Numerical analysis of propeller effects on wing aerodynamic: tip mounted and distributed propulsion

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ABSTRACT

The purpose of this investigation is determinate the effects of propeller on wing aerodynamic, both for a propeller mounted in the middle of the wing, and for tip mounted propeller. Especially, it is investigated how a tip-mounted propeller can decrease wing induced drag, and how distributed propulsion can increase the high-lift aerodynamic. Analyses are carried out using a Virtual Disk Model on CFD software, showing a good agreement comparing numerical results with experimental data obtained by previous works. Wing tip engine with propeller, has been employed on a general aviation aircraft wing with an installed thrust to accomplish with cruise performance, reducing the induced drag. Distributed propeller engines on the wing allows improving of low speed performance, increasing the aircraft lift coefficient. Induced drag can be reduced of about 2-3% a low cruise lift coefficient, until 8-10% at relative high cruise lift coefficient. Maximum achievable lift coefficient could be increased of about 20-30% in clean configuration, and more than 50% in flapped configuration.

KEYWORDS: *aircraft propeller simulation, tip propeller effects, distributed propulsion*

NOMENCLATURE

AR	- Aspect Ratio	RANS	- Reynols Averaged Navier Stokes
C_D	- Drag Coefficient	Re	- Reynold's Number
C_l	- 2D lift coefficient, along wing span	T_c	- Thrust Coefficient
C_L	- Lift Coefficient	V_{stall_clean}	- Clean (Flap up) Stall Speed
$C_{L,MAX}$	- Maximum Lift Coefficient	V_{stall_flap}	- Flap down Stall Speed
b	- wing span	α	- Angle of attack
d	- Propeller Diameter	$\beta_{0.75}$	- Blade angle at 75% of radius
J	- Advance Ration of Propeller	δ_F	- Flap deflection, positive down
M	- Mach Number	η	- non-dimensional wing span y/b
MAC	- Mean Aerodynamic Chord		

1 INTRODUCTION

This paper aims to provide an overview of the aerodynamic effects of tip mounted propeller and distributed wing propulsion on a commuter aircraft wing. Two of most promising fields to improve aircraft performance, enhancing the capabilities in the design of novel aircraft configurations, are the morphing technologies [1] and hybrid-electric, distributed propulsion. Especially for the electric propulsion, the benefits of such an adoption are applicable in the following areas: (i) safety, (ii) emission, (iii) community noise, (iv) operating costs [2]. Ongoing development, research, and eventual production projects, are focusing on the low-power, low-range, limited utility platforms dedicated to the flight training market, as seen in the Airbus E-Fan [3] and Pipistrel Alpha Electro [4] and NASA Sceptor X-57 [5]. These are stepping-stone platforms by their parent companies for entrance into larger, more powerful aircraft.
One of the most significant barriers to adoption of electric propulsion in aircraft is the weight of the onboard energy storage. Current battery technologies yield 60-100x less energy stored per unit mass as compared to typical aircraft fuels [6]. Even with a threefold increase in efficiency, this is a prohibitive mass penalty for a simple powerplant retrofit to yield the same payload and range performance as the gasoline-powered counterpart. However, this impact is lessened if the mission capabilities of the aircraft are matched to actual use. For example, McDonald shows two use cases where current missions are performed by aircraft that have too much payload-range capability [7]; it is these "short-haul" missions that will likely be the early beneficiaries of electric propulsion. Generally electric aircraft can be designed with a different set of requirements, benefiting also from the propulsion integration due to the scale-invariant propulsion efficiency versus power level. Distributed Electric Propulsion (DEP) architectures can yield a net benefit in total efficiency due to synergistic airframe-propulsive coupling [8]. At NASA, the benefits of DEP technology have been investigated, starting from the conceptual design [5] until a flight demonstrator. To establish the potential advantages of tip mounted propeller engine and distributed propulsion, aerodynamic aircraft performance with the adoption of such technologies must be well predicting until a preliminary design stage. Nowadays the use of computational fluid dynamics (CFD) allows to capture more and more aerodynamic phenomenon, and it also enables the creations of surrogates models and design methods to be used during preliminary design stage [9][10][11][12][13] with more reliability. Parametric aerodynamic analyses can be carried out, and results assembled into databases, useful for design purposes, and integrated into aircraft preliminary design and analyses software [14][15]. Developed methods have been validated and used in the design of turboprop and commuter aircraft [16][17].
In this paper CFD is used to evaluate the effects of a propeller tip mounted engine, establishing rules and parameters which mainly affect the aerodynamic results. Firstly, the analysis method has been validated with available experimental results, and then used to evaluate the aerodynamic effects on commuter aircraft wing. Induced drag can be reduced with a tip propeller which rotates in the opposite direction of wing tip vortex. Secondly, the distributed propulsion aerodynamic analyses have been performed to estimate the low-speed, high-lift capabilities of such configurations. Due to the propeller blowing on the wing, the high lift coefficient of DEP configurations can be increased up to 50-80% on a typical general aviation commuter aircraft wing. Moreover, it opens the possibility to design a wing and an aircraft in a different manner, with higher maximum lift coefficient and lower wing surface.

