

ENabling Optimized DISruptivE airframe-propulsion integration concepts

H2020 Research and Innovation Action
Grant Agreement No 860103

Deliverable Reference Number: D5.9

Deliverable Title:
WP5 final public report

Lead participant: GPUP
Contributing participant(s): DLR, UR3, VKI

30 September 2024

Start date of project: 1st of June 2020
Duration: 54 months

Type		
R	Document, report	X
DEM	Demonstrator, pilot, prototype, etc.	
DEC	Websites, patent fillings, videos, etc.	
ORDP	Open Research Data Pilot	
Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (incl. Commission Services)	

APPROVAL

Title	Issue	Revision
WP5 Final Public Report	1	1

Author(s)	Date
H. A. Habid (GPUP), S. Guerin (DLR), A. Franco (DLR), L. Burghignoli (UR3), A. Bresciani (VKI)	30/09/2024

Approved by	Date
C. Schram (VKI)	30/09/2024

Contents

1 Introduction **4**

2 Task 5.1 - Configuration A **5**
- 2.1 Context and objectives . . . 5
- 2.2 Involved partners and work distribution . . . 5
- 2.3 Main achievements . . . 5
  - 2.3.1 GPUP . . . 5
  - 2.3.2 UR3 . . . 5
  - 2.3.3 DLR . . . 6
- 2.4 Lessons learnt . . . 7

3 Task 5.2 Configuration B **8**
- 3.1 Context and objectives . . . 8
- 3.2 Involved partners and work distribution . . . 8
- 3.3 Main achievements . . . 8
  - 3.3.1 UR3 . . . 8
  - 3.3.2 GPUP . . . 9
  - 3.3.3 DLR . . . 9
- 3.4 Lessons learnt . . . 10

4 Task 5.3 Configuration C **11**
- 4.1 Context and objectives . . . 11
- 4.2 Involved partners and work distribution . . . 11
- 4.3 Main achievements . . . 11
  - 4.3.1 VKI . . . 11
  - 4.3.2 UR3 . . . 11
- 4.4 Lessons learnt . . . 12

5 Conclusion **15**

1 Introduction

Work Package 5 focuses on the development of disruptive airframe-propulsion integration concepts to enhance the efficiency, performance, and environmental impact of future aircraft. This work explores the optimisation of novel propulsion systems, specifically Configuration A (boundary layer-rotor interaction), Configuration B (multi-rotor installation), and Configuration C (ducted rotors), with an emphasis on reducing noise emissions while improving aerodynamic performance. A range of computational and optimisation tools are employed, including computational fluid dynamics (CFD), computational aeroacoustics (CAA), and machine learning techniques, to model and predict noise levels in these configurations. Contributions from key partners involve high-fidelity simulations and the development of metamodels aimed at refining noise reduction strategies through the application of artificial neural networks and optimisation algorithms. Key parameters such as propeller geometry, axial positioning, and trailing edge modifications have been thoroughly investigated, yielding promising results in noise mitigation. These findings are pivotal for advancing the design of next-generation aircraft, ensuring enhanced operational efficiency and a reduced noise footprint.

2 Task 5.1 - Configuration A

2.1 Context and objectives

The objective of Task 5.1 is to numerically optimise the Configuration A setup, which investigates the wall-mounted, boundary-layer-ingested buried propulsion system. The aim is to reduce noise generation while improving the performance of airframe-propulsion integration in disruptive aircraft configurations. Two airframe propulsion integration systems are investigated corresponding to configuration A1 (ingestion of boundary layer developing over a flat-plate) and configuration A2 (ingestion of the boundary layer developed due to adverse pressure gradient, developing over S-shaped wall). The tools developed by the partners include using high-fidelity computational fluid dynamic (CFD) numerical simulations as well as the development of the metamodels to predict acoustic emissions and optimise design parameters using artificial neural networks.

2.2 Involved partners and work distribution

The partners involved in Task 5.1 were UR3, GPUP, and DLR. GPUP conducted a sensitivity study using the CABARET algorithm to analyse propeller-boundary layer interaction noise, while UR3 developed metamodels to predict acoustic emissions and optimise design parameters through artificial neural networks. DLR utilised hybrid CFD-CAA approaches to further explore noise mitigation strategies.

2.3 Main achievements

2.3.1 GPUP

The contribution by GPUP in task 5.1 focused on the numerical optimisation of noise generated by the interaction between the propeller and boundary layer in Configuration A2. The main achievement was conducting a sensitivity study using the Wall Modelled (WM) Large Eddy Simulation (LES) CABARET algorithm. This study examined the effect of different inflow velocities and propeller positions relative to an S-shaped surface. The propeller was positioned at 480 mm, 800 mm, and 1000 mm from the inlet, with inflow velocities of 15, 27, 45, 60, and 75 m/s.

