NUMERICAL VS. EXPERIMENTAL ASSESSMENT OF OPTIMIZATION EFFECTS ON AERODYNAMIC PERFORMANCE OF ERICA TILTROTOR FUSELAGE

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Abstract

The results of a CFD-based optimization over a 1/8-scaled model of the ERICA tiltrotor fuselage are compared against experimental data obtained from an extensive wind tunnel campaign carried out at the RUAG facilities, as part of the DREAm-Tilt project funded by the Joint Technology Initiative Clean-Sky program. In particular, the effects of optimized geometries of nose, wing/fuselage junction, sponsons and empennages for drag reduction are investigated. The assessment proved the consistency of the optimization approach and the optimized ERICA geometries as experimental validation was successfully obtained.

1. INTRODUCTION

In the framework of the European JTI CleanSky GRC2 project devoted to drag reduction of airframe and non-lifting rotating systems of the Green Rotorcraft ITD, a CFD-based optimization of the ERICA tiltrotor configuration has been carried out and validated with experimental tests. Specifically, numerical simulations (namely, those performed within the CODE-Tilt project [1], also funded within the European JTI CleanSky Project) dealt with shape optimization of different parts of the ERICA tiltrotor fuselage (nose, sponsons, wing/fuselage fairings, empennages) in order to reduce drag and improve efficiency. CFD coupled with innovative design methodologies based on multi-objective evolutionary algorithms were used to this purpose.

In this paper, an assessment of the benefits achieved through the aerodynamic optimization of the above-mentioned components is described as a result of both experimental and numerical investigations. These activities are part of the DREAm-Tilt project [2] funded by European JTI CleanSky.

In the DREAm-Tilt project, a dedicated wind tunnel campaign on the final optimized fuselage shape (without rotors) has been carried out. In the Large subsonic Wind Tunnel (LWTE) of RUAG Aviation, the drag reduction compared to the original configuration was determined using a 1/8 scaled model. Accurate drag measurements were performed on a power-off model of the isolated ERICA tiltrotor fuselage in both the baseline and optimized configurations. All the optimized components (i.e. nose, wing/fuselage fairing, wing/nacelle fairing, sponsons and empennage) were tested sequentially with the aim of getting an accurate drag breakdown and identifying the contribution of each component to the overall aerodynamic performance of the fuselage. For all the test points, global aerodynamic forces and moments were acquired at several angles of attack, in order to capture the smallest drag variations between the baseline and optimised configurations. Additional experimental techniques such as flow visualisations and PIV measurements were used for a number of test points to get more detailed information about the flow. The corresponding results will be reported elsewhere.

Concurrently, a number of CFD calculations were carried out on both the model scaled fuselage and the full-scale aircraft in order to evaluate rotor interactional effects and the full-scale (free stream Mach dependent) characteristics. In particular, the optimized isolated fuselage scaled configuration (no rotors) was simulated in wind tunnel flow conditions, starting from the numerical models already tested and validated in the CODE-Tilt project [1]-[5]. All the "intermediate" optimized configurations were also analysed, with the optimized components mounted one at a time on the fuselage, in order to replicate the wind tunnel measurements and get a deeper insight into the interference effects of the various components.

The CFD results for wind tunnel flow conditions have been compared with the experimental data acquired in the wind tunnel test campaign. This helped to increase the confidence in both the numerical optimization procedures as well as the assessment of the optimization results by means of numerical methods. In a second stage, the numerical models already tested in wind tunnel conditions were used for assessing the aerodynamic performance of the optimized ERICA fuselage at full-scale conditions including the rotor effects.

2. NUMERICAL SIMULATIONS

2.1. Geometrical Model of baseline and optimized fuselage

A view of the baseline tiltrotor model used in simulations is given in Figure 1. Symmetry of the problem was exploited for simulation at null sideslip angle, hence only half of the aircraft model was used. On the other hand, simulations at non-zero yaw angle were carried out with the whole aircraft.

