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Benchmark of different aerodynamic solvers on wing aero-propulsive interactions

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Abstract. Distributed electric propulsion is a fertile research topic aiming to increase the wing aerodynamic efficiency by distributing the thrust over the wing span. The blowing due to distributed propulsors shall increase the wing lift coefficient for a given planform area and flight speed. This should bring several advantages as wing area, drag, and structural weight reduction, which in turn reduce fuel consumption, allowing airplanes to fly more efficiently. However, there are no consolidated preliminary design methods to size a distributed propulsion system. Numerical analysis is then performed at early stage, where many design variables have not been fixed yet. Therefore, the design space is vast and exploring all the possible combinations is unfeasible. For instance, low-fidelity methods (VLM, panel codes) have a low computational time, but usually they do not account for flow separation and hence they are unable to predict the wing maximum lift. Conversely, high-fidelity codes (CFD) provide more realistic results, but a single drag polar sweep can last days. This work provides a benchmark of different aerodynamic solvers for a typical regional turboprop wing with flaps and distributed propulsion, to better understand the limits of each software in the prediction of aero-propulsive effects.

1. Introduction

Distributed electric propulsion (DEP) is a method to increase the wing lift coefficient by distributing the thrust over the aircraft wing. In this way, the local profile lift increases by the effect of the local flow speed increment, while the wing section is operating essentially at the same angle of attack of the unblown condition. This should bring a sequence of advantages, a sort of beneficial snowball effect in aircraft design. In blown conditions, the wing produces more lift for a given planform area. Since wing loading is constrained by landing requirements (field length and maximum lift coefficient, the last linked to the high lift devices technology), DEP enlarges the design space of the sizing plot, allowing to size the wing for cruise condition, reducing wing area. This in turn would reduce parasite drag and wing structural weight. Also, a lighter wing may allow for an increased aspect ratio, reducing induced drag. The adoption of wingtip propellers, counter-rotating with respect to the wingtip vortex, shall increase the aerodynamic efficiency even more. Finally, propulsive efficiency may increase because the thrust is distributed over a larger area [1–6].

However, these advantages are offset by several significant drawbacks. First, an increased local flow speed on the wing in blown condition means more lift but also more drag, because of the increased skin friction force. Also, the wing operating at higher lift coefficient for a given angle of

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attack means more induced drag at the same attitude and same flight speed. If DEP is provided with propellers, flow swirl must be accounted in wing design because of increased cross-flow and local section stall due to the angle of attack induced by slipstream. Even if DEP may enable a better weight distribution of the engines over the wing and hence lighten the structural weight, the structural dynamics phenomena like whirl flutter with propellers close to each other must be predicted and avoided. This effect is exacerbated for wingtip propellers. Finally, DEP should provide noise reduction because of the inherent quietness of electric drives with respect to gas turbine engines, but the noise produced by many propellers close to each other, eventually staggered and offset phased, shall be investigated.

The distributed propulsion system exploits the advantages of electric drives, which power can be almost linearly scaled with size and can be transmitted by means of electric wires and not mechanical linkage, allowing more design freedom. However, the weight of cables and insulating materials shall not be ignored. Also, the entire powertrain system shall be investigated together with the DEP enabling strategy, since it has been proven that it is convenient to enable the distributed propulsors only in some mission phases like take-off, landing, and/or climb [5–7]. It is here remarked that, depending on the electric energy source and powertrain technologies, the aircraft maximum take-off weight may even increase for a given design range.

Even focusing on the aerodynamic aspects only, it is here remarked that the aero-propulsive interaction is not treated by classic preliminary design methods [8–10] and not completely captured by recent semi-empirical approaches [2,5,6,11]. For this reason, designers tend to perform numerical analyses also in the conceptual design stage, with the objective to explore many configurations and to develop the most promising. However, DEP increases the number of design variables by adding: the number of distributed propulsors, the blown wingspan fraction, the propeller rotational speed, the relative position of DEP with respect to the wing, and so on.

This paper presents in Section 2 the state of the art of the numerical prediction of aero-propulsive effects. Section 3 presents the wing model and flow conditions, a regional turboprop wing with distributed propulsion and flaps deployed. The results of the different aerodynamic codes are compared in Section 4. By assuming the CFD results as reference values (lacking experimental results), the performance of each approach is evaluated. Conclusion are drawn in Section 5.

2. State of the art on the numerical prediction of aero-propulsive effects

Low-fidelity methods like vortex lattice (VLM) methods or panel codes provide a way to explore from hundreds to thousands of configurations within days. However, these methods usually lack the estimation of flow separation and wing stall, hence neglecting the evaluation of the maximum lift coefficient and stall angle. Also, drag is usually underpredicted, with a reliable estimation of the induced drag only. Finally, these methods provide a one-way propulsive interaction, that is the propeller influences the wing aerodynamics, but not vice versa. Often the propeller is treated as an actuator disk with swirl [12], although some approaches introduce the blade element method (BEM) to increase the accuracy [13–15] or even include the possibility to simulate the real rotor geometries, with the last option requiring an unsteady flow field solution and the propeller blade geometry.