The results showed that noise levels, measured as Overall Sound Pressure Level (OASPL), increased with higher inflow velocities. The highest noise was recorded when the propeller was positioned 480 mm from the inlet, likely due to stronger interactions with the boundary layer. Lower noise levels were observed when the propeller was placed 1000 mm from the inlet, where the boundary layer had more distance to develop, resulting in reduced interaction with the rotor.

The numerical simulation used a high-resolution grid with around 1 and 5 million points to simulate the flow around the propeller and accurately capture the interactions between the propeller blades and the S-shaped surface. Noise levels were computed at a 90-degree observer angle using power spectral density analysis, focusing on blade passage frequencies (BPF). Additional contribution by GPUP involved generating a database essential for further optimisation and metamodel development, contributing to the goal of reducing noise emissions in aircraft propulsion systems.

2.3.2 UR3

The contribution by UR3 in task 5.1 was the development of predictive metamodels for optimising noise reduction in Configuration A2. The methodology involved using the Active Artificial Neural Network (ANN) approach, UR3 built metamodels to predict the band-limited Overall Sound Pressure Level (OASPL) at a 90-degree observer angle. The metamodels were based on the numerical data provided by GPUP, which included propeller positions and inflow velocities.

The numerical methodology focused on automatic hyperparameter optimisation within the ANN model, improving the accuracy of noise predictions. Although the dataset was limited, the metamodel was able to provide reliable predictions, with an identified optimal configuration where the propeller was positioned 777 mm from the inlet and the inflow velocity was set to 26 m/s. This configuration resulted in the lowest predicted OASPL, confirming initial observations from GPUP's data.

UR3 also conducted an optimisation study using genetic algorithms to identify the best design parameters for noise reduction. However, they noted that the limited dataset constrained the model's accuracy, and additional numerical simulations would be necessary to improve the reliability of the metamodel. Despite these limitations, the work demonstrated successful application of machine learning techniques for acoustic optimisation.

2.3.3 DLR

The contribution by DLR in task 5.1 focused on simulating and predicting noise generated by propeller-airframe interactions in Configuration A1 (flat plate) and Configuration A2 (S-shaped plate). They employed a hybrid computational aeroacoustics (CFD-CAA) approach to model the tonal and broadband noise generated by a two-blade propeller. The numerical code employed in the study was DLR's TAU and PIANO code. The investigation included different propeller tip-gap distances (5 mm and 70 mm) and rotational speeds (6500 RPM and 8100 RPM). The aim was to understand how these factors affect the noise emission in different configurations.

For the noise computation the Linearized Euler Equations (LEE) was employed which was coupled with a rotor noise model. This model used rotating line sources to represent loading and thickness noise, based on aerodynamic predictions derived from Reynolds Averaged Navier-Stokes (RANS) computations employing an Actuator Disc (AD) model replacing the rotor geometry. These RANS calculations provided the background flow for the noise prediction models and the sources for the corresponding CAA computations. The computational mesh used for RANS simulations comprised of 20 million cells, to ensure accurate of the wind tunnel conditions, the nozzle, and the propeller geometry.

The computational mesh used for the 3D CAA simulations consists of a hierarchical Cartesian grid with a refinement region around the propeller modelled, for a total of approximately 6 mln points. A total of 5 revolutions was simulated, which is sufficient for the hybrid CFD-CAA approach to obtain a pressure signal free of transients.

The numerical results showed that the tonal noise predictions were in good agreement with experimental data, particularly for microphones positioned at a 90-degree observer angle in the overhead and side arrays. The simulations showed how the tip-gap distance and rotational speed influenced the tonal noise components, with the closer tip-gap (5 mm) generally resulting in higher noise levels. The broadband noise predictions, which included contributions from trailing edge noise and leading edge noise, were modelled using the Acoustic Perturbation Equations (APE) in combination with the FRPM model for synthetic turbulence-related noise sources prescription. While in certain cases the trailing edge noise predictions aligned well with experimental results, further tuning was identified as necessary for the leading edge noise components.

In addition to the noise prediction, the study also performed a detailed analysis of the computational cost of the modelling approach. The 3D RANS simulations for background flow required 1280 cores running for 8 hours, resulting in 10,240 core hours, while the tonal noise predictions employed 512 cores running for 1 hour, resulting in 512 core hours (20 times less than the RANS simulation). The trailing edge broadband noise simulations required a higher computational cost compared to the tonal noise predictions (34,560 core hours, 3 times more than the RANS simulation), but overall, including also the RANS and tonal noise CAA simulations, the total computational cost of the hybrid CFD-CAA approach is significantly less than a fully turbulence-resolving LES simulation for acoustic predictions (at least 1 to 2 orders of magnitude, depending on the simulated setup complexity).