The wind tunnel model was created using the actual cross-section shape and size of the RUAG test facilities (Figure 2), while along the longitudinal direction the length was established based on previous experience that suggests to extend the fluid domain 2÷3 aircraft lengths upstream and 5÷6 lengths downstream of the fuselage.

In order to isolate the interference effects of the mounting pylon, the fuselage was simulated and tested both with ventral and dorsal support (ventral configuration is depicted in Figure 2).

Starting from the baseline model, four different configurations of the ERICA tiltrotor were created, replacing, one at a time, the baseline components with the optimised ones. The optimized components in order of assembly were: nose, wing-fuselage junction, sponsons and empennages (Figure 3).

2.2. CFD Model

The superficial mesh over both the baseline and optimized fuselages was generated using Altair® Hypermesh V12 [7]. Triangular elements were employed over the patches and their size ranged from 1 mm to 5 mm approximately.

The volumetric mesh was generated using Hypermesh V12 as well [3]. The mesh is of the hybrid type: triangular-based prismatic elements were created over the aircraft and pylons surfaces in order to better simulate the physic boundary layer, while tetrahedral elements were employed in the rest of the fluid domain. Prismatic cells were set-up so as to ensure a y+ value around 1 everywhere on the fuselage surface. A volumetric growth rate equal to 1.04 and a target mesh size equal to 50 mm were eventually used. A total of 16.2 M elements on the half aircraft was obtained (6.1 M prismatic elements and 10.1 M tetrahedral elements).

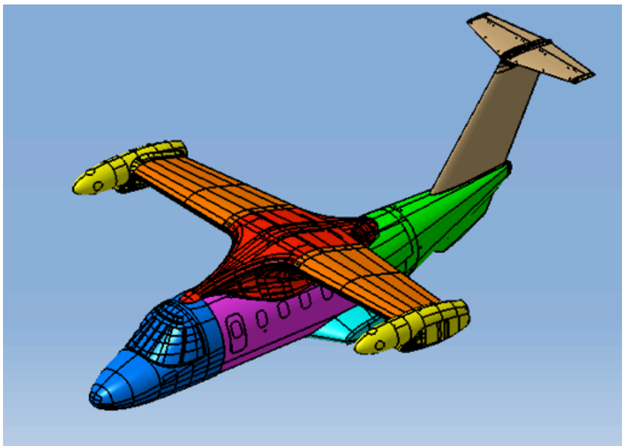

Figure 1: Overall view of the tiltrotor model used in CFD simulations [1].

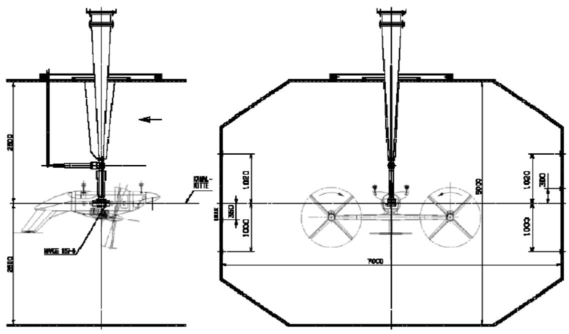

Figure 2: the ERICA 1/8 scaled model in the Large subsonic Wind Tunnel of RUAG Aviation [6].

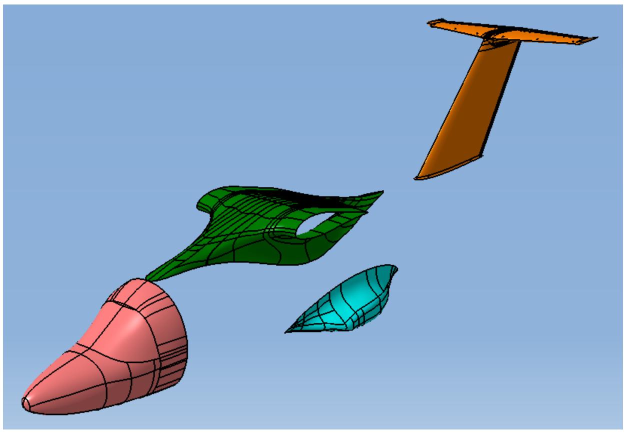

Figure 3: Optimized components coming from CODE-Tilt project.