2 METHOD

Numerical analyses have been conducted using the software STAR-CCM+ v9.06, by CD-Adapco. In all the simulation, a polyhedral mesh has been used, which guarantees a number of cells about five times lower than equivalent tetrahedral mesh. All the simulations have been solved with RANS equation.
To define right mesh, several preliminary aerodynamic analyses have been performed. By looking the equations residuals and aerodynamic coefficients convergence, the lowest number of cells was determined, and so the mesh Base Size, that leads to a stable solution. An example is show on Fig. 1. The final mesh is the better compromise in terms of solution, convergence criterion satisfaction and

mesh size, of about 4e6 polyhedral cells, 20 prism layers on the wall, with a y+ of magnitude equal to 1 (see Fig. 2).

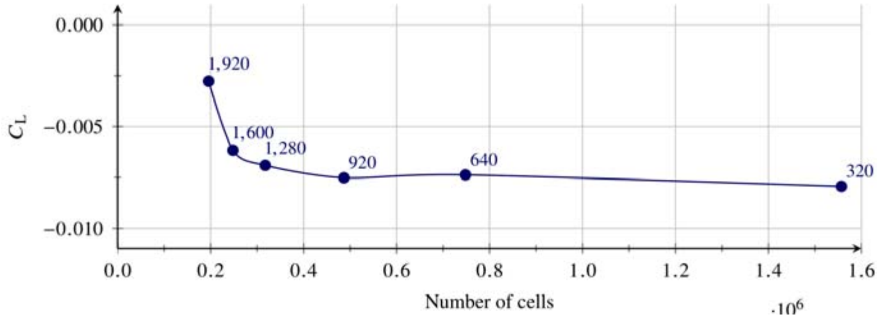


Figure 1: Calculate Lift Coefficient, depending on mesh consistence

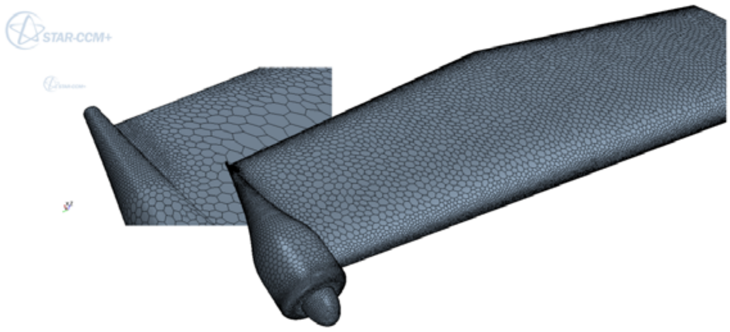


Figure 2: Baseline polyhedral mesh, 4e6 cells, $y^+ \approx 1$

Various analyses have been set on different M and Re numbers, with a k-ε method. Analyses have been based on *Virtual Disk Model* implemented in STAR-CCM+ to define effects of propellers. This method is based on the definition of a Virtual Disk, such as a volume of infinitesimal thickness in which the propeller actuates a pressure jump, and a swirl, to the flow, simulating the effect of a real propeller without the needing of define a real rotating model.
Among the Virtual Disk force definition, a Body Force Propeller Method has been chosen; in this way, the definition of propeller characteristics takes places through the insertion, in the software, of a table that defines Thrust Coefficient, Torque Coefficient and efficiency as a function of the advance ratio J.
So, it has been necessary to define a propeller model based on Renard coefficients, according to propeller model and experimental data measured. Fig. 3 shows the accordance between the numerical model used for propeller coefficient, based on NACA 640 report [18] and experimental data from [19], of thrust coefficient T_c defined as:

$$T_c = \frac{T}{\rho\, V^2 D^2} \tag{1}$$

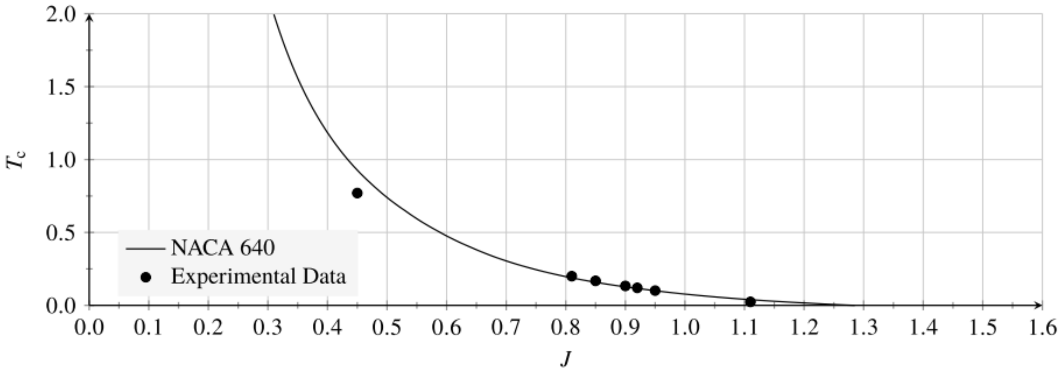


Figure 3: Propeller model (based on NACA 640 report) and Experimental data, Tc curve

2.1 Test cases

To validate the model, two test cases have been analysed, both based on ProWiM (PROpeller WIng Model) configurations of wing-nacelle-propeller. These models have been used in the research of the Delft University of Technology on the effect on the aerodynamic characteristics of the interaction propeller-wing; the experimental data, collected from the TU Delft introduced in [19] and [20], have been compared with the results of numerical analysis conducted via CFD solver, to validate the method. Wing planform with engine positions details of both test cases are shown in Fig. 4 and Fig. 5.

ProWiM model consists in a square no swept, no tapered wing of AR=5.33; constant chord and airfoil NACA 64-2-015A, laminar and symmetric. Nacelle have a cylindrical base shape, with a blunted front edge and a sharp rear edge, and it is mounted with its rotation axis on the MAC-line, at y=0.3m form the wing root (η=0.469). Used propeller is a NACA 5868-9, Clark Y section, 4 blades, with $\beta_{0.75}$ = 25°; its data are got form NACA report 640 [18] by a graph digitalization of curves. Analyses have been set on M=0.14 and Re = 0.80 · 10^6, even for clockwise and anticlockwise propeller rotation direction.

Second test case analysed is ProWiM-2 model, a similar configuration with tip-mounted propeller, defined in [20]. Again, a square no swept, no tapered wing, generated by a NACA 64-2-015A, laminar symmetric airfoil; a cylindrical nacelle with a 5868-9 four blade propeller. In this second case, propeller has a $\beta_{0.75}$ = 23°; again, its data are got form [18] by a graph digitalization of curves. The aerodynamic analyses have been carried out at M = 0.10 and Re = 0.58 · 10^6, even for clockwise and anticlockwise propeller rotation direction. Both test cases examined lead to a good fitting of numerical results on experimental data of [19] and [20].

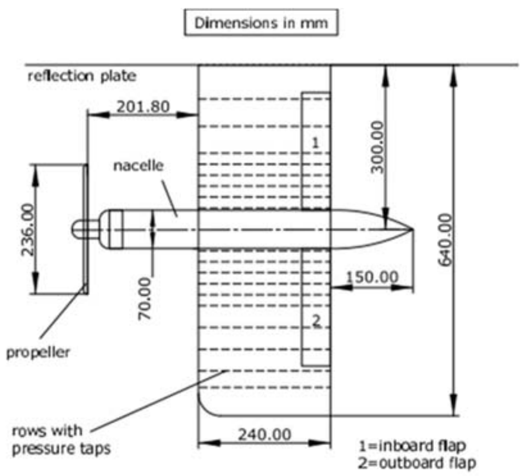


Figure 4: ProWiM model main dimensions [19]

