTOM and L/D is about 1%.

4.4. Multifans

4.4.1. ONERA

For this third configuration, the geometrical parameters have been fixed at 0.6 and 0.5 respectively for the embedded and k-ingestion ratios. As compared to the BLI-SFN configuration, it means that a larger part of the fuselage BL is ingested.

To evaluate to performance of this configuration, as for the other concepts, several assumptions have been made. The reduction of the wetted area is taken into account to evaluate the drag of the configuration and a mass penalty of 10% of the propulsive weight is applied to account for the complex mechanical structure of the multifans engine (based on mechanical shafts and gear boxes, it is reminded that no electric propulsion is used in this study). For the fan efficiency, the intensity of the upcoming distortion has been considered stronger than on the BLI-SFN concept but lower than on the Common Inlet concept (i.e. proportional to the part of the fuselage boundary layer ingested by the engines, around 2%).

The results are presented in Figure 6. As anticipated, the value of the PSC ranges between both previous configurations (0.6%). The gain due the pure BLI effect is largely counterbalanced by the fan efficiency penalty. The reduction of the wetted area is responsible for the increase of L/D of about 2%. This value is comparable with the 2 previous configurations. The mass penalty applied on the propulsion weight is responsible for an important decrease of the overall performance leading to an increase of the MTOM by 2% and of the fuel burned by 0.9%.

4.4.2. DLR

The Multifans configuration of DLR has in total 6 fans propelled by two turbofan engines. The power is transmitted mechanically from one turbofan to two additional fans on each side of the T-tail.



Figure 13: DLR Multifans configuration.

The proposed advantages of the Multifans configuration are: the BLI effect due to reduced intake momentum (PSC), the comparably high amount of boundary layer captured, the reduced wetted area of the pylons, nacelles, and fuselage.

The major disadvantages are the fan efficiency loss, the increased static margin in mid cruise, due to higher influence of the payload on the center of gravity travel, the increased engine mass due to the additional mechanical power transmission system, the corresponding transmission losses (1-2%), the multiple small fans with a lower efficiency than a large fan and the increased wetted area of multiple nacelles and intake ducts.

Due to the uncertainty related to the mass of the transmission system, several scenarios have been considered. In Figure 14, the results showing the relative deviation in block fuel consumption depending on the SFC for different masses of the transmission system are shown. The TSFC is influenced by the increased internal wetted area, the transmission losses, the influence of the boundary layer at core engine, and the increased Fan-efficiency losses due to the small size compared to the BL height and hence the strongly increased relative turbulence. It can be pointed out that for the proposed scenarios, no gain in block fuel consumption can be observed.

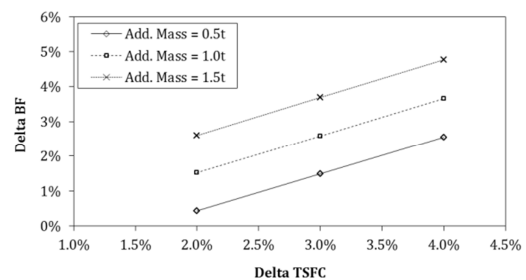


Figure 14: DLR Multifans configuration - Impact of propulsion weight penalty on fuel burned.

4.5. Annular fan

4.5.1. ONERA

For this last configuration, a dedicated parameterization has been defined in order to deal with the third engine located at the rear of the fuselage. In this study, after a parametric analysis, the proportion of the thrust provided by this third engine has been fixed to 20% which represents approximately the contribution of the fuselage drag (friction component) to the overall drag. In the sizing process, the two other engines have been designed taking into account the contribution of the third engine to the overall thrust. The mass of this third engine (and especially its fan mass with a larger diameter due to annular integration) has also been integrated in the total weight of the concept leading to negative snow ball effects. As for the common inlet concept, a fan efficiency penalty of 3% for the third engine has been applied considering that 100% of the fuselage boundary layer is ingested by this third engine.

The results are detailed in Figure 6. The value of the PSC (2.4%) is comparable with the one of the Common Inlet configuration as all the boundary layer of the fuselage is ingested. This latest is nevertheless slightly lower because the third engine contributes only to a small part of the overall thrust (contrary to both engines on the Common Inlet concept). The reduction of the wetted area is limited (1.5%) compared to all other concepts as the integration of the two main engines is identical to the reference configuration. They are only slightly smaller as they provide only 80% of the total thrust (100% on the reference). Due to the third engine located at the rear of the fuselage, the mass penalty is relatively important leading to an increase of the MTOM by 3.6%. In terms of fuel burned, the different positive and negative effects results in a very small increase of the fuel burned (0.1%) compared to the reference underwing mounted engine configuration.

