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Development of innovative movable surfaces for the next-generation civil tiltrotor aircraft

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Abstract

This paper proposes a novel approach based on a series of co-simulations combined with an optimization procedure used to perform the preliminary sizing of the NextGen Civil Tiltrotor control surfaces and the relative actuation system. The activity is collocated in the framework of the FORMOSA CleanSky2 project, which has the aim of designing an innovative solution for the wing movable surfaces able to incorporate multiple functions (download alleviation, flap, aileron) thus reducing the complexity of the actuation system.

Keywords: aeroelasticity, multibody dynamics, vortex-particle method, tiltrotor, control surface design.

Introduction

Tiltrotors are quite challenging vehicles to design since they must be able to combine both helicopter and fixed-wing aircraft characteristics. To control these aircraft is necessary to design suitable control surfaces. Additionally, the actuation system, driven by a complex Flight Control System (FCS), must be able to mix the control input during the different flight conditions that characterize the aircraft mission (Refs. [1], [2]). The design of the control surfaces and actuators selection requires a correct evaluation of the aeroelastic loads during the different maneuvers to improve the vehicle response, increase efficiency, and reduce the weight and complexity of the control system.

In the framework of the FORMOSA project (www.formosa-project.eu), funded by the Clean Sky 2 – H2020 Programme, Politecnico di Milano, CEiiA, and RMIT University joined forces, together with Leonardo Helicopters, for the development of innovative solutions for the wing movable surfaces of tiltrotors able to incorporate multiple functions including download alleviation, flap, and aileron.

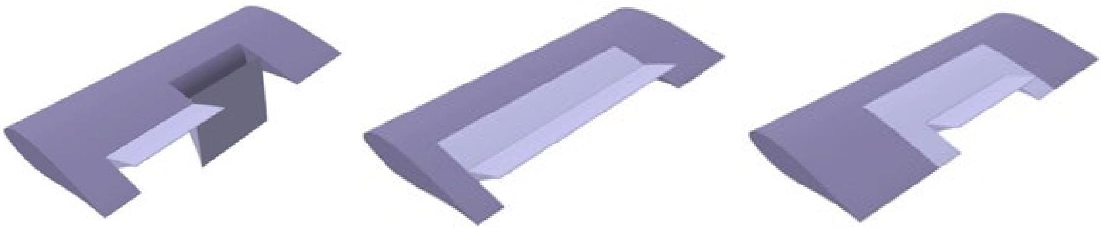
The FORMOSA consortium proposes a new methodology for the preliminary design and optimization of the flaperon control surface of the NextGen Civil Tiltrotor (NGCTR) demonstrator, based on coupled multibody -- mid-fidelity aerodynamics simulations. The coupled tool captures the aerodynamic interference among the rotors, wing, and fuselage during the transient maneuver and ensures quick simulations when compared to high-fidelity CSD-CFD tools. An optimization procedure, based on a Design of Experiment (DoE) approach, is then exploited to define the best configuration to improve the roll performance, trying to reduce the complexity of the actuation system. CFD analyses are limited only to the evaluation of the download during take-off and landing maneuvers.

The present work aims to summarize the activity of the FORMOSA consortium, starting from the trade-off study of different configurations, leading to the preliminary design review.

Tiltrotor Numerical Model

The numerical model of the NGCTR tiltrotor is built considering the full-scale dimensions and components of the aircraft. The model includes the fuselage, the wing equipped with control surfaces, and the two proprotors with the corresponding nacelles. The actual NGCTR flaperon control surface, represented in Figure 1 (left), consists of 2 different movable parts, where each specific wing control surface has been conceived to have a dedicated and specific function.

Figure 1: NGCTR flaperon configurations: baseline (left), Conf. I (center), and Conf. II (right)



The baseline movable surface encompasses an inner large flap up to +70 deg (down) deflections for download reduction and an external flaperon from -35 deg (up) up to +70 deg (down) deflections for roll control and download reduction. The first configuration (Conf. I) proposed by the FORMOSA consortium aims to occupy the least possible space over the wingspan but maintains or even improves performance levels, as well as reduces weight with the actuation mechanisms. The main objective is to integrate both the flap and aileron on the same surface (Figure 1, center), ease their use and reduce the weight of the moveable surface itself. Conf. II, illustrated in Figure 1 (right), builds on the previous solution, with the aileron being nested in the flap. In this proposal, an increase in the actuated area is possible.