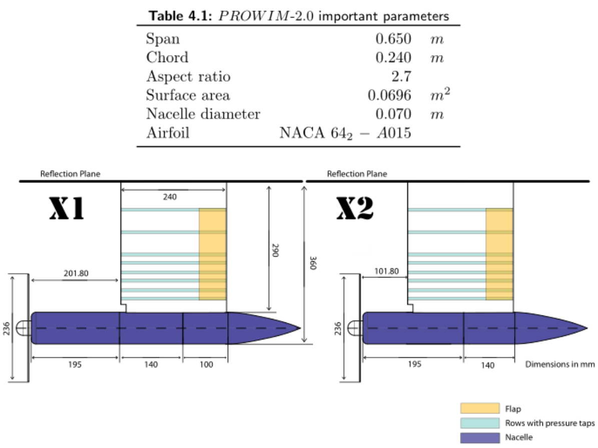


Figure 5: ProWiM-2 model main dimensions [20]

Concerning ProWiM model, since numerical solution fits into experimental data, both for global coefficients (as shown in Fig. 6 and C_l distribution along the span in Fig. 7), the method for this configuration can be considered valid. It is verified that the presence of the propeller increases lift coefficient of wing-nacelle configuration paying a very little rise of drag coefficient.

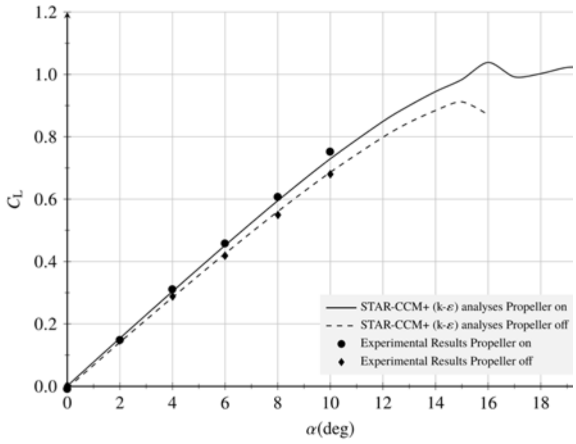


Figure 6: Comparison between numerical and experimental results about C_L on ProWim model

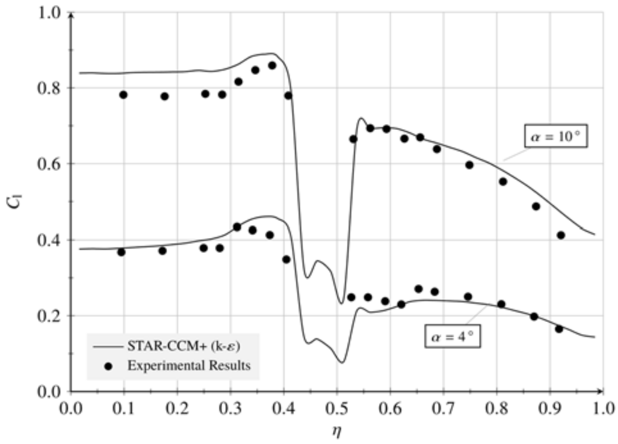


Figure 7: Comparison between numerical and experimental results about C_l on ProWim model, propeller on

As it can be appreciable in Fig. 8, results of analyses on ProWiM-2 model show a good agreement in C_L except stall behaviour, due to different transition method used: a k-ε method for numerical analysis and a free transition on experimental model. On the other side difference of C_D shown in Fig. 9 is mainly due to parasite drag of real propeller in the experiments, not considered on numerical analyses since a real propeller is not present.

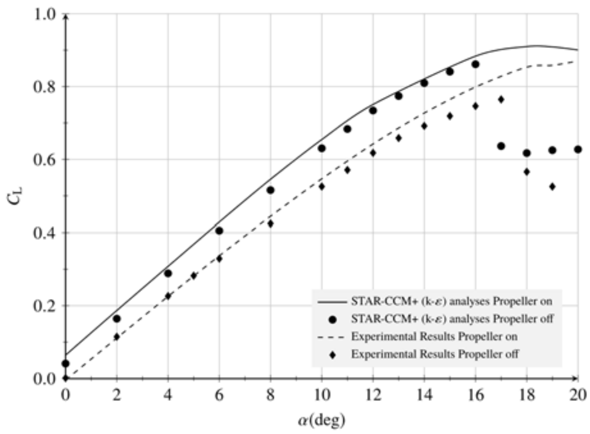


Figure 8: Comparison between numerical and experimental results about C_L on ProWim-2 model