CFD simulations were carried out using Ansys® Fluent V14 [8]. Specifically, a pressure based solver type with absolute velocity formulation and steady approach was used in the analyses. A k-ω SST turbulence model was used, since this was found to give satisfactory correlation against experimental data in CODE-Tilt. Air was treated as an ideal gas with constant specific heats. For the constant pressure specific heat coefficient and for thermal conductivity the default values were used. Viscosity was bound to the three-coefficient Sutherland law. Total pressure and total temperature conditions were imposed at the wind tunnel inlet, while a static pressure was assigned over the outlet section in order to reproduce the flight conditions specified in Table 1. For the turbulence model specifications, a hydraulic diameter equal to the total aircraft length was assigned together with turbulence intensity equal to 0.3%. Aircraft surfaces were treated as hydraulically smooth and adiabatic walls, while a symmetry condition was used for the lateral surfaces of the wind tunnel. A pressure-velocity coupled scheme was used in CFD computations. Regarding the spatial discretization, the least squares method was used for gradient calculation, the second order scheme for pressure and the third-order MUSCL was employed for the remaining scalars.

Table 1: Flight Conditions used for ERICA optimization in CODE-Tilt.

Flight condition	V_∞ [m/s]	P_∞ [Pa]	ρ_∞ [kg/m^3]	T_∞ (OAT) [K]	Mach number	Fuselage incidence [deg]
Forward flight	154.3	38251.4	0.566	239.4	0.497	-1.97

3. COMPARISON AGAINST WIND TUNNEL DATA ON 1/8-SCALED GEOMETRY

3.1. Baseline 1/8-scaled geometry

Aerodynamic coefficients of the baseline 1/8 scaled tiltrotor model (lift, drag and pitching moment) coming from the CFD simulations are summarized in Figure 4.

Experimental data collected during the test campaign were used for direct comparison with CFD results in all the geometrical configurations. During the tests, both free and fixed laminar to turbulent transitions over the baseline fuselage surfaces were studied. However, since experimental runs with single optimized components were carried out only with transition fixed, it was decided to compare all the geometrical configurations at fixed transition in order to make them consistent with each other.

It is worth noting that the experimental model included the propeller stubs, the effect of which on drag was known from previous experiments; therefore the effect of such stubs were properly taken into account upon comparing numerical vs. experimental data.

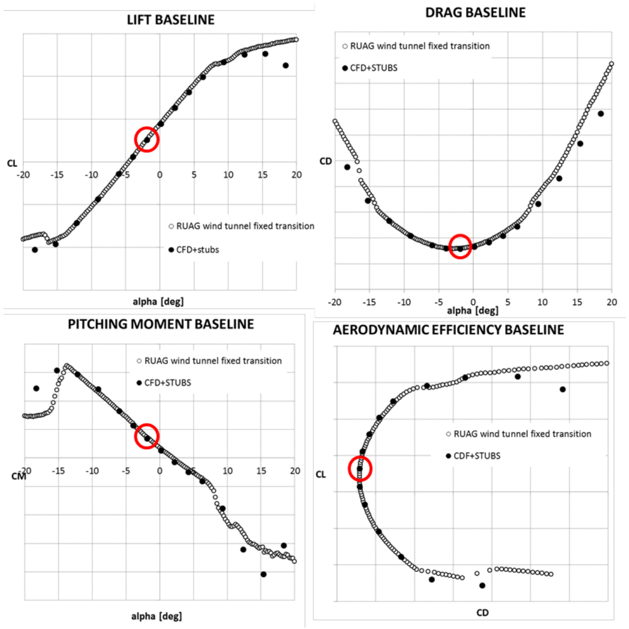

Figure 4: Lift (upper-left), drag (upper-right), pitching moment (bottom-left) and efficiency polars (bottom-right) of the baseline geometry: comparison between the CFD model results and experimental data.

