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Author(s)	Date
E. Manoha (ONERA)	28/10/2024

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C. Schram (VKI)	31/10/2024

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1 Introduction

The ENODISE project, aimed at developing optimized disruptive airframe-propulsion integration concepts, involves extensive experimental research on small-scale laboratory models. This report synthesizes the applicability of these experimental outcomes to full-scale aircraft, specifically focusing on the NOVA configuration developed by ONERA, and the NUUVA V300 and UNIFIER19 aircraft concepts developed by Pipistrel Vertical Solutions.

The ONERA NOVA configuration (fig. 1, left) represents a large commercial transport aircraft. It was of particular interest to assess whether the NOVA airliner, with its unique lifting fuselage and glider-like airframe, would be viable with DEP engines instead of the BLI engines being explored in other projects. The NUUVA V300 and UNIFIER19 (fig. 1, middle and right), respectively a cargo eVTOL and a 19-PAX miniliner, are two concepts of pylon-mounted DEP system proposed by Pipistrel Vertical Solutions as relevant to general aviation and future UAM vehicles.

This synthesis includes an evaluation of the representativeness of the experimental configurations, suggestions for future research improvements, scalability of numerical methods, optimization approaches, and flow control technologies.

2 Extrapolation of ENODISE outcomes towards the NOVA aircraft

2.1 Representativeness of ENODISE Configuration A

Configurations A1 and A2 were primarily investigated to replicate the flow conditions similar to those experienced by the ONERA NOVA concept. Configuration A1 represents a simplified version of Boundary Layer Ingestion (BLI) but does not fully capture the performance characteristics due to the lack of full fuselage simulation. Configuration A2, on the other hand, includes a ducted setup mounted on an S-plate, which is more representative of a real aircraft nacelle despite differences in turbulent boundary layer (TBL) development over the fuselage.

The inflow distortion mechanisms observed in ENODISE's Configurations A are significant as they represent the distortion ingested by a propeller. However, in the case of the rear-mounted propeller on the NOVA concept, the flow tends to be more axisymmetric, diverging from the 2D flow conditions of ENODISE Configurations A. Acoustic reflections and refractions also differ between the experimental setups and the full-scale NOVA aircraft due to varying geometric and aerodynamic conditions. For instance, the acoustic refraction caused by non-homogeneous mean flow is markedly different in wing/full-body aircraft configurations compared to the simplified models used in ENODISE.

2.2 Future improvements necessary to improve the applicability of experimental configurations A towards full scale

To improve the applicability of the configurations A towards full-scale systems, several enhancements are recommended by the ENODISE Consortium.



Figure 1: Aircraft architectures considered to evaluate the extrapolation of the ENODISE research outcomes towards full-scale. Left: ONERA NOVA, middle: Pipistrel Nuuva V300, right: Pipistrel UNIFIER19.

- **Artificial Generation of Realistic TBLs**: Future experiments should focus on artificially generating a turbulent boundary layer (TBL) that develops over a longer distance, particularly along an asymmetrical body rather than a flat plate. This would more accurately represent the flow characteristics seen in full-scale aircraft. Additionally, it is recommended to use a ducted rotor-stator configuration operating at more realistic conditions to simulate the flow dynamics more closely.
- **Realistic Acoustic Effects**: To better capture acoustic installation effects and sound wave directivity, a full-body aircraft model or, at a minimum, a cylindrical shape, is recommended. This would allow for more realistic acoustic simulations compared to the simplified geometries used in current configurations.
- **Optimizing the S-shaped Duct Geometry**: The S-shaped duct in existing configurations is optimized for cruise conditions but may not be the most effective design at lower speeds or at higher angles of attack, such as those encountered during take-off and landing. Refining the S-duct geometry to perform better across a wider range of operating conditions is essential for improving its applicability to full-scale systems.
- **Higher-Speed Ducted Fans**: Future experiments should utilize ducted fans with higher speeds, closer to full-scale applications. These fans should feature slender blade profiles and more realistic rotor-stator interactions. For example, the DLR CRAFT fan, used in boundary layer experiments, had a 50 cm diameter but operated at Mach numbers that were still too low compared to those of the NOVA. Using fans with more realistic blade shapes and higher operational speeds would enhance the realism of the experiments.
- **Exploring Additional Angles of Attack**: Investigating rotor systems at a range of angles of attack beyond the currently tested zero-degree configuration would help to understand the full impact of different inflow conditions on performance. Additionally, testing new shapes for the fuselage or propulsion intake surfaces could provide valuable insights into how these changes affect propulsion efficiency and boundary layer ingestion (BLI). Applying a shroud to the propulsion system and studying various nacelle designs could further refine the BLI concept.
- **Addressing Angular Inflow and Engine Stall Risks**: A closer investigation of angular inflow effects, particularly as most current experiments focus on forward inflow is recommended. In configurations like BLI, engine stall could become a significant issue depending on the maneuver, and understanding how different nacelle and intake designs respond to angular inflow will be crucial for mitigating these risks in full-scale systems.

