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MONNALISA: Modelling nonlinear aerodynamics of lifting surfaces

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The performance-improvement objectives sought in future commercial aircraft may require a significant evolution of the current configurations and technologies for aircraft tails. An "Advanced Rear End" component for the forthcoming generation of ultra-efficient aircraft might consist of a very compact rear fuselage and tail surfaces whose planform may significantly differ from the state of the art in terms of aspect ratio, taper ratio and sweep angle. The Cleasky 2 MONNALISA (MOdelling NoNlinear Aerodynamics of LIfting SurfAces) project aims at developing and validating an innovative, physics-based low-order method to predict the non-linear aerodynamic characteristics of lifting surfaces with controls whose geometry could significantly differ from the usual ones. The development and validation of the method relies on a high-resolution database scanning the extensive space of design parameters: sweep angle, aspect ratio, taper ratio, dihedral angle, shape of the leading edge and presence of ice. A recently validated approach, based on the most advanced techniques of uncertainty quantification, guarantees the reliability of the database of the aerodynamic characteristics that will drive the development of the method. A by-product of the project, the aerodynamic database will efficiently mix highly accurate experimental results, state-of-the-art, high-fidelity numerical simulations and low-fidelity simulations.

I. Introduction

The increasing concerns about climate change call the aviation industry to an exceptional effort to increase the aircraft efficiency and reduce the environmental impact of aviation. The Advisory Council for Aviation Research and Innovation in Europe set the targets for 2050 of a 75% reduction of CO_2 per passenger per kilometer, 90% of NO_x, and 65% of perceived noise [1]. To this aim, the Clean Sky 2 Joint Undertaking (CS2JU) is working to achieve a 30% reduction in CO_2, NO_x and noise [2].

One of the technological demonstrators in the CS2JU is the Advanced Rear End, where new tail configurations are explored and optimised to increase economic, environmental and manufacturing efficiency. The investigation of non-conventional tails is a hot topic in the aeronautic research, due to the potential benefits in terms of payload. To optimise non-conventional configurations, low-cost, accurate models of the nonlinear aerodynamic performance of tail

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surfaces are needed. Indeed, this is a crucial tool to enable a fast survey and optimisation of the possible configurations since low-order numerical methods enable a fast prediction of the non-linear aerodynamic characteristics of lifting surfaces and hinge moments near stall. Notably, the evaluation of the stall behavior of lifting surfaces is essential for the preliminary design of aircraft empennage. Despite this fact, the literature on this topic is quite scarce. While surrogate models have been used in the past, see [3] and the references therein, such models cannot guarantee the necessary accuracy when the performance of swept wings near stall is requested. For this reason, models based on the flow physics are being pursued. An example of a physics-based model working for straight wings is described in [4], unfortunately this model fails on swept wings. Gabor et al. [5] proposed a new non-linear formulation of the classical Vortex Lattice Method (VLM) accounting for the effects of viscosity in the calculation of the aerodynamic properties of lifting surfaces. The mathematical model is constructed by using two-dimensional viscous analyses of span-wise sections of the wing, according to the strip theory [6]. Then, the strip viscous forces are coupled to the forces generated by vortex rings distributed on the wing camber surface, calculated with a fully three-dimensional vortex lifting law. The numerical method was validated against experimental results for both low and high sweep wings, finding good agreement for the lift coefficient and pitching moment coefficient curve derivatives but not for the aerodynamic coefficients at stall. In the work by Gallay et al. [7], a numerical method based on the non-linear lifting line theory coupled to viscous sectional data in presented for the evaluation of the aerodynamic lift curves for various wing planforms. This model uses a Prandtl Lifting Line Theory (LLT) taking viscous effects into account by corrections to the inviscid model that use two-dimensional viscous data obtained through high-fidelity CFD simulations. To accurately capture viscous effects for swept lifting surfaces, the method was coupled to 2.5D polars of the wing sections computed by extruding the 2D mesh along the sweep. The validation against wind-tunnel tests of highly swept wing clearly shows that the use of 2.5D sectional data significantly improves the results compared to 2D sectional data in the pre- and post-stall region, but increasing the computational effort required to provide the viscous polars. Recently, Goitia and Llamas [8] proposed a nonlinear vortex lattice method (VLM) for the stall prediction of generic fuselage-empennage configurations based on a generalized form of the van Dam algorithm, which couples the potential VLM solution with 2.5D viscous data. In particular, the authors present a novel method for computing 2.5D polars from 2D airfoil simulations. Moreover, the method accounts for the effect of the fuselage on the tail plane by modelling the fuselage as a cylindrical surface of vortex rings.