Configurations I and II have the same flap, but different aileron control surfaces. In the preliminary design phase, the goal is to design the aileron control surface and to maximize the flap surface to be able to deflect the largest wing surface during the hover condition, thus reducing the download. The baseline configuration is studied as a reference to obtain a set of data to be compared with the performance of the innovative solutions, allowing to evaluate their effectiveness.

The combination of multibody dynamics with a mid-fidelity aerodynamic approach aims at an ideal trade-off, to obtain at the same time fast and time-accurate solutions for the preliminary design of tiltrotor aileron control surfaces. The multibody software used in this work is MBDyn (http://www.mbdyn.org/). The mid-fidelity aerodynamic solver employed is DUST (https://www.dust-project.org/). Both are developed at Politecnico di Milano and are open source. The communication between the two solvers is managed by preCICE (Precise Code Interaction Coupling Environment), a coupling library for partitioned Multiphysics simulations. preCICE (https://github.com/precice/) is also a free software. The coupled MBDyn-DUST tool, implementing an implicit tight coupling, has been validated as presented in Ref. [3]. The details of the NGCTR model can be found in Ref. [4].

Aileron Optimization Procedure

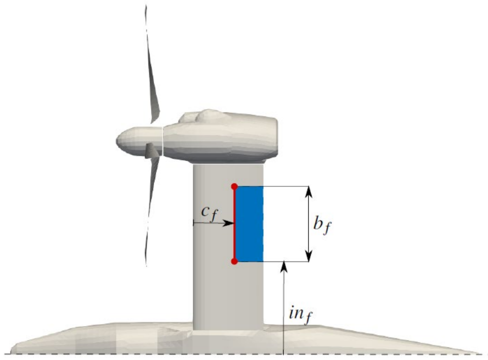
The optimization aims to identify the best geometric configuration of the aileron using as few simulations as possible to reduce the computational cost and therefore the design time. A Design of Experiments (DoE) approach is selected to evaluate the impact of the different geometrical input parameters on a subset of performance output.

The main geometrical design variables used for the definition of the different model configurations, illustrated in Figure 2, are the aileron span (b_f), the aileron inboard location (in_f), and the chordwise hinge axis location (c_f).

The Latin Hypercube Sampling is used to partition the design domain and to identify the initial set of configurations to analyse through the coupled simulations. Through a trade-off study phase, different combinations of these parameters were investigated to understand the impact on the required performance.

The simulations procedure foresees the aileron's deflection according to a step function from 0° to 20°, with the aircraft trimmed in airplane mode at Mach 0.2. The movables are deflected after 0.4 s, to let any initial aerodynamic transient vanish. At the same time, the roll degree of

Figure 2: Geometrical aileron parameters used for the design optimization; the red line represents the hinge axis



freedom of the entire model, initially constrained, is released, and the aircraft starts to roll around the longitudinal axis, assuming positive starboard (right) wing up.

To perform the optimization, a single objective function together with a set of constraint functions are defined and the corresponding response surfaces are built. The objective function is related to a performance index that is assumed as the necessary hinge moment (h_m) requested to actuate and deflect the aileron. The solver tries to identify the solution that minimizes it. The main non-linear constraint function is related to the effectiveness of the movables to take the vehicle to a prescribed bank angle (ϕ = 45°) in a prescribed time (t_b). In general, for the optimization problem the Δt_b reduction, with reference to the baseline configuration, is defined with an imposed boundary as -35% < Δt_b < -25%.

The other constraint is geometric and it is imposed by setting the sum of in_f and b_f less than the aircraft semi-span and greater than a minimum value related to the definition of the clearance span region for the design. Once the response surfaces are available, a single-objective genetic algorithm is adopted to solve the optimization problem. The response surfaces can be therefore exploited by the optimization algorithm to estimate the value of the function at any query point.

Download Prediction

To evaluate the benefits of the new design on the download it is necessary to conduct high-fidelity CFD analyses. The simulations consist of steady-state RANS with SST turbulence model performed with the SU2 solver [5].

