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VENUS PROJECT: INVESTIGATION OF DISTRIBUTED PROPULSION NOISE AND ITS MITIGATION THROUGH WIND TUNNEL EXPERIMENTS AND NUMERICAL SIMULATIONS

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ABSTRACT

The VENUS project is aimed to develop methods and tools enabling a concurrent aerodynamic and aeroacoustic design of a distributed electric propulsion configuration aircraft. As a practical achievement, the study will support the design of a new regional aircraft configuration, in terms of wing and engines' installation, optimized in terms of aerodynamic and aeroacoustic performance. All the produced models, data and documents will be open access for other institutions, in order to establish an "open test-case" for the whole European scientific community, unique in the aircraft design landscape. A wing model equipped with a flap and three propellers powered by electric motors will be tested in the Pininfarina wind tunnel. Acoustic, aerodynamic and wall pressure measurements will be carried out. The propeller geometry is obtained through an aeroacoustic optimization, with aerodynamic constraints. An optimized liner is installed on the wing for acoustic mitigation. The parameters to be changed during the tests include five blade pitch settings, an angle of attack sweep, take-off and landing flap configurations, phase shift between the propellers, different relative distances between the propellers and with respect to the wing. This paper gives an overview of the project prior to the experimental wind tunnel tests.

Keywords: *propellers, acoustic liners, CFD, wind tunnel*

1. INTRODUCTION

Distributed electric propulsion (DEP), is a propulsion configuration that is believed to exploit the benefits of electrical engines to drastically reduce fuel consumption and emissions. In this configuration, the aircraft is delivered with the required energy by multiple, hence distributed, propulsive devices. Regarding air transportation systems, a simple definition of distributed propulsion is a propul-

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sion system where the vehicle thrust is produced from an array of propulsors located across the air vehicle. The distributed thrust capabilities of a distributed propulsion system should as well enable an improvement in the system-level efficiency, capabilities, or performance of the air vehicle [1]. As the DEP systems gain increasing popularity, it becomes crucial to gain insight in the interaction between propellers and their effects on the noise generation. Yet, this topic still requires deeper research from an aeroacoustic point of view. Works on the aeroacoustic interaction between two or more propellers are quite scarce in literature, including [2], [3] [4], [5].

The EU-funded VENUS project will contribute important knowledge on the aerodynamics and aeroacoustics performance of a wide range of DEP configurations through numerical simulations and experimental wind tunnel tests. The consortium has developed methods and tools enabling a concurrent aerodynamic and aeroacoustic design of DEP configuration aircraft. The final step consists in the experimental-numerical assessment of the numerical models. As a practical achievement, the study will support the design of a new regional aircraft configuration, in terms of wing and engines' installation, to target a DEP which is optimized in terms of both aerodynamic and aeroacoustic performance. All the produced models, data and documents will be open access for other institutions, in order to establish an "open test-case" for the European scientific community.

The project involves different international partners, as well as the Pininfarina Wind Tunnel facility. University of Roma Tre is the project coordinator; it was responsible of the design of the acoustic liners and will supervise the wind tunnel testing and perform data post processing. IBK Innovation took care of the model design. The Italian Aerospace Research Center (CIRA) chose the propulsive system, performed the optimisation of the propeller and the CFD simulations on the model. NHOE srl was responsible of the automation and control systems installed on the model. Eligio Re Fraschini SpA was involved in the manufacturing of the entire model, and was in charge of the wind tunnel installation and change of configurations operations.

2. AIRCRAFT USER-CASE DEFINITION

The main objective of VENUS is to have a generic understanding of distributed propulsion aeroacoustics issues. Therefore, in principle, these studies are not related to a specific aircraft and provide generic results applicable to all propeller aircraft. Nevertheless, to obtain realistic results it is necessary to refer to a specific aircraft configuration. Since application of hybrid/electrical distributed propulsion is quite challenging, and the difficulties increase as soon as aircraft range and size is increased, the first potential application for this technology will probably be a short-range Regional Aircraft. A generic aircraft is used as the starting point to define the wind tunnel model representative of a realistic aircraft.