Conversely, high-fidelity methods (CFD) solving a simplified version of the Navier-Stokes equations are more accurate, but the computational time is at least one order of magnitude higher with respect to the low-fidelity methods and usually require a more detailed geometric description of the model, hence they are not the ideal solvers in the preliminary design phase. However, they can operate in full-interaction mode, e.g. the wing upwash influences the propeller disk performance, and can provide a good estimation of the stall angle and maximum lift coefficient [16,17].

2.1. VSPAERO

VSPAERO is a VLM code provided with the suite OpenVSP (NASA Vehicle Sketch Pad). The package is free to download. The solver works by modeling the geometry as a mean camber surface and distributing vortex rings on such surface and downstream in the wake. It does not model flow separation or boundary layer but includes a basic skin friction evaluation. Since it works with a thin (degenerated) curved geometry, VSPAERO provides the effect of curvature (e.g. the lift and moment coefficient at zero angle of attack) but cannot model the effect of thickness.

Propellers can be modelled as actuator disks with swirl in steady flow, requiring the values of diameter, RPM, thrust and power coefficients, or real geometries in unsteady flow. Actuator disks are based on the Conway model [18] for the radial and axial velocity distribution and on the Johnson model [19] for the tangential velocity prediction. Control surfaces can be added as additional surfaces, although no slot or vane can be modelled, or as sub-surfaces, that is the geometry is not altered, only the panels normal vectors are rotated in the solver.

2.2. FlightStream

FlightStream is a commercial subsonic, inviscid, surface-vorticity solver. It includes compressibility effects, propeller modelling, and flow separation. It simulates real shapes (there is no degenerated geometry) much more quickly than CFD and it can run as fast as VSPAERO. As solution time and order of accuracy, it is between VLM and Eulerian codes. The computational grid can be unstructured, usually applied to non-lifting surfaces, and structured, which is suggested for lifting surfaces. Both grid type can co-exist in the same simulation, even on different patches of the same body. FlightStream integrates with the VSP executable to perform Boolean operations on mesh.

The idea at the base of FlightStream is to get the advantages of unstructured meshes (less memory, more freedom in body shape) typical of pressure-field solvers and merge them with the advantages of vorticity-field solvers (fast and reliable solutions on lifting surfaces in attached flow conditions). FlightStream solves a vortex ring distribution on an unstructured grid for an arbitrary body, appropriately treating shed vortices, including wake adaptive propagation, and applying the integrated circulation method [20]. A de-coupled, generalized, compressible flow-separation model [21,22] has been implemented, allowing to estimate the maximum lift coefficient and stall angle, also visualizing a separation contour. Viscous-boundary layer coupling is in development phase and preliminary results will be presented in this paper.

2.3. STAR-CCM+

Simcenter STAR-CCM+ by Siemens is a commercial suite of tools to solve problems involving flow, heat transfer, and stress, bases on object-oriented programming. The STAR-CCM+ flow solver is based on the finite volume method. The domain is divided in cells, formed by faces, which are collection of vertices, points in space defined by a position vector. The volume mesh, i.e. the collection of all the cells, is the representation of the domain where the problem is being solved. Mesh is unstructured, with polyhedral or prismatic cells. The boundary layer can be better captured by extruding a prismatic cell layer from the walls of the bodies of interest.

Propellers can be modelled with different degrees of accuracy. The actuator disk model, renamed virtual disk model, provides a full-interaction mode between wing and propeller aerodynamics and can calculate the flow swirl. However, this model can be enabled only in viscous simulations.

This CFD package can solve the inviscid (Eulerian) flow field, the Reynolds-Averaged Navier-Stokes (RANS) equations, as well as perform Detached or Large Eddy Simulations (DES, LES). The flow can be modelled as laminar or turbulent, with different turbulence models implemented, with constant density or compressible, steady or unsteady. Clearly, it is the most accurate solver used in this work. However, it models the complete three-dimensional domain around the body, hence it needs much more memory and computational power to be executed in a reasonable amount of time.

3. Geometric model and flow conditions

The wing model used in the calculations is illustrated in Figure 1. It is a typical regional turboprop planform, with an aspect ratio AR = 11 and a large, but tapered, outer panel. The leading edge has no sweep angle to keep distributed propellers aligned along the span. Planform parameters are reported in

Table 1. Simulations are performed in take-off condition, with a single slot flap with a 30% chord ratio deflected by 15°. Flow conditions are reported in Table 2.

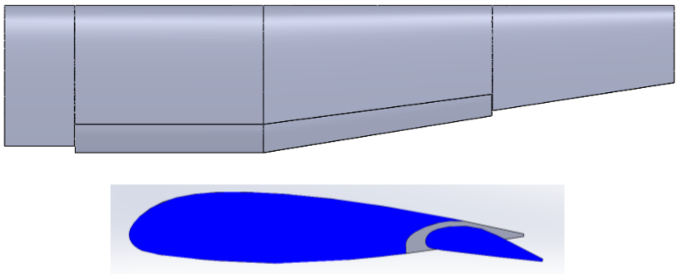

Figure 1. The turboprop wing model with single slot flap.