The development of such nonlinear models requires accurate data on swept wing of different planforms significantly departing from conventional designs. Unfortunately, databases reporting accurate experimental or numerical tests on planforms of unusual shape are seldom available. One example being [9].

In this paper we present the Cleansky 2 MONNALISA (Modelling nonlinear aerodynamics of lifting surfaces) project. The project aims at developing and validating an innovative, physics-based low-order method to predict the non-linear aerodynamic characteristics of lifting surfaces with controls whose geometry could significantly differ from the usual ones, therefore satisfying the need of efficient design tools by the Industry. The development and validation of the method relies on a high-resolution database scanning the extensive space of design parameters: sweep angle, aspect ratio, taper ratio, dihedral angle. Different leading edges and the presence of ice will also be investigated. A recently validated approach, based on the most advanced techniques of uncertainty quantification, guarantees the reliability of the database of the aerodynamic characteristics that will drive the development of the method. The aerodynamic database will efficiently mix highly accurate experimental results with state-of-the-art, high-fidelity numerical simulations, thus minimising the cost of assessing the wing performance in such a wide parameter space within a reasonable budget.

This paper is organised as follows. In Section II, the objectives of the MONNALISA project are detailed and the underlying concept is explained. In Section III, the structure of the project is detailed, while Section IV is devoted to conclusions.

II. Project objectives and concept

This project is meant to contribute to the design of a demonstrator of the Advanced Rear End of advanced and ultra-advanced, short/medium/long range civil aircraft by developing low-cost numerical methods to accurately predict the nonlinear aerodynamic characteristics of lifting surfaces, of the type used in the tails of civil commercial aircraft, characterised by unusual planforms.

The ultimate goal of this research project is therefore to develop a low-order numerical method based, as far as possible, on the phenomenon physics, able to predict the aerodynamic performance of a systematic series of geometries of tails of civil commercial aircraft in the nonlinear regime, near stall.

In pursuing this objective, we will follow an innovative approach in which we:

1) develop a systematic series of wind tunnel tests of several models of tails of civil commercial aircraft covering a wide range of planform parameters, with and without simulated ice shapes. The choice of the test parameters will be driven by advanced Uncertainty Quantification (UQ) techniques coupled to high-fidelity simulation;
2) integrate the experimental database with a systematic series of numerical simulations of tails of civil commercial aircraft in order to increase the resolution of the database with respect to the control parameters. The approach based on UQ will permit to detect regions of the parameter space for which experimental measurements of tails of civil commercial aircraft can be substituted by high-fidelity numerical simulations, thus reducing the number of highly-expensive experimental tests and keeping costs to a minimum;
3) develop Bayesian-based calibration methods using the full database of the aerodynamic performance of tails of civil commercial aircraft in order to extend the prediction of the maximum lift coefficient and hinge moment of tail surfaces given by the low-order numerical technique to an arbitrary Reynolds number;
4) use the developed database to build an error function, which will correct the outcome of the low-order numerical method.

The concept that we develop in MONNALISA project is based on five pillars: high-accuracy, high-fidelity simulations, advanced wind-tunnel testing, high-precision wind-tunnel model production, uncertainty quantification techniques, a state-of-the-art open-source solver. Indeed, scanning a wide range of geometrical parameters such as the