Recent developments showed that there could be a reduction potential of about 1.5-3 times the stated core hours for trailing edge broadband noise predictions. Furthermore, usage of semi-empirical formulas, as in the leading edge noise prediction, could reduce further the computational effort to 0.166 core hours. It will be the subject of future work to evaluate if the expected more accurate FRPM-based predictions of broadband spectra, compared to semi-empirical models, justify the higher computational cost. So far the method demonstrated to provide a fast and robust framework for noise prediction.

2.4 Lessons learnt

The work by GPUP on configuration A showed that the propeller geometrical placement and inflow velocity significantly affect noise emissions in aircraft propulsion systems. The sensitivity study showed that closer proximity of the propeller to the downstream of the S-shaped wall, amplified the noise, particularly at higher inflow velocities. One key lesson was the need for further refinement of mesh resolution from 1 and 5 million grid point to 20 million and above to effectively resolve noise at frequencies beyond 4000 Hz.

The numerical simulation by DLR highlighted the significance of accurately modelling both tonal and broadband noise using hybrid CFD-CAA methods. The results showed that tonal noise predictions aligned well with experimental data at exceptional small computational cost, but further refinement was needed for broadband components, particularly leading edge noise. One of the major lessons was the low computational cost involved in installation noise sources predictions, indicating how higher-fidelity LES simulations would not be necessary for design-stage acoustic predictions.

The use of nueral networks and the development of metamodels by UR3, demonstrated the potential of using machine learning for noise optimisation in disruptive aircraft configurations. However, the work highlighted the limitations of using fixed datasets, which can potentially constrain the accuracy of the predictions. One key lesson was the importance of having more comprehensive datasets for training the models, especially when dealing with complex acoustic mechanism, such as those involved in boundary layer - rotor ingestion noise. Additionally, the research suggested that integrating adaptive sampling could improve prediction reliability for future optimisation studies.

3 Task 5.2 Configuration B

3.1 Context and objectives

Task 5.2 focuses on optimising the performance and noise reduction of multi-propeller airframe-propulsion integration systems, specifically in Configuration B of the Enodise project. The objective is to minimise noise levels generated by the upstream-installed propellers while improving the aerodynamic efficiency. The task specifically aims to investigate the following:

1. Investigate the impact of propeller geometrical parameters (e.g., serrations on the trailing edges) on noise reduction.
2. Perform numerical optimisation of the propeller's axial positions, phase angles, and operational parameters to reduce pressure fluctuation amplitudes and acoustic disturbances.
3. Develop models and methodologies (such as metamodelling and optimisation techniques) to quickly simulate and optimise the configuration for both performance and noise mitigation.

3.2 Involved partners and work distribution

The contributions on this task from project partners (GPUP, UR3 and DLR) involve detailed numerical simulations, metamodelling, and optimisation techniques to explore the effects of these parameters on noise and performance. GPUP focused on the numerical optimisation of configurations with serrated trailing edges; UR3 developed metamodelling and conducted multi-objective optimisation analysis; and DLR and PVS contributed through parametric studies and mid-fidelity RANS simulations.

3.3 Main achievements

3.3.1 UR3

UR3's contribution was to develop a computationally efficient approach to optimise the noise performance of the multi-propeller system, particularly the B1 configuration. For this purpose, an Active Artificial Neural Network (ANN) metamodelling technique to predict the acoustics of the propeller was setup. The ANN models were based on the dataset provided by numerical simulations performed by GPUP, as discussed in Sec. 3.3.2, which included cases with and without trailing edge serrations. ANN metamodels were developed that could accurately predict the area-averaged BL OASPL and maximum BL OASPL values as functions of key variables like the central rotor's axial position and phase angle.

In addition, a multi-objective optimisation of the propeller system using these ANN-based metamodels was performed. This optimisation aimed to minimise both the area-averaged and maximum BL OASPL. The metamodels were able to predict noise performance with sufficient accuracy to explore design variations rapidly, overcoming the need for time-consuming full-scale simulations. The predictive models covered configurations with and without serrated trailing edges, which allowed for a direct comparison of their acoustic benefits. As a result, the developed algorithm quickly identified the optimal configurations for noise reduction. The results showed that the best noise reduction in terms of maximum BL OASPL occurred when the central rotor was placed in an extreme forward position, with a phase angle of around 97◦. This configuration led to the highest reduction in noise levels when using serrated trailing edges. The use of serrations proved to be most effective at higher phase angles, particularly between 90◦ and 135◦, where noise reduction was more pronounced compared to non-serrated configurations. For the area-averaged BL OASPL, the optimal phase angle was around 5◦, indicating that the serrated trailing edges were effective in reducing overall noise at both low and high phase angles.

The work also extended to multi-objective optimisation, where the NSGAII genetic algorithm to optimise both the area-averaged and maximum BL OASPL was employed. The results showed a noise reduction of up to 1 dB in some cases. The Pareto front obtained through this optimisation demonstrated that the optimal configurations often involved the central rotor being positioned forward, with phase

angles finely tuned to minimise noise levels. Notably, the serrated configuration consistently outperformed the baseline (non-serrated) configuration, highlighting the effectiveness of trailing edge serrations in mitigating noise.