Overall, the correlation between experimental and numerical data is very good at low and medium angles of attack, i.e. in the range [-12, +12 deg]. At higher absolute angles of attack, i.e. α> 12 deg and α < -12 deg, discrepancies are slightly higher, even if still reasonably low. In particular, lift coefficient values are excellently captured throughout the overall range of analysed angles of incidence, except for α> 12 deg. For drag, the correlation is very satisfactory in the range [-15, +10 deg], while for α> 10 deg. the numerical calculations tend to underestimate the drag relative to experimental data. However, the correlation in the vicinity of α=-2 deg, which is the attitude used for optimization, is excellent, and this suggests that the model is reliable as far as the evaluation of optimization effects is concerned. For the pitching moment coefficient, the correlation in the range [-12, +12 deg] is also excellent, with the slope of the linear portion of the curve very well captured, while a degradation of results is apparent at the highest values of incidence angles.

In addition, the aerodynamic efficiency of the tiltrotor is illustrated in Figure 4: once again, a very satisfactory correlation with experiment is shown and it can be deduced that the efficiency maximum value is located around α=2.5 degrees.

3.2. Optimized 1/8-scaled geometry

In Figure 5, the overall effects of the inclusion of all the optimized components are shown: specifically, both CFD and experimental data of the optimized 1/8-scaled fuselage are compared against the baseline. In addition, a zoom of the curves near the optimization attitude (i.e. α=-1.97 deg) is given in the same figure.

When for the angles of attack α are close to those used for the optimization, the fuselage features a drag reduction with respect to the baseline equal to 4% and 5% according to CFD or wind tunnel data respectively (percentage values are referred to overall aircraft including the propeller stubs). However, this drag reduction is accompanied with a simultaneous, significant lift decrease. In particular, at α=-1.89 deg, the lift decrease amounts to 17% approximately and 16% according to CFD or wind tunnel data, respectively. Once again, it is worth recalling that this lift drop is due to the geometrical differences between the baseline model tested in wind tunnel and that used for optimization, and was already present in the baseline geometry used for optimization, as will be better shown in the following.

Despite the significant lift decrease, the aerodynamic efficiency of the optimized fuselage is significantly increased with respect to the baseline (Figure 5), not only at the optimization attitude, but also over the whole low/medium range of incidence angles.

Finally, regarding the pitching moment characteristics, the curve slope is increased with respect to the baseline (Figure 5).

3.3. Differential contribution of the optimized components to aircraft performance for 1/8-scaled geometry

In Figure 6, a summary of the achieved optimization results in terms of drag reduction is given: in particular, CODE-Tilt and DREAm-TILT results for each optimized component (both numerical and experimental) are reported and compared against the pertinent GRC target. First of all, it has to be noticed that the original drag reduction calculated in CODE-Tilt refers to the aircraft without rotor stubs: since the stubs contribute to the whole drag in a significant way (around 30% of the total drag), and since they were actually included in the wind tunnel tests, the drag gain coming from optimization was re-calculated including the stubs. As is apparent from the figure, while without stubs the achieved reduction in CODE-Tilt was 7.7%, including the stubs it is reduced to 5.1%. On the other hand, in the present work it was found that the overall drag reduction at design incidence is equal to 4% and 5% according to CFD or wind tunnel data respectively.

Apparently, in spite of the differences in the results between CODE-tilt and DREAm-TILT, the overall target for drag reduction required by GRC (i.e. 3.55%) is achieved and even exceeded, according to both CFD and wind tunnel results. In addition, the experimentally measured drag reduction (i.e. 5%) is very close to that predicted in CODE-Tilt (i.e. 5.1%) when the stubs effect is included.