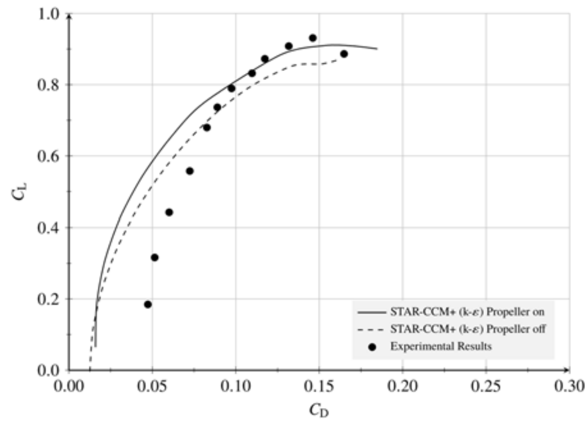
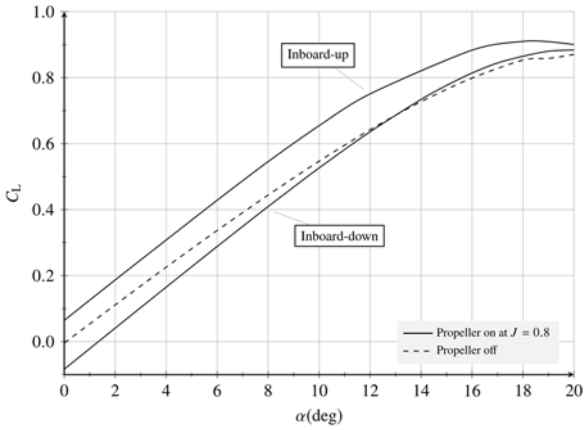


Figure 9: Comparison between numerical and experimental results about C_D on ProWim-2 model

Finally, it has been investigated the effect of propeller rotation direction: it is verified that propeller inboard up rotation not only rise lift coefficient, as shown in Fig. 10, but overall determinates a reduction of induced drag, while an inboard down rotation leads to a higher drag, as shown in Fig. 11, and lower lift.



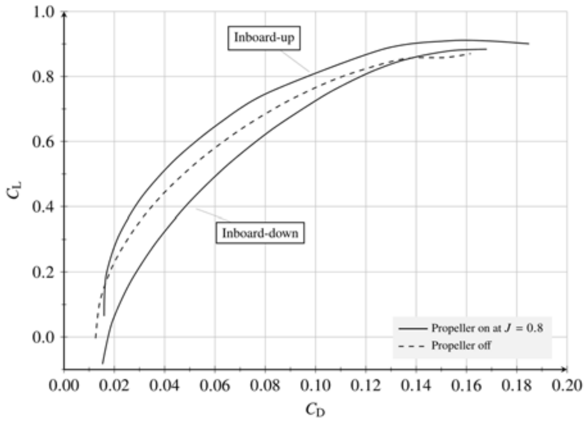
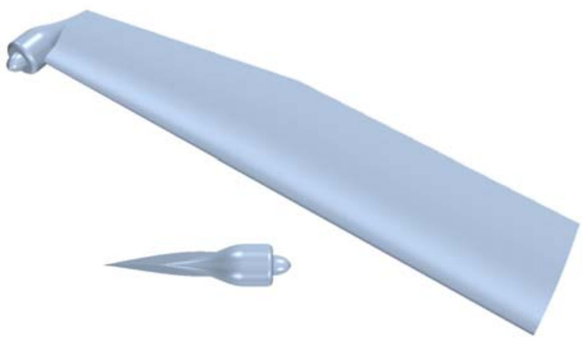


Figure 10: Effect of rotation handedness on Lift Coefficient CL

Figure 11: Effect of rotation handedness on Drag Coefficient C_D

3 WING-TIP PROPELLER CONFIGURATION

Once the data has been validated through comparison between numerical and experimental results, a new model has been defined to investigate effects of tip mounted propeller on a typical commuter aircraft wing. Object of the analyses has been to evaluate how propeller diameter and thrust setting affect aerodynamic drag of the wing, especially to establish a best compromise between thrust setting and propeller diameter that guarantees lower drag.
The wing model is based on Tecnam P2006 wing with a tip-mounted propeller; nacelle main diameter was obtained from Siemens SP260D dimension retrieved from [21], while nacelle shape was obtained evaluating some different concepts, and then choosing the one that provides the lowest drag around a typical cruise condition. The propeller chosen in this investigation is a 2-bladed MT Propeller MTV-21 diameter, according to the one mounted on Tecnam P2006T. While on P2006 each propeller is powered by a Rotax 912S3 of 98.6hp, on this model it has been hypothesized an electrical propulsion, based on Siemens Siemens SP260D.
Three different propeller diameters have been considered between d=1.00 m d=1.78 m; it was supposed that it is not of interest to choose a diameter lower then d=1.00m, because propeller effect would be confined in a too short region; by the other hand, it was chosen of not exceed P2006T real propeller diameter of 1.78 m.