3.3.2 GPUP

GPUP's contribution in task 5.2 consisted in the detailed numerical investigation into propeller-wing interaction noise, focusing on mitigation strategies through the use of trailing-edge serrations on two-bladed Mejzlik propellers. The numerical tool employed by GPUP was the LES CABARET solver, developed and employed in Sec. 2 as well. The numerical setup included are three-propeller configuration (B1), with the propellers placed upstream of the wing in a puller configuration. The study also explored various design parameters, such as axial staggering of the central rotor and phase differences between rotors, to determine their effect on noise reduction.

The study introduced serrated trailing edges on the propeller blades, designed to reduce noise by disrupting vortex structures. A parametric analysis was conducted to compare the pressure fluctuation amplitude and noise characteristics of serrated and non-serrated propellers. The pressure-signal was obtained on the plane located underneath the propeller-wing setup. The work employed two set of criterion to evaluate the noise performance, which included obtaining the maximum pressure amplitude on the plane underneath the propeller-wing setup and maximum Band-Limited Overall Sound Pressure Levels (BL OASPL) with the signal isolated from 1st to 6th blade passage frequency.

The simulations demonstrated that serrated trailing edges could reduce noise by up to 2.5 dB, particularly at phase angles around 90°, where coherent vortex structures were most effectively modified. The optimal noise reduction was achieved when the central rotor was axially displaced forward by 0.2 propeller diameters, resulting in a marked decrease in both area-averaged and BL OASPL.

3.3.3 DLR

As part of this study, DLR has developed a method for predicting the noise emission of a given multi-rotor propulsion configuration. The focus was on the acoustic interference effects. This method allows a rapid assessment of the acoustic characteristics during the optimisation process of the pre-design. The study has identified the optimisation potential of the multi-rotor case by varying the tip spacing and relative phase of the rotors. The configurations studied have shown that the average sound emission can vary locally by up to 9 dB due to multi-source acoustic interference, and can even be lower than that of the single rotor blade configuration. These results demonstrate the complex interaction between configuration design and acoustic performance, highlighting the need for further investigation and optimisation in the field of distributed propulsion systems.

It was also observed that, for the baseline configuration, the noise associated with interaction effects predominates over the self-noise sources, while the rotor-rotor interaction appears to be the most critical noise-generating mechanism. Further analysis should be undertaken to develop a model to determine the aerodynamic interaction between adjacent rotors. This could allow rapid variation of the various parameters and help to identify the key parameters.

The contribution by DLR in this task also involved conducting a parametric study and noise prediction analysis of the configuration B, multi-rotor setup. The work employed a hybrid CFD-CAA approach to compute the aerodynamic and acoustic performance of different propeller setups, including variations in rotational speed and blade phase angle (0 and 30 deg) of the six-bladed propellers. The focus was on predicting both tonal and broadband noise components. For this, DLR's TAU and PIANO codes were employed.

For the noise computation the Linearized Euler Equations (LEE) was employed which was coupled with a rotor noise model. This model used rotating line sources to represent loading and thickness noise, based on aerodynamic predictions derived from Reynolds Averaged Navier-Stokes (RANS) computations employing an Actuator Disc (AD) model replacing the rotor geometry. These RANS calculations provided the background flow for the noise prediction models and the sources for the corresponding CAA computations. The computational mesh used for RANS simulations comprised of 20 million cells, to

ensure accurate of the wind tunnel conditions, the nozzle, and the propeller geometry. The computational mesh used for the 3D CAA simulations consists of a hierarchical Cartesian grid with a refinement region around the propeller modelled, for a total of approximately 20 mln points. A total of 5 revolutions was simulated, which is sufficient for the hybrid CFD-CAA approach to obtain a pressure signal free of transients.

The results showed that the tonal component was accurately predicted and aligned well with the experimental results. In addition, the noise reduction trends in multi-propeller setups were identified. By varying the phase angle (0 and 30 deg), between the propellers, the study demonstrated that altering the rotational phase could reduce the overall noise levels. The simulation results showed that a phase difference of 30° between the three rotating propellers yielded significant noise reductions.

In addition to the noise prediction, the study also performed a detailed analysis of the computational cost of the modelling approach. The 3D RANS simulations for background flow required 1280 cores running for 8 hours, resulting in 10,240 core hours, while the tonal noise predictions employed 2048 cores running for 1 hour, resulting in 2048 core hours (5 times less than the RANS simulation). The trailing edge broadband noise simulations required a higher computational cost compared to the tonal noise predictions (34,560 core hours, 3 times more than the RANS simulation), but overall, including also the RANS and tonal noise CAA simulations, the total computational cost of the hybrid CFD-CAA approach is significantly less than a turbulence-resolving LES simulation for acoustic predictions (at least 1 to 2 orders of magnitude, depending on the simulated setup complexity).