The numerical model considered in this phase is shown in Figure 3. The rotor is modelled as an Actuator Disk. The imposed thrust is obtained by DUST considering the hover flight condition at Sea Level Standard ISA+0°.

The boundary conditions adopted are:

- Total conditions inlet: imposed free-stream pressure, temperature, and zero velocity;
- Back pressure outlet: imposed free-stream pressure;
- Actuator Disk: prescribed thrust (pressure jump);
- Constant heat flux wall: boundary condition on the surface wing, nacelle, and hub.

A multi-block unstructured mesh is generated where the entire domain was split in 3 blocks to set different refinement levels, as shown in Figure 4. The computational domain is extended sufficiently far from the model to avoid artificial boundary effects.

Figure 3: Numerical model adopted for download CFD simulations (left: baseline; right: new configuration)

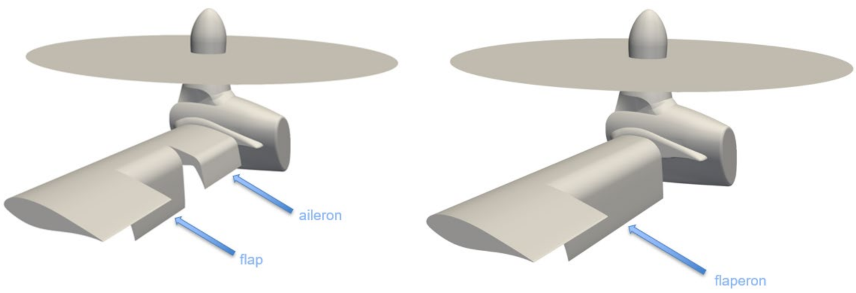
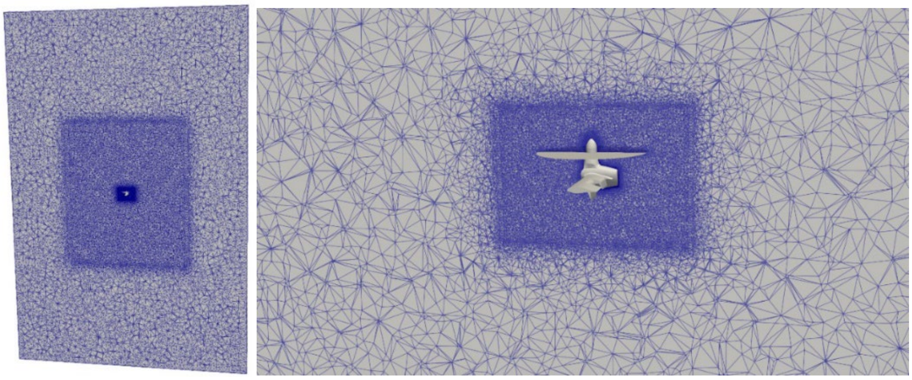


Figure 4: Overview of the unstructured multi-block grid



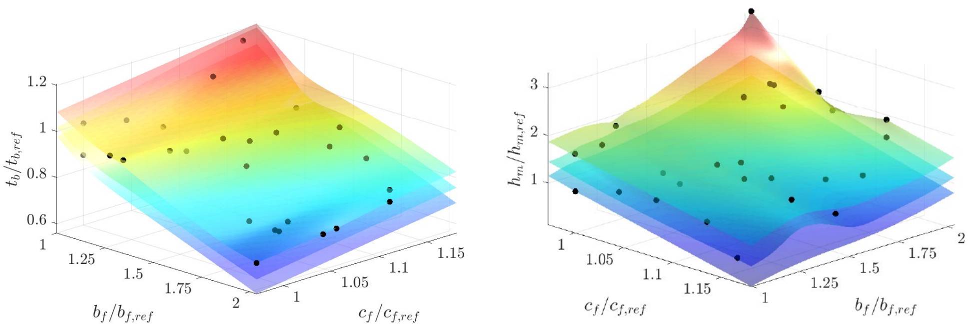
Results

Trade-off analysis

The results of the optimization phase and the design procedure are reported in the following. Note that the numerical values are dimensionless with respect to the corresponding baseline reference configuration indicated with the subscript *ref* since they are linked to a real vehicle managed by Leonardo Helicopter.