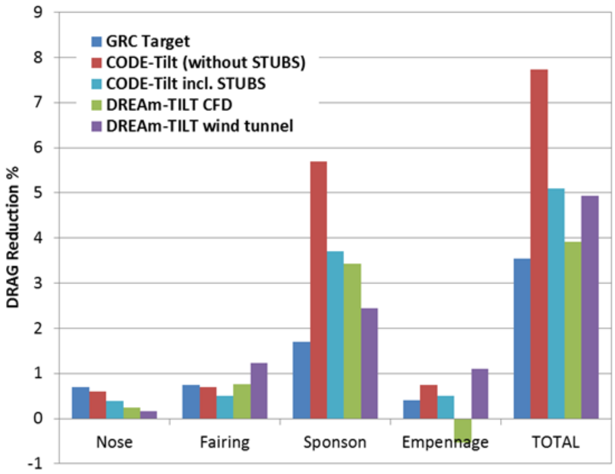

Figure 6: Summary of achieved optimization results in terms of drag reduction: CODE-Tilt and DREAm-TILT results vs. GRC target, numerical and experimental results.

4. EXTRAPOLATION TO FULL-SCALE

In the following, the numerical results obtained using numerical models already set-up and validated against wind tunnel data over the 1/8 model scale aircraft are presented with the aim of assessing the aerodynamic performance of the optimised ERICA fuselage at full scale conditions. Therefore, an accurate analysis of the effects of shape optimization of all components on the aircraft performance at Mach and Reynolds numbers typical of the full scale operating conditions has been performed. It is worth considering that also the rotor effects were included in the numerical simulations by using an actuator disc approach (Figure 7). To this purpose, a pressure jump distribution was defined over the disc.

4.1. Baseline Vs. Optimized geometries at full scale conditions

The simulation results of the fully optimized fuselage (i.e. fuselage with optimized nose, wing/fuselage junction, sponsons and empennages) at full-scale conditions are reported hereafter and compared against the baseline.

The numerical values of the aerodynamic coefficients of the full scale optimized fuselage (lift, drag and pitching moment) coming from CFD are shown in Figure 8, together with those of the baseline geometry. A zoom of the curves near the optimization attitude (i.e. α=-1.97 deg) is shown in the same figure.

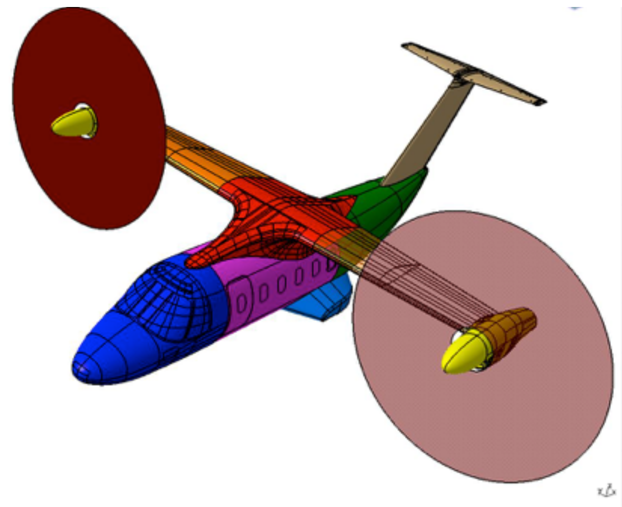

Figure 7: Overall view of the tiltrotor model used for full scale simulations.

From Figure 8, it is apparent that a significant drag reduction is achieved for -18 deg<α<4 deg. In particular, for α close to the optimization attitude, a drag reduction equal to 4.5% is achieved thanks to the optimized components (percentage values are referred to the overall aircraft without propeller stubs). However, this drag reduction is accompanied with a simultaneous lift decrease, mainly due to the wing/fuselage junction, and partially also to the empennage. In particular, at α=-1.97 deg, the lift decrease amounts to 6% approximately.

In addition, from Figure 8 it is apparent that the linear portion of the lift curve is slightly shifted downward in the vicinity of the optimization attitude, even though its slope is left nearly unchanged.

Despite the lift decrease, it is worth noting that the aerodynamic efficiency of the optimized fuselage is significantly increased with respect to the baseline, over a range of incidence angles close to the optimization one.