Recent developments showed that there could be a reduction potential of about 1.5-3 times the stated core hours for trailing edge broadband noise predictions. Furthermore, usage of semi-empirical formulas, as in the leading edge noise prediction, could reduce further the computational effort to 0.166 core hours. It will be the subject of future work to evaluate if the expected more accurate FRPM-based predictions of broadband spectra, compared to semi-empirical models, justify the higher computational cost. So far the method demonstrated to provide a fast and robust framework for noise prediction.

3.4 Lessons learnt

The results from GPUP's numerical investigation showed that serrated trailing edges on two-bladed propeller blades significantly reduced noise levels, particularly at phase angles around 90°. The study demonstrated that axial displacement of the central rotor plays an important role in noise mitigation, with forward displacement proving to be the most effective. It also highlighted the importance of high-resolution numerical grids, as further validation with higher grid density is necessary to improve the accuracy of noise predictions.

The DLR study, carried out using an analytical approach, has shown the importance of *pure* acoustic interference in a side-by-side multi-rotor configuration. The sensitivity of the results to rotor spacing and relative phase is high. Further analysis, supported by LBM simulation results, has shown that the aerodynamic interaction between the rotors can be the dominant acoustic source when the rotors are close together. The investigation by DLR also found that the hybrid CFD-CAA approach effectively predicts tonal noise in multi-propeller configurations, with close alignment to experimental results at exceptional small computational cost. For the six-bladed propeller, it was shown that varying the phase angle between propellers significantly impacts noise reduction, with a phase difference of 30° showing promising results. Further refinement of the model is required to improve the prediction of trailing and leading-edge broadband noise. One of the major lessons was the low computational cost involved in installation noise sources predictions, indicating how higher-fidelity LES simulations would not be necessary for design-stage acoustic predictions.

The work of UR3 showed that that ANNA metamodels are highly effective in predicting acoustic behaviour, allowing for rapid optimisation of noise performance. The combination of metamodels and multi-objective optimisation techniques reduced computational costs while providing accurate results. The study confirmed that serrated trailing edges and forward axial positioning of the central rotor significantly reduce noise levels, especially at high phase angles. However, expanding the dataset used for training the metamodels is necessary to further improve prediction accuracy.

4 Task 5.3 Configuration C

4.1 Context and objectives

VKI has developed a multi-disciplinary design optimization framework to improve the noise emissions of a quadcopter in forward flight while enhancing its aerodynamic performance. The design parameters are the spanwise distribution of the sweep angle and chord length of the propeller blades, with the intention of minimizing aerodynamic interactions and tonal noise emissions. Afterward, VKI investigated optimized configurations for Config. C with the noise mitigation strategy implemented. Two main noise mitigation strategies have been considered and reported in D6.3: 1) for co-rotating propellers, varying the clocking angle between the two rotors; 2) for contra-rotating propellers, using a shroud with a liner. A preliminary sensitivity study is used to determine the most interesting parameter space to be explored numerically and to provide the data for the metamodel that UR3 uses for the numerical optimization study.

4.2 Involved partners and work distribution

VKI and UR3 were involved in Task 5.3. VKI performed a numerical shape optimization on a quadcopter drone and provided the experimental data for the metamodel of UR3 for co-rotating propellers. UR3 built the metamodel and performed multi-objective optimizations.

4.3 Main achievements

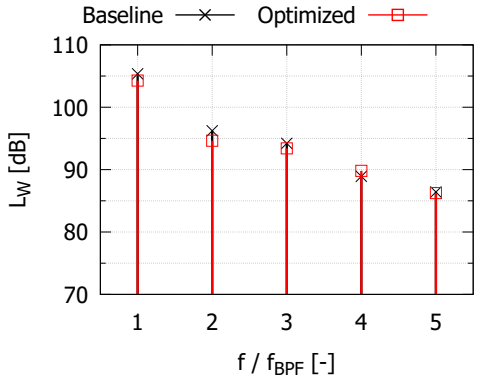
When considering the quadcopter drone optimization, it appears thus that only a small noise reduction can be obtained when selecting the sound power at the first Blade Passing Frequency (BPF), $L_{W,1}$, as the objective function, which contrasts with the significant abatement obtained when trying to minimize the sound power at the third BPF, $L_{W(A),3}$. The reason is that the Blade Loading Harmonics (BLH) that contributes the most to the first BPF is $p = 2$, since the Bessel function decays relatively fast for integer orders different from zero. However, the fact that the steady loading is one order of magnitude larger than the BLH $p = 2$ still makes it the dominant contributor to the summation, even after being weighted down by the small value of the Bessel function J_2. As a result, the optimizer is unable to reduce $L_{W,1}$ without degrading the mean lift $\overline{L}$, the latter being strongly constrained in this optimization exercise. The main results are summarized in figure 1.