The first concept considered ([6], [7]) employs two large tip tractor propellers associated with all mission phases, and a series of smaller tractor foldable propellers that are designed to operate in the low-speed range. The tip "cruise" propellers can be driven by a thermal or electrical engine and have an opposite sense of rotation with respect to the wingtip vortex in flight in order to reduce the induced drag. The "low-speed" propellers, usually driven by electrical engines, augment the low-speed flow-field over the wing by enhancing dynamic pressure and changing the local angle of attack distribution. This effectively scales the low-speed, high-lift capabilities of the aircraft, much like a large, complex flap system [8]. This is probably the most common DEP system concept. One of the focus points of this kind of configuration is represented by the design of small tractor propellers distributed along the wing. Usually, they are conceived as deployable devices to operate in the low-speed range in order to maximize the dynamic pressure increment without paying too much attention to propulsive efficiency. Moreover, the tip Mach number has to be minimized in order to reduce the noise impact [9]. On the other hand, they can also be used in high-speed range, by considering a second design point in which the propulsive efficiency is maximized in low-trust conditions.

For the VENUS project, the proposed solution is a 48 passengers Regional Aircraft with a typical mission of 200 Nm. For this aircraft, a configuration with 8 distributed propellers along the span and two additional tip propellers is proposed. It is assumed that thrust is provided entirely by DEP during take-off and landing and by the tip propellers during cruise condition. It is supposed that each DEP propeller has a 2-meter diameter and provides $4900\,\mathrm{N}$ thrust. Top level aircraft requirements are defined using as reference one of the most widely used regional aircraft, the ATR42. Information presented in the following have been obtained by using public domain net available information [10]. Public domain information has been integrated with hybrid-electrical propulsion considerations. It is supposed that the aircraft will be equipped with a tip propeller (to be used mainly in climb and cruise) and a distributed propulsion (DEP) to be used mainly in landing and take-off phase. ATR design range is 600 Nm. Nevertheless, usually a regional aircraft is used for shorter range (about 200 Nm) and therefore the hybrid-electrical propulsion system is optimized for this reduced range.

3. OPTIMISATION OF THE PROPELLER GEOMETRY

The design of the propeller geometry is performed in three steps: initial shape, refined shape using design of experiments (DOE) and final optimized shape. For the first step, a method inspired to the work of Adkins and Liebeck is used to generate an initial chord and twist distribution for the take-off condition. The potential of the obtained geometry is explored by means of a DOE which uses low and high bounds for the involved design variables. Results from DOE allow for the identification of a restricted design space. Finally, on this design space, an aeroacoustic optimization is launched to look for the best compromise of the blade planform maximizing the propeller performance and minimizing the acoustic radiation. The blade design is performed at full scale level. Subsequently, constraints are taken into account when the blade is scaled down.

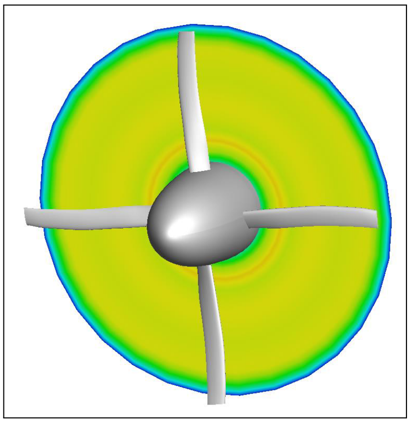

Figure 1. Optimized blade geometry and velocity distribution in the propeller outflow.

The optimisation requirements are to provide propeller geometry (blade number and external shape) while (i) maximizing propeller efficiency at takeoff, (ii) maximizing the radial uniformity of the velocity along the disk, (iii) minimizing the radiated noise in the far field. The optimized blade is shown in Fig. 1. Blades have been manufactured in carbon fiber with an aluminium root. Modal tests have been performed on the blades to verify the natural frequencies from the numerical Campbell diagram. A picture of the manufactured blade is shown in Fig. 2.

Figure 2. Photo of one manufactured blade.

4. OPTIMISATION OF THE MULTIPLE PROPELLERS LAYOUT

An optimisation procedure is built up with the aim to obtain the best possible improvements in tonal noise and aerodynamic performance of a multiple propeller combination by modifying the propellers' layout of the wing-DEP wind tunnel model. The aerodynamic and aeroacoustic design activity of the multiple propeller combinations has been carried out by setting up a multi-objective optimization procedure which, by the use of a suitable medium-fidelity aerodynamic solver and an aeroacoustic solver based on the Ffowcs Williams–Hawkings formulation, investigated several different layouts of the VENUS wind tunnel model with the aim to identify solutions providing low-noise and high-aerodynamic performance when compared to a baseline configuration. A multi-objective optimization (MOO) using a genetic algorithm (GA) and the covariance matrix adaptation evolution strategy (CMA-ES) was carried out, as a two-point optimization (take-off and landing) leading to about 8000 two-point numerical simulations. The main outcome of this activity is represented by the 35° de-phasing of the central propeller, which turned out to be the most powerful measure for noise reduction. No other means proved to be equally effective. The optimized layouts show several common trends. In particular, we observe that:

- the best solutions are found by staggering and moving away, as much as possible, the outer propeller disks with respect to the central one. However, the opposite behaviour is found when searching for the maximization of the propellers' efficiency or the minimization of the noise;
- the close proximity or even the overlap of the propeller disks are effective in improving both the aerodynamic

and acoustic performance. Indeed, three solutions lying on the 2D Pareto front displayed such a behaviour;

- in all the cases, the optimized positions for the propellers' hub centers are found to be located below the wing plane.

5. DESIGN OF THE LOW NOISE TECHNOLOGY DEVICE

An acoustic liner is specifically designed for the partial absorption of the noise generated by the rotor scattering on the wing. The design is made in order to obtain a broad frequency range of absorption, and a high absorption coefficient in the range of interest. The liner is positioned on the pressure side of the wind tunnel wing model, near the leading edge (Fig. 3) and is very compact, smaller than a quarter of the wavelength of the acoustic perturbation. For this reason, and to maximise the liner absorption, a microperforated panel (MPP) was chosen with sub-millimetric diameters of perforations, designed to be effective for a non-normal incident field. A picture of the manufactured low noise device insert is shown in Fig. 4.

Some preliminary numerical analysis has been performed by CIRA, analysing the relative importance of the tonal contributions at the multiples of the BPF in the incident acoustic field and the scattering effect produced by its interaction with the wing. Simulations suggest that the incident field has a relevant energy content up to the 9th BPF multiple, and that the scattering is more relevant starting from the 5th BPF. No application on wings based on absorbing liners are available in literature. Therefore, the models used for the design of the device are borrowed from standard acoustic applications and well assessed in that field. The Maa analytic model for MPP with back cavities was used for the analysis and optimization of the low noise device. The selection of the final configuration, which is an arrangement of four different MPPs with a cavity separated by internal septa, was based on the results of the numerical optimization and on the indication from the mentioned numerical analysis by CIRA.

The microperforated panels are designed through a lumped parameters model [11]. The main design parameters are the holes diameter, the cavity depth, the thickness of the MPP and the porosity. The best compromise is found through an optimization with four objective functions related to the absorption coefficient and its integral in a specific range of BPF. The optimisation is driven in quiescent fluid and the performance is then checked under grazing flow. Two extensions of the Maa model including the effect of flow [12], [13] are applied on the final configuration to verify the absorption properties of the designed device in the presence of a free stream Mach number comparable to the wind tunnel experimental conditions. The study suggests that the device has a promising noise absorption potential. However, the use of liners on a wing is not a standard approach and thus it requires an experimental investigation as it may introduce some new issues (e.g., self-noise, boundary layer thickening, etc.) that cannot be addressed analytically or with affordable numerical simulations. For this reason, a successful use of the MPP would represent not only an interesting feature for future practical applications but also a considerable scientific outcome of the VENUS project.

6. TEST PLAN

Regarding the wind tunnel test campaign, a scale model 1:3.6 has been selected. This solution corresponds to a full scale solution with thrust divided 50% between DEP and main propeller. The model dimensions are resumed in Table 1. Tests are carried out in the Pininfarina wind tunnel facility, an open jet wind tunnel with an acoustically treated test section. The wind tunnel is equipped with three spiral microphone arrays for source localization and a linear array for polar directivity (Fig. 6). The tests are performed at a wind tunnel speed of 20 m/s and a propeller speed of 3300 rpm, giving an advance ratio of $J = 0.63$. The model is installed horizontally, in order to simulate 2D conditions, and the wing is positioned upside down, as shown in Fig. 5.

Table 1. Full scale and model characteristics.