4.5.2. DLR

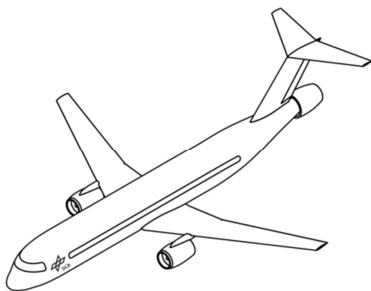


Figure 15: DLR Annular Fan configuration.

The “Annular Fan” configuration offers the benefit of a comparably simple integration of a boundary layer ingesting propulsor at the fuselage. Due to the distribution of engines the impact on the center of gravity is moderate when compared to the Common Inlet configuration. The tail strike is critical for a configuration with an aft fan. The small, rearward shift of the CG that is observed on the Annular Fan configuration prevents the requirement for an increase of the landing gear length. For the three engine configuration, the size of the vertical tailplane can be reduced compared to a twin-engine arrangement. Also, the T/W ratio can be reduced because of the reduced thrust loss in case of an engine failure.

The distribution of the thrust from two large to three smaller engines leads generally to a reduction in efficiency. Also, a higher mass and a larger wetted area expected. The size of the empennage is increased due to the shorter lever arm available.

For the design of the “Annular Fan” configuration the following is applied: The same static margin at cruise conditions as for the reference aircraft is required. The HTP volume coefficient as for the reference is used. The VTP volume coefficient is reduced by 5% due to the T-tail arrangement. The same field length requirements and approach speed as for the reference are applied. The same wing aspect ratio and the same high lift system as the reference configuration are used.

For the first analysis, several simplifying assumptions have been made. An equal thrust share for all engines is assumed. The mass penalty for the fuselage due to an additional engine is neglected. The impact of the operating engine on the fuselage drag is not taken into account. The distortion of the fan due to non uniform inflow profile caused by the vertical tailplane is neglected.

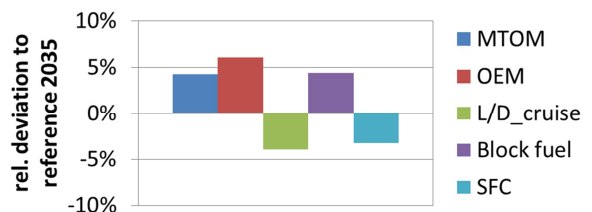


Figure 16: DLR Annular Fan configuration - Overall performances.

The analysis shows that compared to the advanced reference configuration the Annular Fan concept offers an increase in MTOM by 4%, a

reduction of L/D by 4%, a reduction in SFC of 3% for the whole propulsion system, and an increase in block fuel mass by 4%.

A detailed decomposition of effects shows that the mass of the propulsion system is increased by 14%. The mass of the VTP and HTP are respectively 20% and 23% higher than the reference. The additional nacelle and the larger empennage are responsible for an increase in the total viscous drag by 9%.

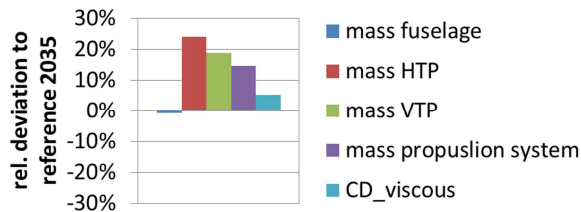


Figure 17: Comparison of component masses and drag.

Additional parameter studies indicate that 10% increase in fuselage mass corresponds to 1.6% increase in block fuel consumption. An increase in fuel flow by 5% leads to an increase in block fuel by 6%.

Finally, the impact of BLI is evaluated at overall AC level including the corresponding snowball effects. The consideration of a lower inflow Mach number leads to a reduction in SFC of about 9% for the engine that is affected by BLI. Thus, the impact for the whole propulsion system is around 3%. The block fuel is reduced by 3.3%. The impact on MTOM and L/D ratio is about 1%.

5. Comparison of BLI engine integration concepts

In this first part of the paper, the results of ONERA and DLR have been described independently in order to understand the different assumptions made by each partner and their impact of the final performance of each concept. In this second section, the overall performances are compared with a focus on the fuel consumption which represents the main key performance indicator (KPI) to discriminate the different concepts.

5.1. Overall performance

It is important to remind that the results obtained by both partners of the four BLI concepts are compared with their own references. DLR considered the advanced classical configuration (with 2035 technologies) whereas ONERA considered the CERAS-CSR01 as reference without advanced technologies. This discrepancy

can explain few differences on the conclusions drawn by the partners, but does not affect the consistency of the comparison as pure effect of engine integration is searched for.