4.3.1 VKI

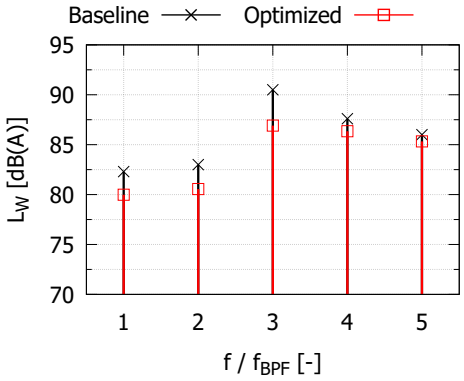
Regarding the optimization of Config. C (shrouded contra-rotating rotors with liner as noise mitigation strategy) the trends suggested that the optimum in terms of low noise levels and thrust has to be searched for large separation distances. For this reason, a numerical optimization based on the separation distance only would give an optima at the boundary of the optimization region where probably other considerations like structures, safety, and space are more important and should be considered in the design phase. Hence, a numerical optimization has not been performed for this configuration. Instead, when considering co-rotating co-axial propellers the maximum in the figure of merit is observed for a clocking angle of -20°, i.e. with the front propeller leading, at a distance of 28 mm. Low levels of broadband noise are noticed for approximately the same combination of axial distance and clocking angle, while the tonal noise is minimal for large clocking angles. These results, summarized in figure 2, confirm the findings of previous literature and allow UR3 to perform a multi-objective optimization of the axial separation and clocking angle.

4.3.2 UR3

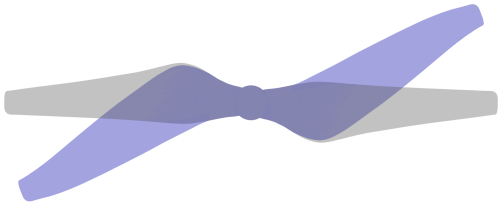
The experimental data provided by VKI for Conf. C with coaxial co-rotating open rotors were used by UR3 as input for the in-house developed Active Artificial Neural Network to build metamodels for both tonal and broadband noise and the figure of merit as functions of the axial spacing between the rotors and the clocking angle. These metamodels enabled a multi-objective optimization study to identify potential trade-off configurations between emitted noise and aerodynamic performance. In particular, three distinct



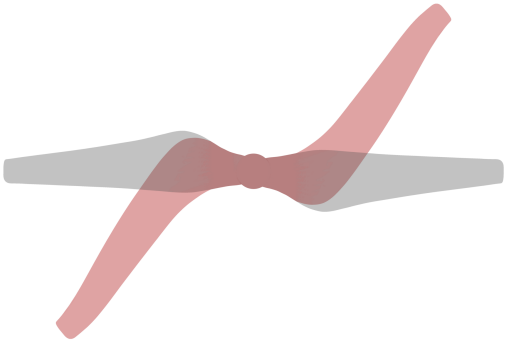
(a) Objective function: $L_{W,1}$.



(b) Objective function: $L_{W(A),3}$.



(c) Objective function: $L_{W,1}$.



(d) Objective function: $L_{W(A),3}$.

Figure 1: Baseline and optimized SWL spectra (top) and planforms (bottom, counterclockwise rotation direction).

optimizations based on the NSGA-II algorithm were performed, namely: (i) tonal noise vs figure of merit, (ii) broadband noise vs figure of merit, and (iii) broadband noise vs tonal noise. The obtained results, shown in Fig. 3, highlight the existence of trade-off configurations in terms of broadband and tonal noise for clocking angle values between about -32° and -60° and rotor spacing between about 23 mm and 24.5 mm. These configurations show a modest variation in the figure of merit, which however remains close to its maximum value.

4.4 Lessons learnt

The numerical optimization of shrouded contra-rotating co-axial rotors should be carried out taking into consideration aspects like structures, safety, and space because the optima in terms of aerodynamic and acoustic performance has to be searched for large separation distances. Instead, when considering co-rotating propellers, the optimization carried out by UR3 on the basis of the metamodels obtained using the Active Artificial Neural Network from the experimental data, highlighted the existence of trade-off configurations in terms of broadband and tonal noise for clocking angle values between about -32° and -60° and rotor spacing (non-dimensionalized by the rotor diameter) between about $z/D = 0.069$ and $z/D = 0.074$.