Finally, regarding the pitching moment characteristics, the linear portion of the curve is shifted upwards with respect to the baseline, and its slope is slightly decreased.

4.2. Differential contribution of the optimized components to aircraft performance for full-scale geometry

In Figure 8, a summary of the achieved optimization results in terms of drag reduction is given: in particular, CODE-Tilt and DREAm-TILT results for each optimized component are reported and compared against the pertinent GRC target and the results over the 1/8th scaled model (both numerical and experimental).

First of all, it is worth underlining that the original drag reduction calculated in the CODE-Tilt project refers to the aircraft without rotor stubs: since stubs contribute to the whole drag in a significant way (approximately 30% of the total drag), and since they were actually included in the wind tunnel tests, the drag gain coming from optimization was re-calculated including stubs. As apparent from Figure 8, while without stubs the achieved reduction in CODE-Tilt was 7.7%, including the stubs it is reduced to 5%. On the other hand, in the present work, it was found that the overall drag reduction at design incidence and full-scale conditions is equal to 4.5% ca. (not including stubs and rotor). Drag reduction is lowered at 4.2% when rotors are included. In any case, inclusion of rotors seems to preserve the majority of the beneficial effects coming from optimized components.

Thes inconsistencies with the original findings from the optimization (in particular with regard to the empennage contribution) could be due, to differences in the numerical model set-up (especially regarding the computational grid). Also, during optimization one optimized component at a time was taken in consideration and optimization of each component was carried out with all the other components in their baseline version. Hence, no interference effects among optimized components were considered. These effects are included in the CFD simulations at full-scale conditions. Therefore, this could be an additional explanation for the differences observed here with original values coming from components' optimization, especially for empennages, that are located downstream of all the modified components.

5. CONCLUSIONS

In the present paper, the results of a validation of CFD numerical simulations for both the 1/8- and full-scale model of ERICA tiltrotor are illustrated, based on a direct comparison against experimental data coming from an extensive wind tunnel campaign carried out at the RUAG facilities. In particular, the baseline and fully optimized configurations were analysed.