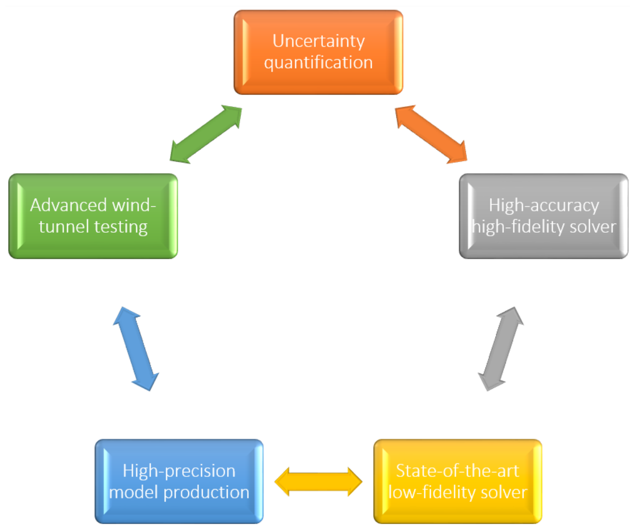

Fig. 1 The five pillars defining the concept to be developed in MONNALISA.

aspect ratio, the taper ratio, and the sweep angle by experimental techniques is very expensive, if the results have to be accurate enough to develop the rear end of next-generation aircraft. A standard approach, based only on wind-tunnel tests is not feasible due to the high cost. Indeed, the required size of the model, its precision and stiffness require highly expensive production techniques. Moreover, the production of an extensive experimental database will require an extensive use of the wind tunnel. To keep costs to a reasonable level, we pursue a disruptive concept: to avoid the costly and time-consuming scanning of the entire parameter space by wind-tunnel tests using recent branching techniques instead that rely on UQ to select the most critical configurations on which wind-tunnel tests must be carried out, the remaining configurations being evaluated by means of high-fidelity CFD simulations. The synergy between UQ techniques, high-precision model manufacturing, highly accurate wind-tunnel measurements and CFD simulations will allow MONNALISA project to produce a reliable database to aerodynamically characterize unconventional tail-plane aerodynamic surfaces in a wide geometrical-parameter range.

The aerodynamic database obtained by this advanced technique will be used to develop a low-order method to predict the maximum lift coefficient of tail planes in the scanned parameter range. The method will exploit low- and mid-fidelity, physics-based numerical methods implemented in an open-source library developed by the POLIMI partner [10]. Ground-breaking calibration methods, integrating the most advanced UQ technologies, will also be leveraged to calibrate an error function of the low-order, physics based method developed to predict the nonlinear aerodynamics and maximum lift coefficient of the tail planes in the select parameter space. The main points of our concept are therefore:

1) High-quality, open-source Reynolds-averaged Navier–Stokes (RANS) simulations under uncertainty with an

accurate selection of the parameters for which wind-tunnel tests have to be run. The RANS simulations coupled with the Eigenspace Perturbation Method (EPM), taking into account system uncertainties, will permit to compute an accurate numerical prediction with turbulence uncertainty estimates so as to predict the regions of the parameter space where the wind-tunnel tests are most valuable;
2) Ground-breaking calibration methods, integrating the most advanced UQ technologies to calibrate the low order model for nonlinear aerodynamics;
3) High-quality wind-tunnel models to cover the whole range of parameters by targeting selected values of the geometrical parameters. Models will be machined from aluminum alloy to guarantee the precision and repeatability over time of the experimental results. Thermographic scans will be used to evaluate the transition point;
4) Advanced, physics-based modelling that hinge on advanced open-source software. Significant advance in stall prediction techniques is expected.

III. Overall approach and methodology

This project is focused on the development of a methodology permitting to generate informative data (coming from selected experiments and high-fidelity numerical simulations) and use them to increase the accuracy of low-order numerical methods for an extended range of conditions. In this section, specific methodologies and actions related to each topic (wind-tunnel design and testing, physical modelling, numerical simulation and uncertainty quantification) and their interaction are illustrated.

A. Wind tunnel testing of tail planes

A relatively small set of reliable wind-tunnel experiments will be carried out on a systematic series of swept wings, scanning the design space to produce the aerodynamic database needed to develop and calibrate the low-order method. Thus, a set of wind tunnel models will be produced and tested in the "Galleria del Vento del Politecnico di Milano" (GVPM), a medium size low-speed wind tunnel suitable for aeronautical testing. The test chamber is 4m wide and 3.84m high with 55m/s maximum speed. The models will be in the form of "half wing". In order to avoid a direct interference with the chamber-floor boundary layer, a dummy floor will be adopted [11]. The dummy floor will act as symmetry plane. Furthermore, to improve the root conditions, a moderate suction will be provided in front of wing leading edge on the floor in order to reduce the effects of possible flow separation at the leading edge of the wing. In other words, a sort of hybrid effect will be adopted: first of all a much thinner boundary layer at wing-floor intersection will be obtained using the dummy floor; second, a suction on the dummy floor will further reduce the boundary layer. The correct direction of streamlines in the wing-floor intersection area will be checked by means of surface oil visualizations. A sketch of a model in the test chamber is presented in Figure where the dummy floor is not shown in order to highlight the underneath tilting table.