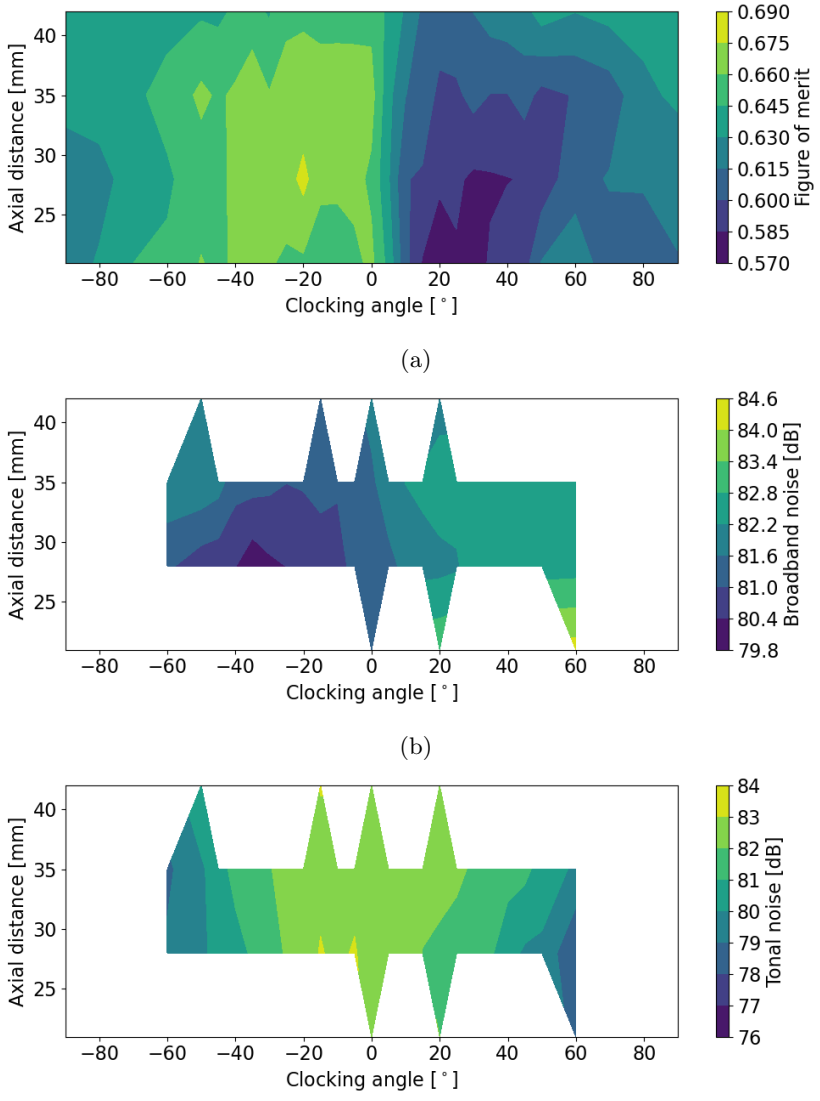
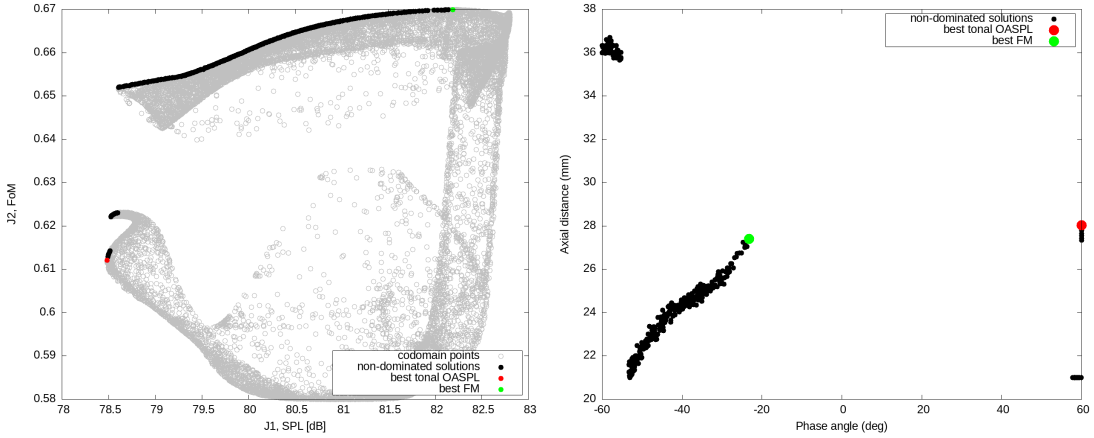
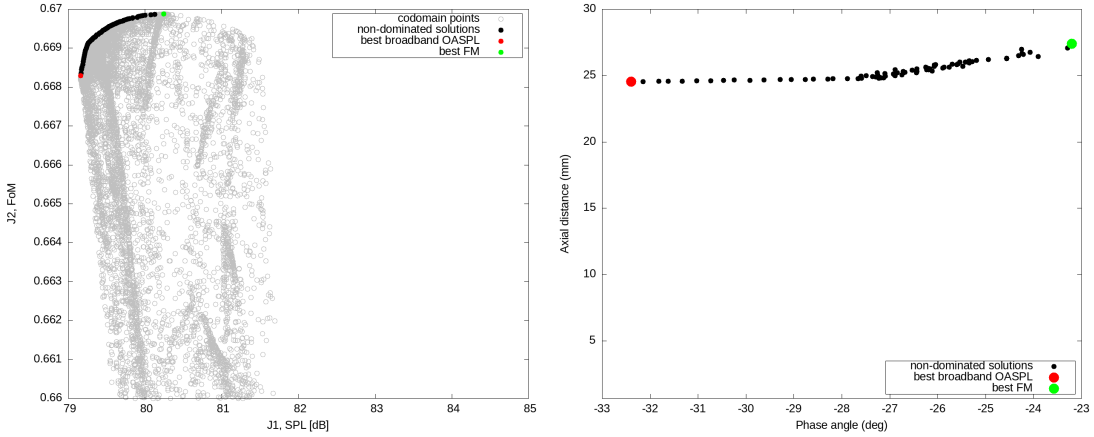


