

ENabling Optimized DISruptivE airframe-propulsion integration concepts

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Author(s)	**Date**	
S. Guérin (DLR)	25/09/2024	
Approved by	**Date**	
C. Schram (VKI)	26/09/2024	

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1 Introduction

Based on the work carried out in ENODISE, and supplemented by the results of other research, we give some guidelines for reducing the acoustic impact of integrating a propulsion system with the rest of the aircraft. Three types of propulsion systems are considered: propeller, fan and tandem rotors. Two different cases of integration are considered. These are illustrated in Figure 1: 1) the engine ingests the boundary layer from the fuselage, 2) the propulsion system consists of several propellers placed side by side and interacting with a wing.

The guidelines presented here have been jointly compiled by the ENODISE partners during a dedicated workshop on 4 September 2024. In this document, we first present some general guidelines and then those more specific to the different configurations considered in the project.



Figure 1: Test cases of new architecture: (left) NOVA and (right) UNIFIER19.

2 General guidelines

For the concepts under consideration, installation effects on propulsion noise are expected to be particularly important not only for propagation (e.g. through reflection from surrounding airframe surfaces) but also for generation.

There is a direct effect on rotor noise and an indirect effect due to e.g. the impact of aerodynamic interaction on rotor wakes. The noise level can be significantly increased. Therefore, in addition to aerodynamic and structural effects, acoustic effects should be considered as early as possible as part of a multidisciplinary design strategy. This also means that low to medium order methods need to be available to allow these effects to be predicted at a reasonable computational cost.

Several scenarios should be considered when designing the propulsion system. Variation of the design space in terms of engine geometry and performance characteristics should be always considered. For example, reducing the rotor Mach number while increasing the number of blades may in some cases be beneficial for noise reduction, as this can reduce both the blade loading and the sound radiation efficiency. Such trade-off studies are recommended.

Passive and active noise reduction strategies (e.g. quarter-wave resonators mounted on the wall in front of the propeller, trailing edge serrations) should also be considered at the pre-design stage, as such measures may be effective in reducing noise but may also have negative effects elsewhere (e.g. increase in overall weight).

3 Specific guidelines

3.1 Boundary-layer ingestion

The ingestion of the boundary layer to fill the velocity deficit created by the aircraft wake is a solution that improves the propulsive efficiency of an aircraft and, as a consequence, can be considered as a promising solution to reduce fuel/energy consumption. In some cases, such as when a turbofan is buried in the fuselage, it can even help to reduce the overall weight and drag.

However, the aerodynamic (or isentropic) efficiency [1] of a rotor ingesting a boundary layer decreases with the degree of inflow distortion, especially if the mean flow variation of the boundary layer is not axisymmetric. In the latter case, the rotor experience variations in flow incidence/load as it rotates. If the flow incidence is too high, it can become critical and lead to stall. In general, the rotor will generate a higher aerodynamic loss in the presence of an inflow distortion. Since the level of disturbance experienced by the rotor increases with the rotor immersion depth, it is clear that improving propulsive efficiency using BLI technology and reducing noise are inherently conflicting objectives. A compromise must be necessarily found.

However, the impact on noise emissions can be largely reduced by subtle changes in the positioning of the rotor within the boundary layer that have less effect on propulsion efficiency. By varying the distance between tip and wall, ENODISE results have shown that immersing the propeller up to the last millimetres to the wall generate a relatively large amount of additional noise for little aerodynamic gain.

It is clear that increased turbulence cannot be avoided in BLI configurations, but it should be attempted to be reduced. Thus, boundary layer separation should be avoided. If this isn't possible, the propeller should not be located in the separated region or near a reattachment point.

The propeller experiments have shown that the direction of the propeller sources is maximum in the direction of the blade normal when immersed in a turbulent boundary layer. This may provide opportunities for innovative acoustic solutions (e.g. shielding).

Mitigation methods may include active boundary layer suction, the use of vortex generators and acoustic liners.

3.2 Distributed propulsion

In distributed propeller configurations the main problem is the aerodynamic interaction between adjacent propellers. Tip-to-tip and wake interactions between propellers should be avoided by maintaining sufficient separation distance and/or by using a shroud.

Beyond a certain distance between tips, the propellers can be considered to behave aerodynamically as if they were isolated from each other. In this case, there is pure acoustic interference, which has a significant effect on the directivity pattern. The sound pressure levels increase and decrease over a much smaller distance when compared to an isolated propeller.

If it is not possible to increase the distance between the propellers, phase synchronisation may be a solution for noise reduction, at least as long as the propeller thrust (often controlled by rpm) is not used as a means of flight control.

3.3 Propeller–wing interaction

Increasing the distance between the propellers and the airframe is beneficial for noise, but different noise generation mechanisms have different sensitivities, so it is important to properly identify the dominant mechanism (e.g. potential vs. viscous interactions).

The puller configuration results in significantly lower unsteady propeller loads than the pusher configuration. In the former case, the rotor inflow is clean, whereas in the latter case the rotor absorbs the highly non-uniform and turbulent wing wake. In ENODISE the acoustic optimum was shown to be antagonistic to the aerodynamic optimum for the pusher configuration.

In the puller configuration, the rotor is expected to work more efficiently and therefore produce less noise. A large part of the noise emission is due to the wing being affected by the rotor wake. From an aerodynamic point of view, the unsteady lift fluctuations produced on the wing are not a problem, as wings are designed to withstand strong gusts.

3.4 Coaxial rotors

The counter-rotating configuration is noisier than the co-rotating configuration. Local clocking angle optima can be found for the aerodynamic performance of the co-rotating configuration. Increasing the

[1] The overall efficiency includes a product of these propulsive and isentropic rotor efficiencies.

longitudinal distance between the propellers reduces the noise emission. Compared to a shrouded rotor configuration, the non-shrouded case shows a contraction of the flow tube, which makes aft rotor cropping impractical. The addition of a shroud (originally thought to provide acoustic shielding benefits) actually increases noise emissions (tip gap noise, scattering effects), some of which can be mitigated by an over-the-tip liner.

3.5 Rotors above the wing

In ENODISE, the strongest noise emission by rotors above the wing was observed when the propellers were placed close to the wing trailing edge. There is a large sensitivity close to the Green's function singularity. Comparatively, the change of axial position of the propeller has a small effect on the aerodynamic performance. A compromise has to be found. This highlights the importance of installation effects.