	Full scale	Model 1:3.6
Prop diameter [m]	2	0.556
Wing chord [m]	2.285	0.635
U_∞ [m/s]	63	20
rpm	2500	3300

The model is equipped with load cells for torque measurements, a specifically designed mechanism to change the AoA, as well as rotary encoders and accelerometers to allow for the speed and phase control of the propellers. The model struts are connected to the global balance beneath the test section floor, in order to measure the aerodynamic forces involved. The flap and the wing are instru-

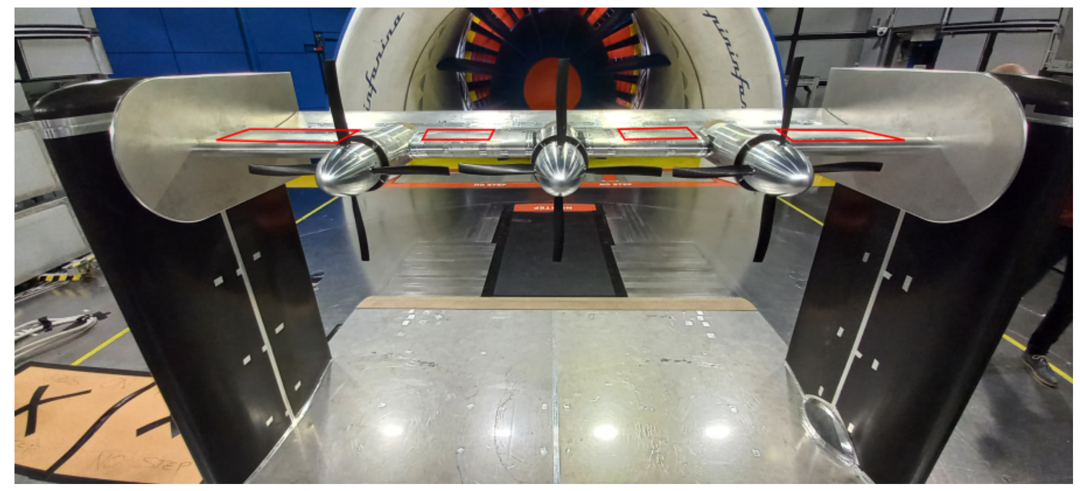

Figure 3. Location of the low noise device on the wing model.

Figure 4. Close-up of the low noise device insert.

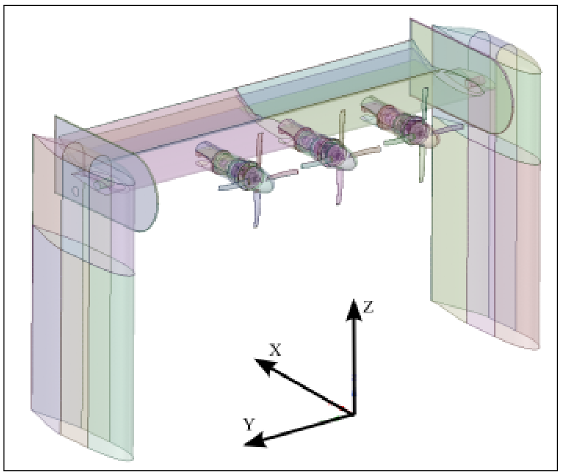

Figure 5. CAD drawing of the wind tunnel model.

mented with 96 pressure taps and 44 microphones in relevant locations, in order to measure the static pressure distribution and the wall pressure fluctuations respectively. Their position is shown schematically in 7. The pressure taps are acquired by two Chell μDAQ 64 channels pressure scanners. Knowles FG-23629-P16 capsule electret microphones are used to capture the fluctuating pressure. These measurements allow to investigate the interaction between the propeller wake and the wing and flap, and their role in the noise generation process.

The tests are performed varying the distances between the outer propellers and the central one ΔY and the distances with respect to the wing ΔX, resulting in eight different combinations XY. The distance with respect to the wing (ΔX) can take only three values: baseline (X_{BL}=449 mm), X_{BL}-60 mm, X_{BL}+60 mm, as it is varied using specifically designed removable inserts. The hub-to-hub distance (ΔY) between the outer nacelles and the central one can vary continuously between 694 mm and 547 mm, and the baseline value is 583.8 mm (Fig. 8) The take-off (TO) and landing (LA) configurations are investigated, resulting in two different flap settings, $\delta = 20°$ and $\delta = 35°$. The phase shift between the propellers is controlled using a PID controller. For each geometrical