2.3 Strategies to improve the scalability of the numerical methods to apply configurations A to full scale

Several strategies have been proposed to address the scalability concerns, considering factors such as Reynolds numbers, Mach numbers, and computational costs.

According to ONERA, the question of scalability is the same for aerodynamic and acoustic problems, meaning that a larger scale means larger Reynolds numbers leading to more grid points. High-fidelity CFD is limited by Reynolds number effects, but not hampered more by transition artifacts. Moreover, the lattice Boltzmann method (LBM) requires specific developments to reach higher Mach numbers. Finally, the analytical models as proposed by DLR remain one of the best options today, and improvements should be gained through mid-fidelity methods like panel methods and BEM.

According to DLR, scaling laws can be derived from analytical models and should remain applicable for ducted configurations. Mach and Reynolds number effects are not an issue for acoustic prediction models. However, high Mach numbers would introduce complex mechanisms (e.g. BL-shock interactions) that are not easily modeled nowadays. Acoustic analogies, in particular, may not be applicable anymore.

A promising strategy to improve the scalability of the simulations could be based on the combination of multi-fidelity methods, which have benefited from intense efforts over the past couple of years.

2.4 Applicability of optimization methods to the NOVA aircraft, and improvement strategy

Surrogate models and Artificial Neural Networks (ANNs), as proposed by Uniroma Tre, are effective for full-scale configuration optimization, especially when combined with low-order methods for parametric studies and optimization. A multi-fidelity approach holds promise for enhancing the limits of optimization. For DLR, the analytical methods used in ENODISE remain useful for assessing trends in acoustic impacts based on engine and operational parameters. Additionally, the actuator line source model, paired with LEE, provides a balance between low-cost analytical methods and high-fidelity simulations.

2.5 Potential towards full scale of flow control technologies studied on Configurations A, and possible certification showstoppers

ONERA suggests that trailing edge modifications, which have already been successfully implemented on full-scale wind turbines and turbofan nacelles, are relatively cost-effective. The primary concern with such modifications would be potential structural issues arising from extreme geometric changes. In contrast, while acoustic liners have been used in full-scale engine nacelles, they remain a more exploratory option for mitigating boundary layer ingestion (BLI) installation effects. Additionally, shape morphing of the S-duct using deformable surfaces could improve the quality of the ingested flow across a broader range of operational conditions, including cruise, takeoff, and landing phases.

According to the University of Bristol, trailing-edge blade serrations have shown promise in reducing high-frequency noise. However, further research is required to evaluate the impact of leading-edge serrations on turbulence-induced noise and any potential penalties in thrust performance. These leading-edge modifications may also raise safety concerns, particularly regarding their impact on bird strike resilience. Furthermore, while porous media and acoustic liners present a potential solution for noise mitigation, their maintenance may be challenging due to dirt and grime accumulation. This issue calls for additional research into material science and the durability of such solutions.

From UTWE's perspective, addressing safety concerns related to the fuselage and nacelle shapes is critical for understanding and mitigating risks associated with blade stall and fan/compressor surge. Flow control techniques, such as vortex generators and active boundary layer control (e.g., suction), could be explored as potential methods to reduce these risks while also mitigating BLI noise.

3 Extrapolation of ENODISE outcomes towards towards the UAM aircraft (NUUVA V300 / UNIFIER19)

3.1 Representativeness of ENODISE Configuration B and C

Configurations B1, B2, and C in the ENODISE experiments are analyzed with respect to their applicability to the NUUVA V300 and UNIFIER19 aircraft concepts. The NUUVA V300, which lacks a tractor configuration where a propeller blows air over the wing, differs significantly from the ENODISE setups. The UNIFIER19, however, aligns more closely with the tested configurations due to its use of closed propellers and the associated installation effects.

The differences between the ENODISE configurations and full-scale concepts include variations in propeller positioning (upstream vs. downstream of the wing), the presence of contra-rotating propellers, and the installation effects due to support arms. These factors influence the aerodynamic behavior, such as blade-vortex interaction (BVI) and wake interactions, which are critical in understanding noise generation and propulsion efficiency in full-scale applications.

3.2 Future improvements necessary to improve the applicability of experimental configurations B and C towards full scale

To improve the applicability of experimental configurations B and C for full-scale aircraft, several future improvements have been identified by the ENODISE Consortium across various experimental setups and methodologies.