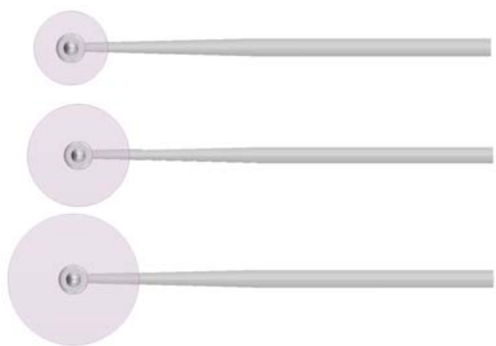


Figure 12: Wing-tip propeller configuration used in the analyses

Figure 13: Three different propeller disks used in the analyses

Main aerodynamic results are summarized in Fig. 14. The presence of a propeller at the wing tip have a beneficial effect on drag reduction; the higher is the diameter of the propeller, or the higher is the thrust provided by the propeller, the lower is the induced drag. It can be noticed that setting on the propeller leads to an effective reduction of C_D for a larger propeller, while for short diameter propellers (such as d=1.00m) there is additional drag induced by the presence of the active propeller. By the other hand, analyses suggest that using a diameter too large will not lead to a further drag reduction, or even affect negatively the drag.

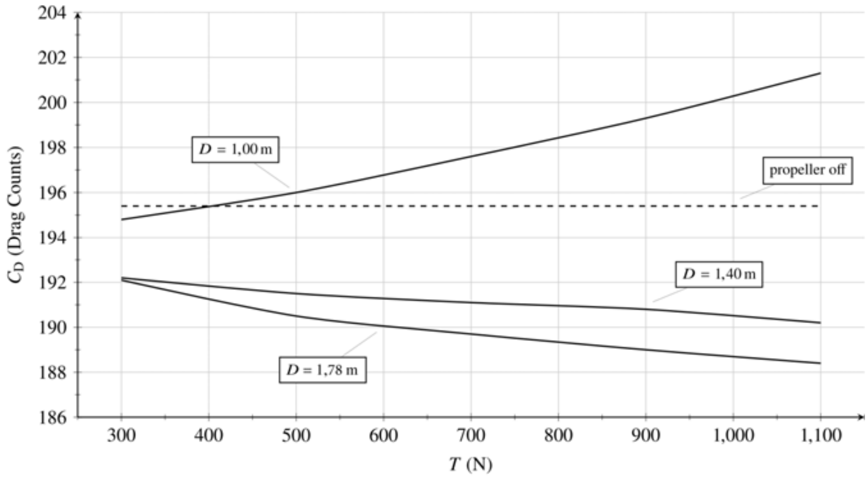


Figure 14: Effect on C_D of wing-tip propeller, variating diameter D and Thrust T, for a cruise condition $C_L = 0.4$

It seems clear that drag reduction is due to a vorticity reduction, since the vorticity developed by the propeller is opposite to, and then attenuates, the wing-tip vorticity. It is possible to see that, drag coefficient decreases when thrust increases (and lift coefficient increases). Only for d=1m, especially at low lift coefficient, the trend is opposite: this is due to the evanescence of the vortices introduced by the low diameter propeller, compared to the engine nacelle. The propeller vortex does not more counteract the wing tip vortices, especially at low value of lift coefficient, where vorticity sheds into the flow near to the wing tip where nacelle is located. When lift coefficient increases, the wing tip vortex moves forward and increases, and the propeller tip vortex can now interact with it, reducing the drag coefficient, more and more when thrust increases. This effect is clearly shown in Fig. 15 and Fig. 16, where it is to clarify that vorticity absolute value is shown, and so sign of vorticity is not visible.
It is important to emphasize that asymmetric thrust in an engine failure situation, and consequent big yaw moment because of a higher arm, represents a serious limitation to the development of tip-mounted propeller aircraft, at least for high AR wings.
On the other hand, it will be clear that usage of distributed propulsion can even obviate this problem. At end, it is obvious to highlight that a tip-mounted propeller needs to reconsider structural design in a proper way, but it also opens the possibilities to consider a different engine design integration to reduce drag, especially at higher lift coefficient.