Figure 18 shows the fuel burned deviations compared to the reference configurations for ONERA (blue) and DLR (grey). For both partners, the ranking between the concepts is identical. Only two concepts enable a fuel burned reduction, the most promising is the Common Inlet concept followed by the BLI-SFN configuration. For the other concepts an increase of the fuel burned is observed, the multifans concepts being the least promising configuration.

Looking into the details of those results, even if the ranking is identical important differences can be noticed between ONERA and DLR. For the unfavorable configurations (Annular Fan and Multifans), the results obtained by ONERA are more optimistic than those of DLR. Indeed, the fuel burned increases are respectively 0.2% (Annular Fan) and 1% (Multifans) for ONERA but 4.4% and 4.6% for DLR (see Figure 18). These trends can be partially explained by the MTOM deviations which are also more significant for DLR compared to the reference concepts but can also be explained by different results obtained in terms of L/D and SFC.

On the contrary, for the most promising concept (Common Inlet), the fuel burned reduction is consistent between both partners (3.5% for ONERA and 4.2% for DLR) even if a more important discrepancy is observed on the MTOM reduction (1.6% for ONERA, 4.0% for DLR). For the second best concept (BLI-SFN), the DLR values are more optimistic (-2.4%) than the results obtained by ONERA (-0.4%). This trend is also observed on the MTOM (+0.4% for ONERA, -1.5% for DLR).

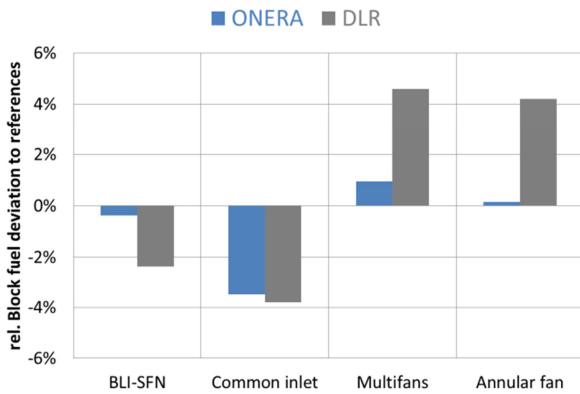


Figure 18: Fuel burned deviations of 4 BLI concepts compared to the reference configurations.

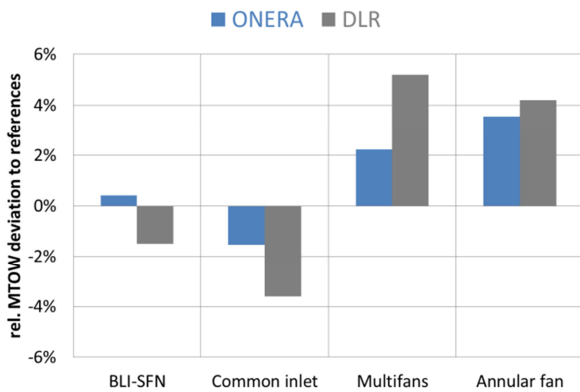


Figure 19: MTOM deviations of 4 BLI concepts compared to the reference configurations.

In order to better understand the main differences between ONERA and DLR on the two most promising concepts (Common Inlet and BLI-SFN), the impact of different effects are analysed in the ladder charts in the following section.

5.2. Ladder charts

In Figure 20 and Figure 21, the ladder charts detail the impact of different effects between the reference underwing mounted engine configuration and the new concepts.

Effect 1: Rear engine integration

This first effect corresponds to the displacement of the engines from the underwing to rear fuselage. As expected, a penalty of around 2% is observed (1.5% for ONERA, between 2.5% and 2.9% depending on the workflow for DLR) for both configurations.

Effect 2: Buried engine integration

The second effect is related to the integration of the buried nacelles into the fuselage. This effect accounts for the drag reduction based on the

wetted area, the structural masses associated to the new engine integration and the secondary integration effects. This effect is relatively important for both configurations. Indeed for the BLI-SFN concept, the positive impact on the fuel burned is estimated at 3.2% for ONERA and 4.2% for DLR. For the Common Inlet configuration, this positive impact is evaluated at 3.9% for ONERA and 2.5% for DLR.