- **Enhancement of Experimental Representativeness**: The B3-VTOL configuration, with a rod placed beneath the propellers, would improve the setup's fidelity for a full-scale NUUVA V300. Using a pusher propeller behind a cylinder that represents the fuselage will further improve the accuracy of the pusher propeller configuration.
- **Forward Flight Effects and Propeller Layout**: It is essential to account for forward flight effects to simulate real-world propulsion system behavior. It is worth considering changing the propeller layout to a quadcopter configuration to investigate upstream-downstream propeller interactions in forward flight. Furthermore, integrating a simplified cabin model is recommended to assess its impact on flow dynamics and acoustic fields.
- **Scaling Up Propeller Size and Operational Conditions**: Scaling up the size of the propellers and comparing their effects with those of smaller propellers previously studied will help understand scaling effects and their impact on performance. Investigating realistic operational conditions such as takeoff, cruise, and landing, with particular attention to varying angles of attack during these phases of flight is recommended. Include high-solidity rotors or fans in the analysis to better understand their impact on aerodynamic performance and noise generation.
- **Staggered Propeller Configurations**: Explore staggered propeller configurations, which could optimize the performance of aircraft such as the UNIFIER19, and potentially reduce noise emissions.
- **Aerodynamic Optimization via RPM Modulation**:For aircraft like the UNIFIER19, modulating the RPM of propellers along the span may offer a promising method to reduce induced drag. This presents an interesting optimization challenge for the propulsion system design.
- **Reduction of Propeller-Airframe Separation and Investigation of Tip-Tip Interactions**: Reduce the separation between the propeller planes and the leading edge of the wing to investigate potential viscous interactions that could affect aerodynamic performance and noise emissions. Investigating tip-tip interactions, especially in larger configurations, to assess their impact on overall system performance is also recommended.
- **Study of Propeller-Wing Interactions in Pusher Configurations**: In the case of the UNIFIER19, the pusher propeller ingests both the boundary layer (BL) developing over the fuselage and the wakes from the Y-tail empennage. This combined interaction requires further study, as it may have significant effects on flow dynamics and acoustic characteristics.

3.3 Strategies to improve the scalability of the numerical methods to apply configurations B and C to full scale

As for the NOVA configuration, ONERA maintains that high-fidelity simulations will be constrained due to the significant computational cost associated with Reynolds number effects. An analytical model, such as the one proposed by ECL, remains a viable option, though further advancements are expected to arise from mid-fidelity approaches like panel methods and Boundary Element Methods (BEM), as suggested by ONERA and Uniroma Tre for configuration B.

DLR highlights that analytical models can effectively account for scale effects, including variations in size, blade profile shapes, and operational speeds. From an acoustic perspective, the impact of compressibility (Mach number) and viscosity (Reynolds number) is minimal. The actuator line model proposed by DLR offers a favorable trade-off between computational cost and accuracy, making it suitable for this context.

The numerical approach developed by RWTH (Aachen University) utilizes unstructured hierarchical Cartesian meshing and solution-adaptive mesh refinement (AMR), which is already optimized for "exa-scale" computing hardware. This method could potentially be used for large-eddy simulations (LES) of the full-scale NUUVA V300 propulsion system operating at low Mach number conditions to assess aerodynamic and aeroacoustic performance. However, due to the high computational demands, this approach is not feasible in the short term for full-scale simulations. For specific scenarios, such as propeller/airframe interaction noise, simplified setups—similar to those used in the ENODISE configurations—could be developed. These would reduce computational costs while allowing for the application of the numerical method. Furthermore, noise reduction strategies, such as the use of porous materials, could be revisited. While porous materials were not effective in the ENODISE configurations due to the larger distance between the propeller and the airframe, this may differ for the NUUVA or UNIFIER19 cases.

Siemens's numerical approach, as employed in the ENODISE project, combines finite-volume CFD flow simulations with frequency-domain finite-element models for sound propagation. This method is theoretically applicable to simulating the full-scale NUUVA V300 propulsion system. However, the primary bottleneck lies in the computational cost of flow prediction. Strategies that exploit the symmetries in interactions between adjacent components—similar to the approach used by RWTH for configuration B1—could offer a path forward for handling large models like the NUUVA and UNIFIER19 systems.

The numerical method developed by GPU Prime is tailored for structured grids and utilizes a sliding interface technique, making it applicable to the full-scale NUUVA V300 system. However, its application may be limited in high Reynolds number and Mach number regimes. Extending the study of propeller-wing interaction noise to larger scales would require increased grid resolution. However, recent updates to the code, including its adaptation for multi-GPU use, have alleviated this limitation, allowing for more scalable simulations.