The wing root will be fixed to a multi-component highly accurate balance system installed below the dummy floor, to measure lift, drag, and pitching moment. The control-surface deflection will be actuated by an electrical motor and remotely controlled, with a frequency up to 2 Hz and a deflection in the interval to $\pm 35°$. The hinge moment will be measured by a torsiometer. For each tested model configuration, forces and moments will be measured in a wide range of angles of attack α at 50m/s. An IR camera will be used to detect the transition line and its evolution during the α sweep.

Models will be machined from aluminium alloy in order to fulfil the tight specifications in terms of dimensional tolerance and roughness. All the models will be finished with matt black epoxy paint to allow IR thermography. PIV surveys will be carried out to describe the flow field structure.

B. Wind-tunnel model design and manufacturing

The technology adopted for manufacturing the wind-tunnel models significantly impacts the quality of the experimental results. With this consideration in mind, we opted for a machined model made of metallic. We decided to keep the number of parts composing on wind-tunnel model to a minimum while maintaining the modularity of the wind-tunnel model. The models consist of three parts. A leading edge up to 30% of the chord, a central portion, and the moving flap on the trailing edge. The leading edges are interchangeable to increase the number of different configurations tested. Particular care will be devoted to avoid any step between the leading edge and the central portion of the wing, that would promote transition. The wind-tunnel model concept is illustrated in Figure 4. Since the number of wind-tunnel models that can be built within a reasonable budget is quite limited, we propose an innovative approach

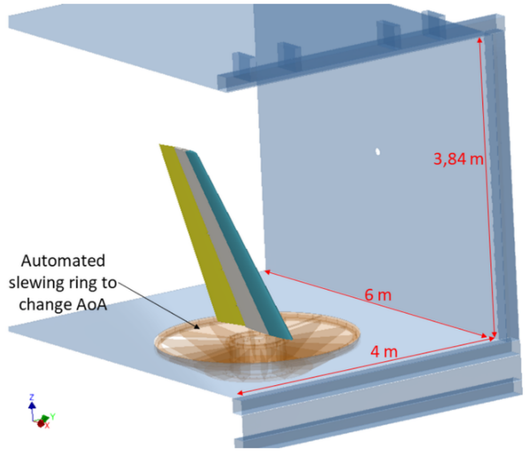

Fig. 2 Wing installed in the wind tunnel. The dummy floor is not shown to highlight the tilting table used to adjust the angle of attack.

to the construction of the aerodynamic database that leverages uncertainty quantification tools to optimally blend experimental results and high-fidelity CFD simulations in a controlled way.

C. High-fidelity modelling of nonlinear aerodynamic

Numerical simulations of the aerodynamics of tail planes using high-fidelity flow models such as the Reynolds-Averaged Navier-Stokes (RANS) can be successfully used to predict the aerodynamic force coefficients up to a sufficient level of accuracy for the industrial applications. In MONNALISA, high-fidelity RANS simulations of the planform are carried out using the open-source toolkit SU2 [12]. In close proximity of the stall conditions of interest within the MONNALISA project, however, the steady RANS model does not deliver satisfactory results and a more complex, unsteady description should be considered. Ideally, either Direct Numerical Simulation (DNS) or Large Eddy Simulations (LES) should be capable of representing strongly separated flows, though the computational requirements are still too demanding for the relatively complex geometry and high-speed operating conditions targeted by MONNALISA. A Detached Eddy Simulation approach is preferred in MONNALISA, which combines the RANS and LES approaches in a non-zonal fashion. In fact, the Delayed Detached Eddy Simulation (DDES) model [13] implemented in SU2 will be used for all high-lift conditions identified in WP2. In DDES, molecular and turbulent viscosity information are included into the model to delay the switching in boundary layers. Current capabilities to predict the onset of stall are strongly influenced by the uncertainties associated with turbulence models and to the accuracy of the transition models in both low- and high-speed boundary layer flows. In MONNALISA, the uncertainty related to the turbulence models is specifically targeted with the help of high-fidelity simulations using an Eigenspace Perturbation Method (EPM) approach [14], as described below. State-of-the-art transition models will be implemented in SU2, in addition to the ones already available, to accurately determine transition from laminar to turbulent boundary layers and improve the prediction of stall onset.