Working with a function of three parameters a response volume is obtained. To give a visual representation it is possible to freeze one specific parameter and show the parametric surface. In Figure 5 each surface corresponds to a different (fixed) value of in_f, giving an analytical description of the time to bank t_b and of the hinge moment h_m as a function of the two parameters b_f and c_f. The black dots are the values obtained from the coupled simulations.

Figure 5: Response surfaces for time to bank (left) and hinge moment (right)



Overall, lower t_b values are obtained when increasing both the aileron span and the chord size. It should be pointed out that a reduction of $c_f/c_{f,ref}$ represents an increase in the aileron chord dimension since the position of the hinge axis c_f is measured from the leading edge, leading to higher hinge moments. The volume described by the response surfaces is the domain within the optimizer that will search the optimal configuration of the three parameters b_f, c_f and in_f such that the time constraint is satisfied and the hinge moment minimized.

A single-objective genetic algorithm is adopted to solve the optimization problem. The results obtained for configurations I and II. are reported in Table 1. From the response surfaces, it is evident that is necessary to maximize the aileron span to reduce the time to bank, while the chord must be contained to minimize the hinge moment.

Table 1: Optimization results

Conf. I		Conf. II	
Optimal geometry		Optimal geometry	
$b_f/b_{f,ref}$	2.034	$b_f/b_{f,ref}$	1.948
$c_f/c_{f,ref}$	1.056	$c_f/c_{f,ref}$	1.056
$in_f/in_{f,ref}$	0.507	$in_f/in_{f,ref}$	0.548
Performance		Performance	
Δt_b	-25 %	Δt_b	-25 %
Δh_m	+75.7 %	Δh_m	+60.4 %

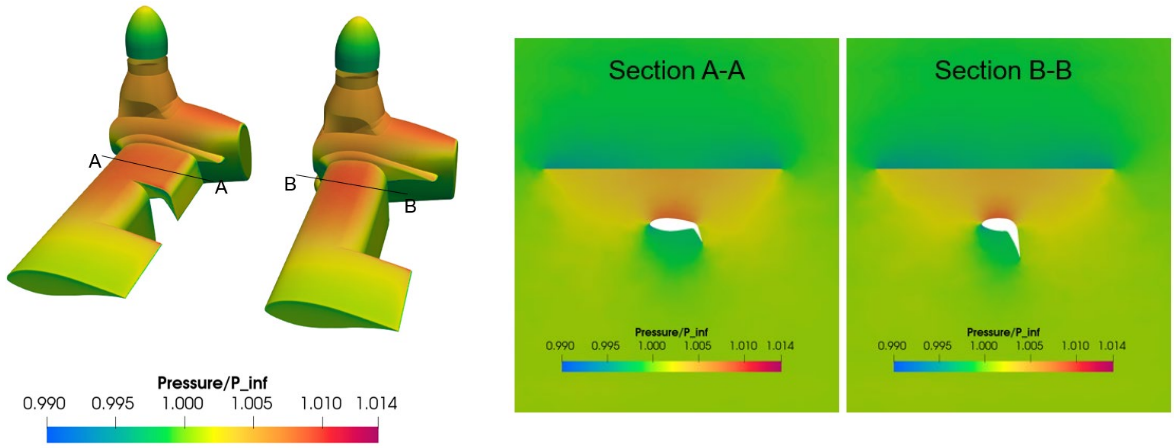
The two solutions satisfy both the roll performance requirement, reducing the time to bank when compared to the baseline solution. As expected, a higher aileron span is needed, while the chord is slightly reduced. The lowest hinge moment is obtained for conf. II, which shows an increment of about 60% compared to the baseline solution, due to the improvement in vehicle performance.

CFD analysis

Following the results obtained for the manoeuvring performance, the download for the innovative configuration is investigated and compared to the baseline solution. For the baseline configuration flap and aileron are deflected by 70° and 60° respectively, while the new design is characterized by a flaperon deflection of 70°. Considering the baseline model, a sequence of grids is generated with three different levels of fineness, to carry on a grid sensitivity study. The load convergence is achieved with 30M elements mesh. For the download evaluation of the new configuration, a grid with the same parameters as the baseline one is considered to preserve the convergence criteria.