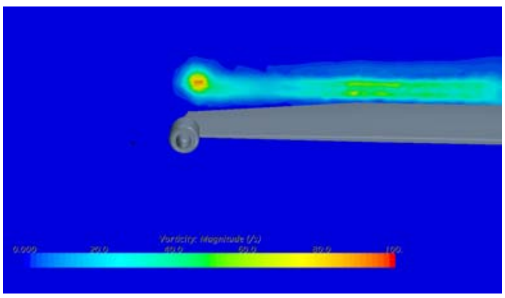


Figure 15: Vortcity induced on a plane 1.0m backward trailing edge by propeller off (d=1.78m)

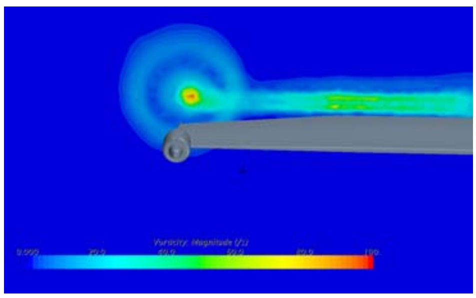


Figure 16: Vortcity induced on a plane 1.0m backward trailing edge by an active propeller (d=1.78m T=700N)

4 DISTRIBUTED PROPULSION CONFIGURATION

The overall power plant was set to keep overall power of 100hp as for Rotax engine used on P2006T for each wing; once evaluated that the power needed to fly in cruise condition is of 60hp, remaining 40hp required to take-off and climb was distributed over the inner propellers, in two different configurations, respectively with five and seven inner propellers, as shown in Fig. 17 and Fig. 18.

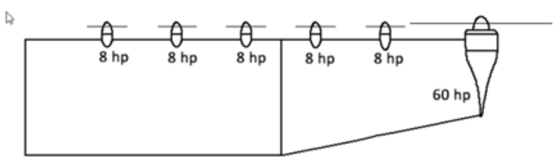


Figure 17: Sketch of 5+1 propeller configuration

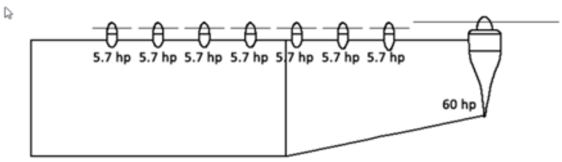


Figure 18: Sketch of 7+1 propeller configuration

The diameter of each propeller is kept constant d=0.50m for each different configuration.
For low speed performance, two different stall speeds have been considered, flap down stall speed V_{stall_flap} = 23.56 m/s and flap up stall speed of V_{stall_up} = 27.26 m/s, and so, keeping a fixed power distribution, a different thrust setting was defined.
Fig. 19 and Fig. 20 show the results propeller off and propeller on, with and without trailing edge simple hinged flap, of lift and drag coefficients respectively.
The analyses demonstrate that the inner propellers induce a higher lift coefficient for each angle of attack, and even a higher lift curve slope (see Fig. 19). Furthermore, even if the effect of inner propellers induces a higher drag coefficient of the wing for C_L<1, for high lift condition distributed propulsion also positively affects aerodynamic drag. This assumption is valid both for five and seven inner propellers.
Similar analyses have been repeated for a flap down configuration, in typical take-off (δ_F = 20°) and landing (δ_F = 40°) flap settings, obtaining similar results. It is interesting to see the comparison between propellers on and propeller off case with and without flap, for the same configuration with five inner propellers (see Fig. 19 and Fig. 20); propellers on provide a higher lift condition for higher α, and at the same time, in a certain range, exhibit a lower C_D (see again Fig. 19 and Fig. 20). Of course, the lift increment leads to a induced drag increment.
Evaluating the different behaviour of the configurations analysed, it is possible to assert that even if a seven inner propellers configuration exhibit with propellers set off a better lift performance to each angle of attack, and even a lower aerodynamic drag, this feature is lost for propellers set on (see also Fig. 21). In this case, in fact, it is possible to observe that five inner propellers configuration provides a higher C_L for high angles of attack, which is a range of major interest; moreover, it is possible to say that there are no appreciable differences in drag polar between seven propellers configuration on and five propellers configuration, for propulsion set on.