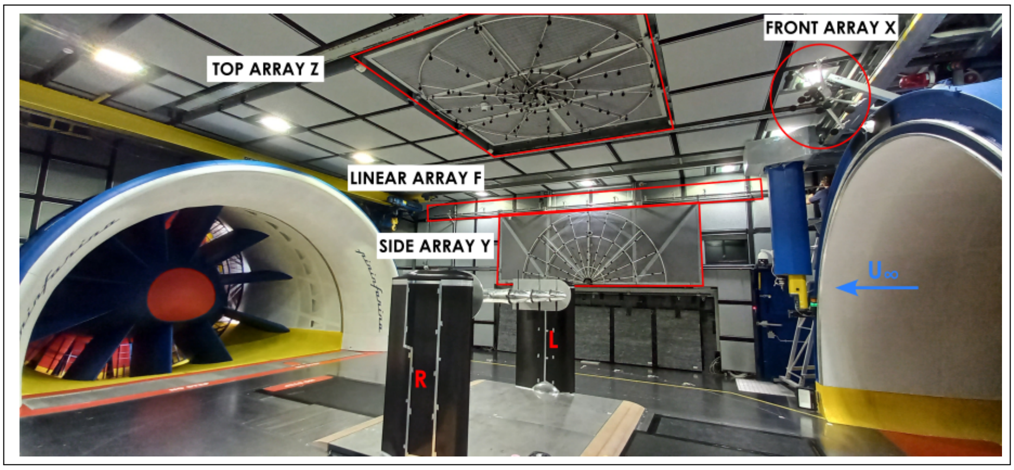

Figure 6. Installed model and microphone arrays Pininfarina wind tunnel.

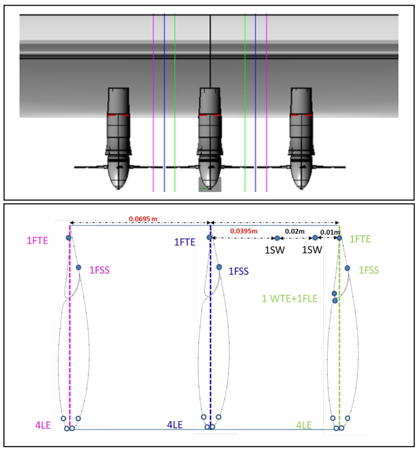

Figure 7. Steady (small dots) and unsteady (blue dots) pressure sensors positions.

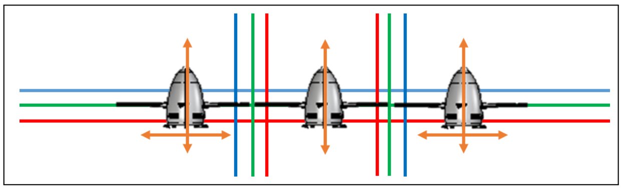

Figure 8. Sketch of the nacelles movements ΔX and ΔY; green=BL, red=closest, blue=farthest positions.

configuration, two phase angles are tested. Each test point consists of an angle of attack sweep between $-1°$ and $11°$ with a step of $1°$. Some of the configurations are tested with and without the acoustic liner installed, to be able to evaluate its effect on the noise emissions. The parameters varied during the tests are summarized in Table 2. Prior to the tests, the pitch angle has been calibrated in order to guarantee that the nominal thrust is achieved inside the wind tunnel. Also the phase shift influence on the propellers has been verified, to confirm that the 35° is the one which minimizes noise emissions, as indicated by the numerical simulations.

Table 2. Parameters varied during wind tunnel tests.

Parameter	Value
AoA α	$-1° \rightarrow 11°$
Flap angle δ	20° (TO), 35° (LA)
Phase shift $\Delta\varphi$	$0°, 35°$
ΔX, ΔY	XY1 $\rightarrow$ XY8
Low noise device	on, off

7. PRELIMINARY RESULTS

In this section, some preliminary results from the wind tunnel test campaign are shown. The spectra of the noise emitted by the clean model and by the baseline configuration are compared in Fig. 9. A good signal to noise ratio is achieved, allowing the propeller contribution to be identified in terms of broadband noise at mid to high frequencies as well as tonal noise at the propeller BPF up to the 15th harmonic, and in correspondence of some of the shaft frequency harmonics. The beamforming maps computed at the 10th BPF harmonic allow to identify the acoustic footprint of the model with a sufficiently good resolution, in order to compare the different DEP configurations, and provide the one with the best aeroacoustic performances. An example is shown in Fig. 10 for the baseline configuration in take-off. An example of the pressure coefficient measured along the model is shown in Fig. 11.