Figure 2: (a) Figure of merit, (b) broadband noise, and (c) tonal noise for coaxial co-rotating rotors.



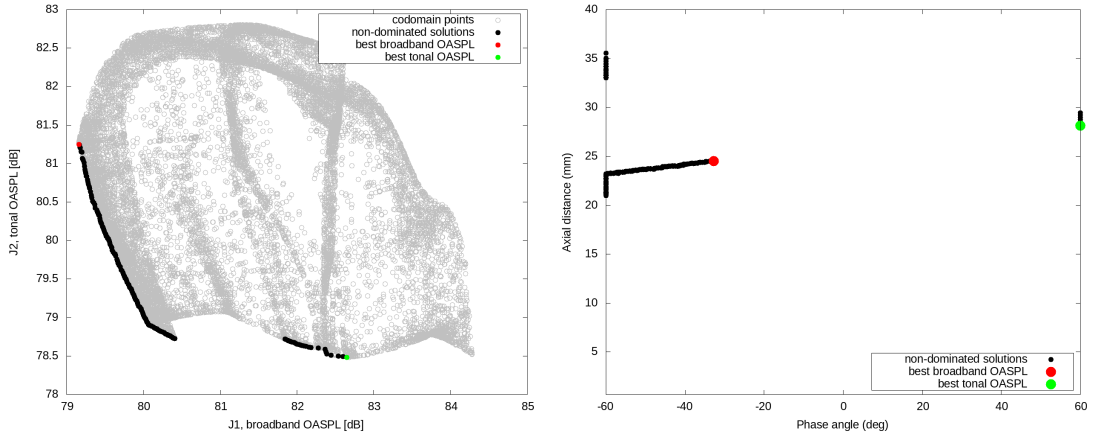
(a) Codomain (Pareto front)

(b) Domain



(c) Codomain (Pareto front)

(d) Domain



(e) Codomain (Pareto front)

(f) Domain

Figure 3: Configuration C (co-rotating open rotors): Tonal noise vs figure of merit (top), broadband noise vs figure of merit (centre) and (bottom) broadband noise vs tonal noise bi-objective optimizations.

5 Conclusion

Work Package 5 focused on optimising airframe-propulsion integration to enhance aircraft performance and reduce noise emissions. Three rotor/airframe configurations, referred to as A, B, and C, were examined to investigate the effects of propeller design, positioning, noise reduction, and aerodynamic efficiency. Advanced simulations and optimisation techniques were employed in this optimisation study.

For Configuration A, focusing on wall-mounted, boundary-layer-ingested propulsion systems, GPUP's high-fidelity simulations demonstrated the critical role of propeller placement and inflow velocity in noise emissions. The optimal configuration identified by UR3's metamodel, with the propeller positioned 777 mm from the inlet and an inflow velocity of 26 m/s, resulted in the lowest predicted OASPL. This configuration achieved a notable reduction in noise compared to baseline configurations.

Configuration B, addressing multi-rotor airframe propulsion integration, yielded promising results through the application of serrated trailing edges. GPUP's numerical simulations showed noise reductions of up to 2.5 dB, particularly at phase angles of 90°. Further optimisation by UR3, utilising artificial neural networks (ANN), demonstrated that positioning the central rotor forward with a phase angle of 97° produced the most significant noise reductions. The multi-objective optimisation indicated that forward axial positioning and phase tuning were critical to minimising noise.

For Configuration C, focusing on the noise and aerodynamic optimisation of quadcopter rotor systems, VKI and UR3's multi-objective optimisation provided clear evidence of effective trade-offs between noise reduction and aerodynamic performance. The optimal co-rotating configuration achieved with a $-20°$ clocking angle and a 28 mm axial separation produced the best balance of thrust and low broadband noise. Additionally, the optimised clocking angles between -32◦ and $-60°$ and rotor spacing of 23 mm to 24.5 mm further reduced both tonal and broadband noise without compromising performance.

In conclusion, Work Package 5 demonstrated that through CFD, CAA, and machine learning-based optimisation techniques, significant improvements in noise mitigation and aerodynamic efficiency can be achieved in airframe-propulsion integration systems.