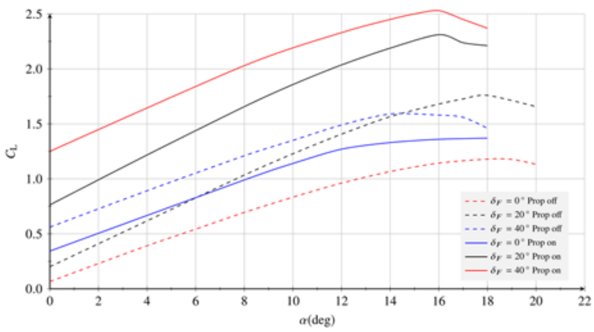


Figure 19: Results of 5+1 propeller configuration behaviour for C_L

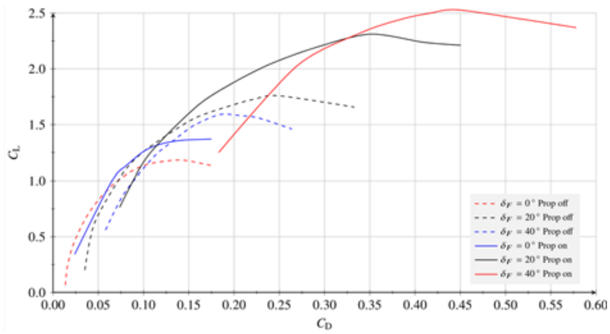


Figure 20: Results of 5+1 propeller configuration behaviour for C_D

Moreover, considering the high $C_{L,MAX}$ provided with coupled usage of distributed propellers propulsion and a flap with a typical deflection of $\delta_F = 20°$ as shown in Figure 22 can lead to a such high $C_{L,MAX}$ to reduce considerably wing surface needed, or alternatively the take-off ground distance, or even both of them.
Besides, evaluating differences among flapped wing for five inner propellers and seven inner propellers, it seems clear that while for both flap up configurations and propeller off once there are no appreciable differences, for a flapped configuration with active propellers using seven propellers brings to a higher C_L for every α.
On the other hand, the usage of more propellers on a flapped configuration conduce to negative effect on aerodynamic drag, even if it could be a required goal in landing configuration.

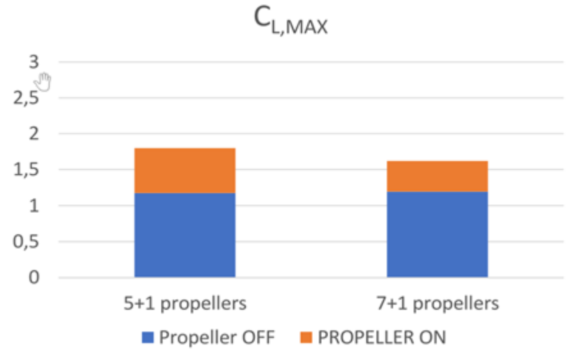


Figure 21: Variation of $C_{L,MAX}$ for $\delta_F = 0°$ with propeller on and off

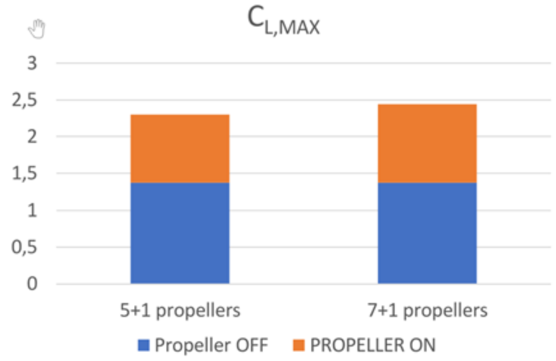


Figure 22: Variation of $C_{L,MAX}$ for $\delta_F = 20°$ with propeller on and off

5 CONCLUSIONS

Wing tip propeller and distributed propulsion aerodynamic effect on general aviation commuter wing have been analysed, showing the possibility to reduce the induced drag (from 2% to 10% 0.4<CL<1.0), increasing the high lift capabilities of about 20%(flap up) and 60-80% (flap down). Tip propeller diameter must be properly dimension according to nacelle size and thrust settings to optimize the drag reduction. Distributed propulsion can guarantee higher lift coefficient, improving the wing design and aircraft performance.

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