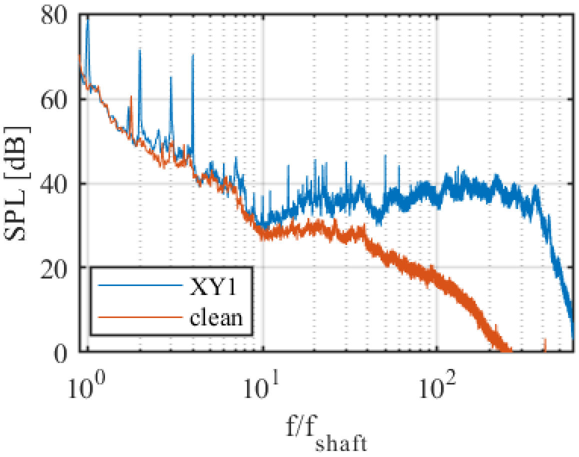

Figure 9. Spectra of the noise emitted by the baseline configuration and by the clean model in take-off.

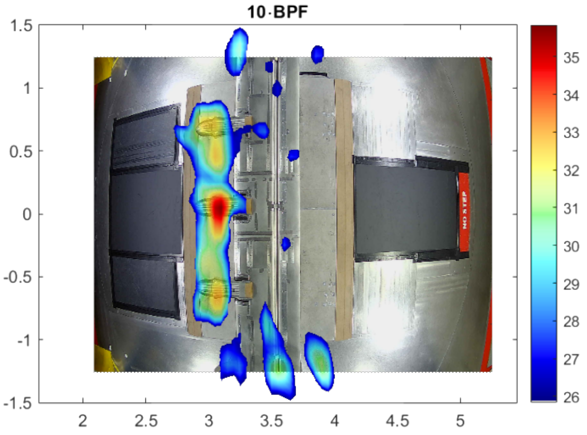

Figure 10. Beamforming map at 10 times the BPF, on the baseline configuration in take-off.

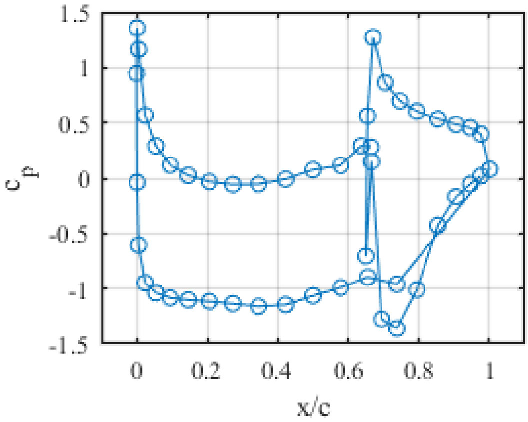

Figure 11. Pressure coefficient measured along the left side of the model, on the baseline configuration in take-off.

8. CONCLUSIONS

The VENUS project is aimed to improve knowledge about distributed electric propulsion configurations using experimental as well as high fidelity numerical data, defining an open test-case for the scientific community. In order to define a realistic application, a 48 passengers regional aircraft with a typical mission of 200 Nm has been chosen. For this aircraft, a configuration with 8 distributed propellers along the span and two additional tip propellers is proposed. It is assumed that thrust is provided entirely by DEP during take-off and landing and by the tip propellers during cruise condition. The blade geometry has been optimized to have a uniform velocity in the propeller inflow. Blades have been manufactured and and have undergone modal tests to verify the natural frequencies from the Campbell diagram. The multiple propellers layout has undergone a numerical optimization process, which provides the most interesting configurations to be tested in the wind tunnel. An innovative acoustic liner has been specifically designed to be installed on the wing, in the propellers wake, for noise mitigation purposes.

Measurements include the forces acting on the model and the propeller torque. Farfield aeroacoustic measurements are performed using four microphone arrays. The steady and unsteady pressure are measured in strategic positions along the wing and the flap, to gain insight in the interaction between the propeller wake and the wing. Different parameters are taken into account, including the angle of attack, the flap angle, as well as the hub-to-hub distances between the propellers, their distance with respect to the wing and the phase shift between the propellers. The model has been successfully manufactured and instrumented and the wind tunnel tests were performed in June in the Pininfarina Wind Tunnel. The post processing of the experimental database is an ongoing activity. The preliminary results show a good signal to noise ratio, and allow to identify the propellers contribution, in order to provide the DEP configuration with the best aeroacoustic performance.

9. ACKNOWLEDGMENTS

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