A download reduction of 9% was found, showing the benefits of reducing the wing area and the corresponding rotor footprint. Figure 6 (left) depicts a comparison between the baseline and the new configuration in terms of dimensionless surface pressure. It can be noticed that the pressure on the nacelle remains similar while the main difference is the footprint of the rotor wake on the wing. Figure 6 (right) shows the flow field slices at sections A-A and B-B contoured by the dimensionless pressure.

Figure 6: Surface adimensional pressure contour (baseline and new configuration)

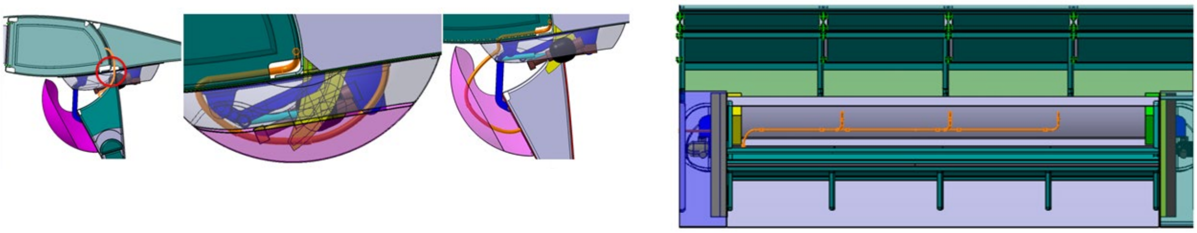


Actuation system

To minimize the download during take-off/landing manoeuvres it was established that the exposed airflow area should be minimized, which means that the flap must finish its motion below the wing. The flap hinge moments are retrieved with the aircraft flying in a trimmed condition at 270 kts, at Sea Level Standard ISA+0° conditions. This critical load case is used for the flap actuation system's initial sizing. The flap analysis is valid for the two configurations. Some characteristics, such as bandwidth and response time were defined as project requirements. The results of the trade-off study include the aileron geometrical parameters, the pressure distribution on the aircraft surface, and the hinge moments for both configurations I and II. These data are the input for the design of the aileron actuation systems, leading to the evaluation of the overall dimensions necessary for the installation of the actuators.

The flap's aerodynamic shape constrains the available volume since the aileron actuators will be placed inside it. The aileron presents the main challenge of having the power supply enter the flap box from the lower wing skin, to avoid shearing the cables during the deflection of the flap. See Figure 7.

Figure 7: Aileron cable routing (left) and system architecture (right)



In this case, electromechanical actuators are the preferred choice, since they present a simpler and more flexible power supply composed of only cables, which should also be more efficient. The full summary of the selected actuators is presented in the following.

Table 2: Flap and aileron actuator characteristics

Requirements	Flap Actuator
Dimensions	290 mm x 215 mm x 120 mm
Stroke	106 mm
Stall load	180 kN
Estimated Weight	5.4 kg
Speed	1 stroke/s
Bandwidth	7 Hz

Requirements	Conf. I	Conf. II
Dimensions	455mm 255mm* 95mm*	420mm 255mm* 95mm*
Stroke	+/- 16mm	+/- 18mm
Stall load	10.1kN	9.6kN
Estimated Weight	5.5kg	5.55kg
Speed	1 stroke/s	1 stroke/s
Bandwidth	7Hz	7Hz

Note: *based on existing products

Conclusions

The paper presents a novel approach, based on a series of co-simulations performed with a coupled multibody – mid-fidelity aerodynamic tool and an optimization procedure, to perform a preliminary design of two innovative wing control surfaces able to incorporate multiple functions (download alleviation, flap, aileron) for the NextGen Civil Tiltrotor.

The two proposed solutions have the same flap but different ailerons. In the preliminary phase, the design was mainly focused on the aileron, to improve the roll performance in airplane mode. The flap surface has been maximized to be able to deflect the largest wing surface during the take-off, landing, and hovering conditions, thus reducing the download effect. The download prediction and the flap optimization have been performed with the use of CFD solvers, leading to a download reduction of the 9% when compared to the baseline configuration.

Acknowledgments

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