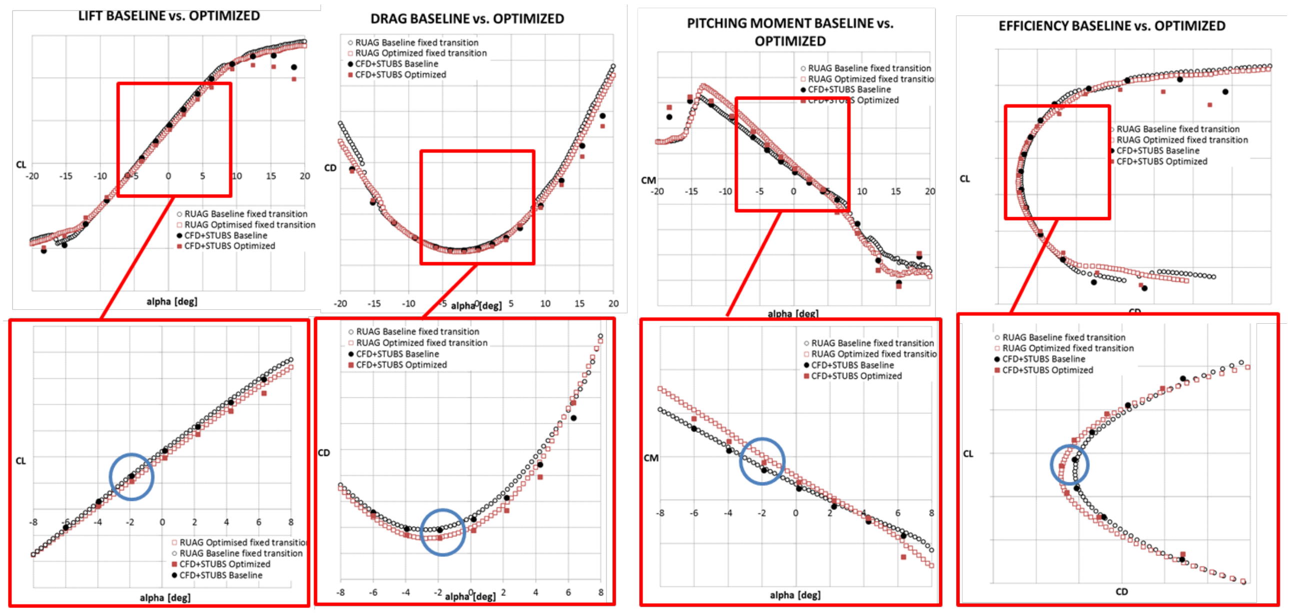

Figure 5: Lift, drag, pitching moment and efficiency polars of the baseline and the optimized 1/8-scaled fuselage geometry: comparison between CFD results and experimental data. Overall polars (top) and zoom around the optimization attitude (bottom).

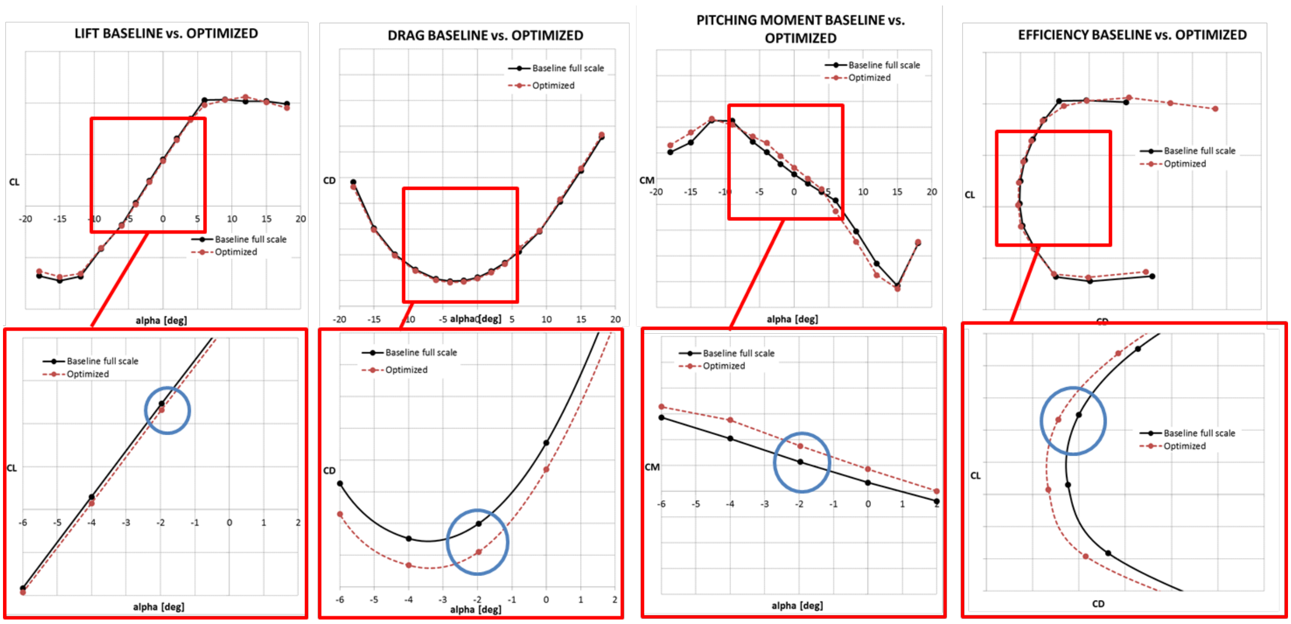

Figure 8: Lift, drag and pitching moment polars and efficiency curve of the full-scale optimized geometry compared against the baseline. Overall polars (top) and zoom around the optimization attitude (bottom).