High-fidelity CFD simulations are also used in MONNALISA to extend the aerodynamic database to the compressible flow regimes that cannot be investigated in POLIMI low subsonic wind tunnel. In MONNALISA, DDES is also applied to the simulation of iced surfaces. Numerical simulations using the in-house ice-accretion software PoliMIce [15] from POLIMI are carried out in MONNALISA to provide the ice shape. Moreover, PoliMIce will also provide a more precise characterisation of the fully 3D ice surfaces in terms of surface roughness and the interaction between ice formation and the flow unsteadiness.

D. High-fidelity simulation and Uncertainty Quantification

To fully achieve the promises of numerical simulations in sciences and engineering, it is essential to assess and improve their predictive capabilities continuously. Obvious improvements concern the modelling aspects (higher fidelity) and numerical efficiency (to enable higher resolution). However, as the computational capabilities are progressing, it is becoming more and more evident that accounting for the various uncertainties involved in the simulation process is critical. The reason is that the accurate simulation of a complex system has a practical utility if, and only if, one can prescribe with sufficient precision the system investigated. In other words, obtaining high-fidelity predictions on a system different from the one targeted presents limited interest. The problem here is that, except for purely academic situations, specifying precisely all the properties and forcing applied to a complex system is impossible. Whether the precise definition of the system is impossible because of inherent variability, lack of knowledge, or imprecise calibration procedures (experimental setups and measurements are inherently inexact), totally eliminating uncertainty sources is not an option. As a result, the simulation should account for these uncertainties and quantify their impact on the predictions (similarly to the experimental error characterization) in order to assess objectively the truthfulness of the simulation and enable fully informed decision making. As a matter of fact, reliable numerical predictions require both sophisticated physical models and the systematic and comprehensive treatment of inherent uncertainties, including the calibration and validation procedures.

In the context of RANS simulations, turbulence closures are needed to reconstruct the Reynolds stress term resulting from the time-averaged decomposition of the Navier–Stokes equations. Unfortunately, the strong inherent model-form assumptions usually underlying RANS turbulence closures question the credibility of CFD predictions for some particular flow configurations. Results provided in different paper works confirm that RANS-based predictions are questionable for a wide variety of applications of industrial relevance. In this project, we focus on the application of the Eigenspace Perturbation Method (EPM) [14], which is designed to compute the turbulence uncertainty estimates of QoIs in CFD simulations. Namely, the approach renders up a relatively cheap framework for the estimation of the model-form uncertainty relative to the structural deficiencies of the Reynolds stress tensor in RANS models. In particular, the approach was devised to estimate the L2 [16] uncertainties arising from the process of relating the microscopic state of a flow to macroscopic quantities e.g., the Boussinesq hypothesis. Note the deliberate use of the word estimation, rather than quantification, implying the computation of reasonable and informed uncertainty estimates rather than rigorous and provable bounds. Practically, the EPM relies on the eigendecomposition of the anisotropy Reynolds stress tensor. Uncertainty estimates are obtained by injecting specific perturbations to the eigenspace namely, by varying the shape, the amplitude and the orientation of the ellipsoid associated with the Reynolds stress tensor, during the CFD solution iterations. Overall, EPM could be exploited to derive an estimator of the numerical turbulent prediction accuracy. Unfortunately, the EPM only provides reasonable and informed turbulence uncertainty estimates rather than rigorous and provable bounds. That is, though we reasonably expect the true performance to be included within the EPM turbulence uncertainty bound estimates, there is absolutely no guarantee for that. Though we still acknowledge that the true performance may not be included within the turbulence uncertainty bound estimates, we will propose in this project to require that turbulence uncertainty estimate is below a given threshold to consider the model as predictive. In this way, we basically limit the dispersion of predictions. By including turbulence closure model-form error and the other sources of uncertainty, we can reasonably expect predictions to be reasonably close to the truth. To summarize, the EPM method allows identifying under which conditions the solver is reliable. The underlying assumption of the project, which will be verified according to the results obtained, is to carry out experimental measurements exclusively in the conditions in which the numerical solver is considered unreliable. In practice, the following approach will be pursued:

- A Design Of Experiment (DOE) including the operating conditions and any uncertain parameter will be defined.
- For each element of the DOE, we will perform an EPM analysis using SU2. Note that the size of the DOE (here indicated with N elements) will be compatible with the available computing resources, and that we need to analyze each condition first to provide a more precise estimate of the size.
- Based on the previous analysis, we will identify the portions of the input parameter space for which numerical simulation are not sufficiently reliable.
- Depending on the structure of these regions, a minimum number of relevant configurations will be chosen for experimental analysis.

E. Low-fidelity modelling of nonlinear aerodynamics

In order to develop a low-fidelity model for capturing the aerodynamic performance of swept wings with generic geometry, POLIMI will took advantage of the DUST software [17], a mid-fidelity, fast, reliable tool developed in the frame of a research collaboration between POLIMI and A^3 by Airbus. In MONNALISA project, the approach to multi-fidelity modelling of tail-plane aerodynamics will start from the validation of the state-of-art low fidelity aerodynamic methods (as surface panels, vortex lattice, lifting lines, vortex particle methods for the wake) already implemented in DUST to predict the maximum lift of a tail plane with sweep and dihedron angle within the range of parameters covered by the systematic series of geometries tested in the wind tunnel or with high-fidelity simulations. The development of the low-fidelity aerodynamic solver will be completed in this framework by the implementation of innovative physics-based numerical methods for the evaluation of stalled conditions for airfoils. With this aim, the more promising technique investigated in the recent literature will be implemented in DUST and checked by comparison with the wind tunnel tests and high-fidelity-simulation results. In particular, the use of lifting line elements will be thoroughly investigated in this project with the aim of adding the modelling of viscosity effects. Indeed, lifting line elements provide a 1-D line vortex model for thin lifting bodies, with tabulated sectional aerodynamic coefficients naturally including the viscous effects. Lifting line elements are modelled as vortex rings, whose stream-wise sides are represented by the trailing vorticity, and vortex-doublet equivalence reduces the solid body modelling to a surface distribution of doublets and sources. The tabulated data of the steady-state aerodynamic coefficients are generally produced by means of high-fidelity 2D CFD simulations of experiments of the airfoil sections constituting the tail-plane geometries investigated. Steady loads are evaluated with the tabulated steady sectional aerodynamic coefficients, while the unsteady loads are computed with the unsteady version of Bernoulli's theorem. Moreover, the use of a novel approach to vortex-lattice elements will be investigated with the aim of implementing an effective physics-based model to consider viscosity effects. In particular, the non-linear vortex lattice method proposed by Goitia and Llamas [8] will be thoroughly investigated in this project. This method, based on a generalized form of the van Dam algorithm, showed encouraging results for the evaluation of the stall prediction of generic fuselage-empennage configurations. In particular, the potential-flow VLM solution is coupled with 2.5D viscous polars taking the effect of the empennage sweep into account that can easily be obtained from 2D airfoil simulations using the novel physics-based method described by the authors. Moreover, in this project, the method to obtain the 2.5D polars will be validated by both high-fidelity CFD and wind tunnel data for some selected configurations. A further tool useful to improve the capability to evaluate the empennage aerodynamics performance is the vortex particle modelling of the wake that includes the modelling of the viscous and turbulence effects and avoids the numerical instabilities occurring with connected models of the wake in practice. The vortex particle method implemented in DUST naturally fits the Cartesian Fast Multipole Method (FMM) [18] needed to accelerate the computation of particle interactions. Thus, the $O(N^2)$ computational cost of the direct computation of the interactions between N particles is reduced to the $O(N)$ computational cost of the FMM evaluation, in the ideal case. An adaptive Octree structure generates a background hierarchical decomposition of the domain into clusters of cells and the interactions between clusters of well-separated particles are then evaluated with the Cartesian FMM. Typical computational time for the evaluation of the performance of a single empennage configuration could be in the order of few seconds considering a modern laptop architecture.