3.4 Applicability of optimization methods to the NUUVA V300 / UNIFIER19 and improvement strategy

ONERA acknowledges the potential of surrogate models and Artificial Neural Networks (ANNs), as proposed by Uniroma 3 for configurations A, B, and C, to push the optimization boundaries for full-scale NUUVA and UNIFIER19 configurations. The approach suggested by VKI is considered a good representation of current capabilities, combining high-fidelity simulations (URANS) with a parametric study for broadband noise, and an optimizer applied to low-order methods.

According to VKI, the panel method (specifically FlightStream) shows promise as a tool for aircraft optimization by providing reasonable estimates of the loads on propeller blades, including potential interactions with the downstream wing and between propellers. However, its ability to predict the loads on downstream components, such as the wing affected by propeller wakes, still requires further validation.

At GPU Prime, the optimization method that combines LES simulations on a coarse grid with the MAM optimization technique holds promise. However, a major challenge is establishing a seamless workflow between the MAM tool and LES simulations, as mesh modifications are required at each new design iteration. While the use of GPUs for LES reduces computational time, the iterative process of adjusting the mesh at each design point remains a significant obstacle.

For DLR, the analytical methods used in ENODISE remain valuable for evaluating trends in the acoustic impact of design choices, such as the number and shape of the blades and operational parameters like inflow Mach number and angle of attack. Additionally, the actuator line model proposed by DLR offers a favorable balance between computational cost and accuracy.

3.5 Potential towards full scale of flow control technologies studied on Configurations B and C, and possible showstoppers

ONERA's opinion regarding the BLI concept is consistent with what was said for configuration A: trailing edge modifications, already implemented in full-scale wind turbines and turbofan ducts, are cost-effective, with only potential structural concerns arising from extreme geometric changes. In contrast, the use of liners, although employed in full-scale engine nacelles, remains a more exploratory approach for mitigating BLI installation effects.

RWTH suggests that a tractor configuration can significantly reduce the unsteady load noise generated by the propeller, compared to a pusher configuration. Increasing the clearance between the propeller and the airframe may also help lower unsteady loading noise. Additionally, porous liners could be installed on the airframe to further reduce noise levels. For distributed propellers with small tip clearances, phase synchronization technology could help minimize tonal noise. This approach may be particularly useful for a UNIFIER19 DEP configuration, where flight control is managed by control surfaces and the propellers are not used for yaw control. However, in a NUUVA-like aircraft, which relies on RPM variations for attitude control, the phase can therefore not be maintained to ensure destructive interferences between rotors.

Siemens highlights that flow control technologies, such as variations in propeller separation, installation angles, and rotor synchronization, offer promising noise reduction potential without requiring modifications to propeller geometry, unlike concepts such as blade serrations or lined ducts. Additional research is needed to determine if these non-intrusive strategies can effectively reduce noise in full-scale geometries and meet certification standards.

VKI suggests that for coaxial co-rotating systems, the clocking angle between the two propellers could serve as a viable flow/noise control strategy. However, based on ENODISE results for configuration C, introducing a shroud around the blades appears to be more detrimental than beneficial for noise emissions. This penalty could potentially be mitigated by using an over-the-tip liner, should a shroud be required for safety reasons, such as blade containment constraints.

DLR proposes that for the UNIFIER19, increasing blade loading, reducing the number of blades, and shortening their span could help minimize propeller-propeller interactions and associated noise.

4 Conclusion

This report synthesizes the findings from the ENODISE project, emphasizing their applicability to full-scale aircraft. The insights gained highlight the potential and limitations of the current experimental setups and numerical methods.

On the experimental side, the ENODISE configurations provide valuable insights into certain aspects of full-scale aircraft behavior, however, limitations due to differences in scale, geometry, and flow conditions have been highlighted. Further adjustments and enhanced experimental setups are required to increase the representativeness of these models for full-scale applications.

Recommendations for future research include improving experimental setups to better replicate full-scale conditions and enhancing numerical methods for scalability and accuracy. Addressing these challenges will be critical to advancing the applicability of ENODISE outcomes to full-scale aircraft.

More specifically, future projects aiming to build on ENODISE's outcomes should consider more realistic boundary layer developments, as the TBL resulting from long-distance development on a cylindrical body differs significantly from a flat plate. Furthermore, a broader range of flight conditions should be experimentally explored to better simulate real-world conditions. Integrated geometries, such as full-body aircraft or at least cylindrical models, are recommended to obtain more realistic acoustic installation effects and directivity.

To achieve higher Technology Readiness Levels (TRL), future research should also focus on developing more realistic noise mechanisms, especially those related to rotor-stator interactions and the effects of incoming boundary layers on rotor wake development and advection through stator vanes.