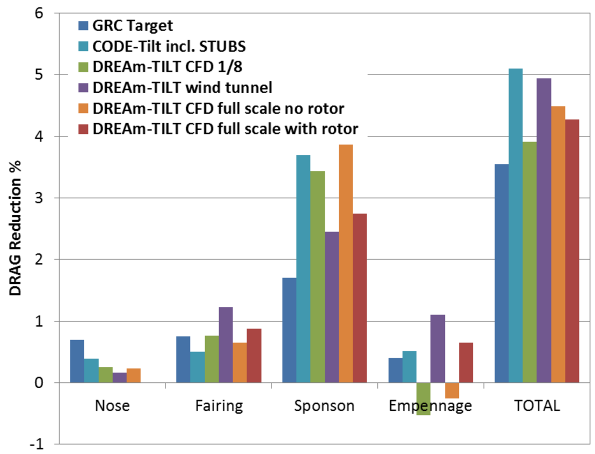

Figure 8: Summary of achieved optimization results at full scale conditions in terms of drag reduction: CODE-Tilt and DREAm-TILT results vs. GRC target, numerical and experimental results.

Overall, the fully optimized 1/8-scaled fuselage gives an overall drag reduction at α=-1.89 deg. equal to approximately 4% and 5% compared to the baseline according to numerical or experimental data respectively. Simultaneously, the lift decrease byf 17.3% (CFD) or 15.6% (wind tunnel). The largest contribution to the drag reduction comes from the optimized sponsons, followed by the optimized wing/fuselage fairing. The overall target for drag reduction required by GRC (i.e. 3.55%) is achieved and exceeded according to both CFD and wind tunnel In addition, drag reduction measured in the wind tunnel (i.e. 4.9%) is very close to that predicted in CODE-Tilt (i.e. 5.1%) when the stubs effect is included.

Regarding optimization at full-scale conditions, the numerical results indicate that, for the baseline configuration, the slope of the lift curve is increased compared to the scaled model due to increased Mach and Reynolds number (even though this effect is partially counterbalanced by geometrical differences in wing/fuselage fairing). The drag at the aircraft attitude subject to optimization was decreased with respect to the scaled model. Inclusion of rotor effects has negligible impact on the aerodynamic coefficients, at least over a range of incidence angles close to the optimization one. On the whole, the full-scale, fully optimized fuselage gives an overall drag reduction at α=-1.97 deg equal to 4.5% with a simultaneous lift decrease of 6%. When rotor effects are taken into account, the drag reduction is 4.2% with a lift decrease of 6.6%. Alos in the full-scale case, the largest contribution to drag reduction comes from the optimized sponsons, followed by the optimized wing/fuselage fairing.

On the whole, in spite of the differences in results between CODE-tilt and DREAm-TILT discussed above (especially the negative contribution of the empennage found from CFD calculations at full scale conditions), the overall target for drag reduction required by GRC (i.e. 3.55%) is achieved and overcome. In addition, the experimentally measured drag reduction (i.e. 4.9%) is very close to the original one predicted in CODE-Tilt (i.e. 5.1%) when the stubs effect is included.

6. ACKNOWLEDGMENTS

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8. LIST OF SYMBOLS

α	angle of attack	deg
V	Velocity	m s^{-1}
ρ	Air density	kg m^{-3}
q	Dynamic pressure (1/2 rV^2)	Pa
P	Static pressure	Pa
P_0	Total Pressure	Pa
T	Static temperature	K
T_0	Total temperature	K
C_P	Pressure Coefficient $(P-P_\infty)/q_\infty$	
C_{P_tot}	Total pressure loss coefficient $(P_{t\infty}-P_t)/(P_{t\infty}-P_\infty)$	

L	Lift	N
D	Drag	N
S	Side force	N
M	Pitching Moment	Nm
Y	Yawing Moment	Nm
C_L	Lift coefficient	
C_D	Drag coefficient	
C_M	Pitching moment coefficient	
C_Y	Yawing moment coefficient	
C_S	Side force coefficient	
M	Mach number	
Re	Reynolds number	