Effect 3: Pure BLI effect – Increase of the propulsive efficiency

This third impact is directly related to basic physical principle of BLI concept, i.e. an increase of the propulsive efficiency thanks to the ingestion of the fuselage boundary layer. As expected, this positive effect is more important for the Common Inlet concept where 100% of the boundary layer of the fuselage is ingested by the engines. The estimations are 3.1% and 4.6% for the Common Inlet configuration respectively for ONERA and DLR; 0.2% and 1.8% for the BLI-SFN concept.

Effect 4: Fan efficiency penalty

The last effect accounted in this study is the estimation of the fan efficiency penalty due to the ingestion of distortions by the fan stage. On the BLI-SFN configuration, this penalty is consistent between both partners (around 1% on the fuel burned) but for the Common Inlet concept, the difference is important. Indeed, DLR neglected this penalty whereas ONERA applied a penalty of 3% on the fan efficiency leading to a fuel burned increase of 2%.

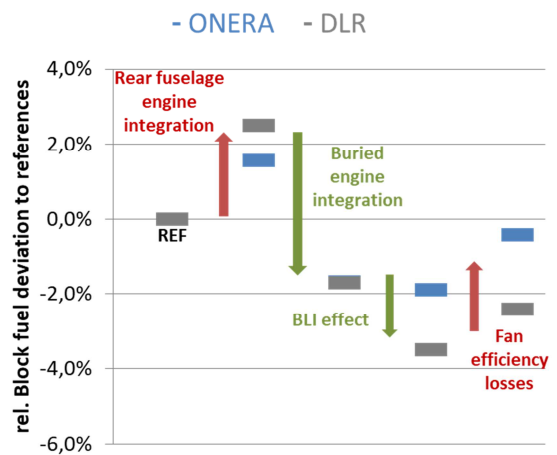


Figure 20: BLI-SFN - Ladder chart of the fuel burned deviations.

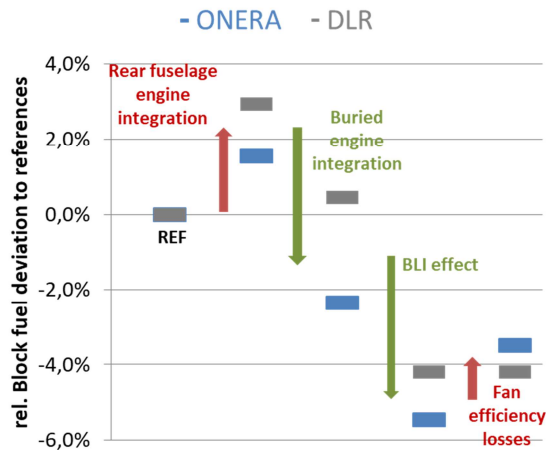


Figure 21: Common Inlet - Ladder chart of the fuel burned deviations.

6. SUMMARY

This paper summarizes the performance analysis done by ONERA and DLR on four innovative engine integration concepts including BLI at aircraft level. The detailed analysis of the results highlights a good coherence of the performance in terms of fuel burned between ONERA and DLR. Indeed, for this key performance indicator the ranking between the configurations is identical. Nevertheless, when looking at the absolute values some discrepancies can be observed especially for the two configurations with the worst performances (Annular fan and Multifans) where the ONERA results are more optimistic.

A more detailed comparison of the performance on the two best configurations (BLI-SFN and Common Inlet), shows that the different integration effects have been evaluated with few discrepancies between ONERA and DLR but which remain limited (see ladder charts).

7. CONCLUSION AND OUTLOOK

This study highlights that among the different BLI concepts assessed by ONERA and DLR, the common inlet concept seems the most promising one with potential fuel burned reduction of about 4% for a SMR mission if the results are compared with a reference underwing mounted engine. For the bizjet mission (not detailed in this paper), the results are even more promising (around 6%) as the reference configuration is a rear mounted engine fuselage configuration.

The study also demonstrates the difficulty to analyze in depth the results coming from different OAD processes especially considering various BLI concepts. Indeed, beyond the complexity of

the engine integration itself which can lead to significant differences, the way of integrating the 'pure' BLI effect is also important. The PSC can be either attributed to aerodynamics, to the SFC through the new engine sizing or to both. But no uniform methods exist in the literature up to now, and the fact that results between DLR and ONERA are in the same order of magnitude despite different approaches gives confidence in the ranking of the configurations, as well as in the expectation for the best ones.

In order to refine the results detailed in this paper, higher-fidelity analysis will be performed on the most promising concept (i.e. the Common Inlet concept) in 2020 and 2021. This work includes a detailed aerodynamic shape design of the air inlet (possibly on new aircraft concepts) to assess more precisely the PSC and characterize the upcoming distortions upstream of the fan stage.

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