The final task will be to take advantage of the wind tunnel campaign data and high-fidelity numerical simulations for extending the validity domain of the low order method. The goal is to adapt the low-fidelity model with information from experiments and from high fidelity CFD simulations, in order to make it able to capture the relevant aerodynamic characteristics of any trapezoidal wing planform, at an arbitrary Reynolds number. To achieve this goal, the implementation of an adaptation model management strategy [19] and the use of multi-fidelity data-driven models will serve as an additive correction function enhancing the low order method. Nowadays, data-driven approaches represent a flooding field and a plethora of established techniques is available. Among them all, but not limited to, the aim of the project is to implement multi-fidelity Gaussian regression models combining CFD and wind-tunnel data.

F. Work-package structure

Five work packages (WP) have been planned within the MONNALISA project to meet all the objectives. The work plan foresees one management work package (WP1) divided in two tasks that will deal with the coordination and the administration of the project and dissemination/exploitation, and four additional work packages that will deal with technical activities, as shown hereafter, see also the work breakdown structure in Figure 3. WP2 is dedicated the design of experiments and high-fidelity simulation with uncertainty quantification. WP3 is dedicated the design and manufacturing of the wind-tunnel models. WP4 is related to wind-tunnel testing and high-fidelity simulations to produce the aerodynamic database. WP5 is devoted to the multi-fidelity modelling of non-linear aerodynamics (POLIMI).

IV. Conclusion

In this contribution, we described the Clean Sky 2 MONNALISA project. The final goal of the project is to develop a physics-based low-order model to accurately and efficiently predict the nonlinear aerodynamic properties of swept wings of unusual planform geometry. To achieve this goal a large database of the aerodynamic properties of several different wings will be produced by mixing experimental measurements and high-fidelity simulations. Uncertainty Quantification

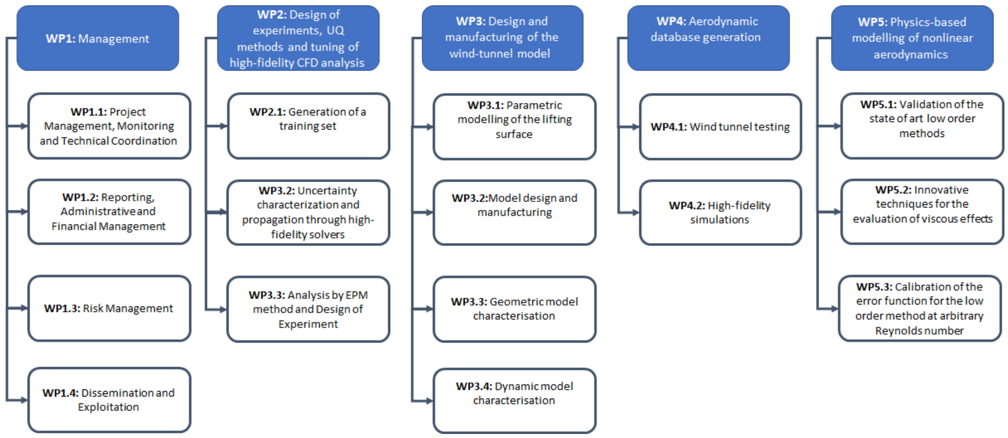

Fig. 3 Work breakdown structure of the MONNALISA project.

will be used to locate regions of the parameter space where simulations cannot be relied on and therefore experiments are needed, in order to reduce the number of different configurations to be tested in the wind-tunnel, ultimately reducing costs. The database will be made openly available and will therefore fill a gap in the availability of reliable data on the aerodynamic performance of swept wings of unusual shape. The database will drive the development of the low-order method. In particular, an adaptation model management strategy will be leveraged to produce an additive correction function to enhance the low-order method in the critical regions of the parameter space.

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