Table 1. Wing model geometric parameters.

Symbol	Description	Value
b	wing span	24.572 m
c	mean aerodynamic chord	2.28 m
S	wing planform area	54.5 m^2
AR	aspect ratio	11.08
y_k	kink span station	4.75 m
c_r	root chord	2.57 m
c_k	kink chord	2.57 m
c_t	tip chord	1.41 m
ε_t	wingtip twist angle	1.5°

Table 2. Flow parameters.

Symbol	Description	Value
α	angle of attack	0°-25°
δ_f	flap deflection	15°
M	Mach number	0.146
Re	Reynolds number	7.68×10^6
ρ	flow density	1.225 Kg/m^3
p	static pressure	101325 Pa
a	sound speed	340.3 m/s

Four propellers have been distributed along the half wing span $b/2$, allowing space for the fuselage and a wingtip propeller (not modelled in this work), see Figure 2. The propellers diameter D_p has been sized to blow on the available wing span b_a with $0.01D_p$ of space between the propellers:

$$b_a = \frac{b}{2} - b_{fus} - b_{tip} = (12.256 - 2 - 1.965)\ \text{m} = 8.321\ \text{m}$$

$$D_{max} = \frac{b_a}{N_{DEP}} = \frac{8.321}{4} = 2.08\ \text{m} \ \longrightarrow\ D_p = 2.06\ \text{m}$$

A hypothetical total take-off thrust T of 25000 N has been applied at an airspeed V of about 50 m/s, yielding to 6250 N of thrust per propeller. The rotational speed of each propeller has been determined by assuming a tip Mach number of 0.7, yielding to 2200 RPM for each propeller. Table 3 reports the complete input data set for the simulations.

As concern the blown (prop-ON) condition, propellers have been modelled as actuator disks with swirl in all the three software. Therefore, the geometry of the blade is ignored. Also, no nacelle have been included, so that the aero-propulsive interaction neglects their presence.

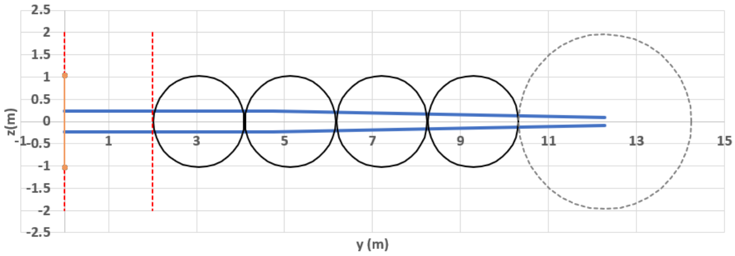

Figure 2. Schematic distribution of distributed propellers.

Table 3. Propeller design parameters.

V (m/s)	50	D_p (m)	2.06	J	0.66
T_{tot} (N)	25000	Disk area (m^2)	3.33	C_T	0.210
N_{DEP}	8	Disk pressure jump Δp (Pa)	1876.24	C_P	0.175
T (N)	6250			η	0.79
P shaft (kW)	394.75	$\Delta p/\rho V^2$	0.613	RPM	2200

4. Aero-propulsive interaction benchmark

The objective of the benchmark is to compare aerodynamic coefficients, chordwise pressure coefficient distributions, and spanwise lift distribution, in both unblown and blown conditions, to better understand the limits of each software. The idea is to provide suggestions to the designer in selecting the method that best fits his needs. Probably, in the conceptual design phase, he/she would trade accuracy for solution speed, yet keeping some high fidelity features like flow separation. Figure 3 shows how the different solvers perform with respect to CFD (red lines). The scale of the prop-ON and prop-OFF charts are the same to appreciate the effect of DEP.

VSPAERO, which is the VLM code, seems to perform very well in both prop-ON and prop-OFF conditions. However, it fails to predict the C_M trend, which is important for aircraft stability, and lack a flow separation model. Moreover it underpredicts the lift coefficients at high angles of attack in unblown conditions, probably because of the degenerated geometry that is not modelling the slotted flap and the thickness effect.

The Eulerian curve also overestimates lift coefficient and aerodynamic efficiency, since there is no wall shear stress and boundary layer. Also, the virtual (actuator) disk model is not available in STAR-CCM+ inviscid calculations, hence prop-ON solutions are not available for this model.

FlightStream presents a default inviscid solver with a pressure separation model, which actually is able to capture the stall angle, but significantly overpredicts the lift coefficient and the aerodynamic efficiency. The new viscous – boundary layer coupling feature improves the results quality, bringing them closer to the RANS values. Also, the pitching moment curve is shifted with respect to the reference RANS values, but the general trend is well preserved.

For a full polar sweep, both VSPAERO and FlightStream inviscid solver need about 10 minutes on an entry-level (Intel Core i3) laptop. On the same machine, the FlightStream viscous – boundary layer coupled solver needs about 40 minutes. The RANS calculations need a dedicated workstation and the computational time required is of the order of one day per full polar sweep, with a coarser resolution on the angle of attack range.

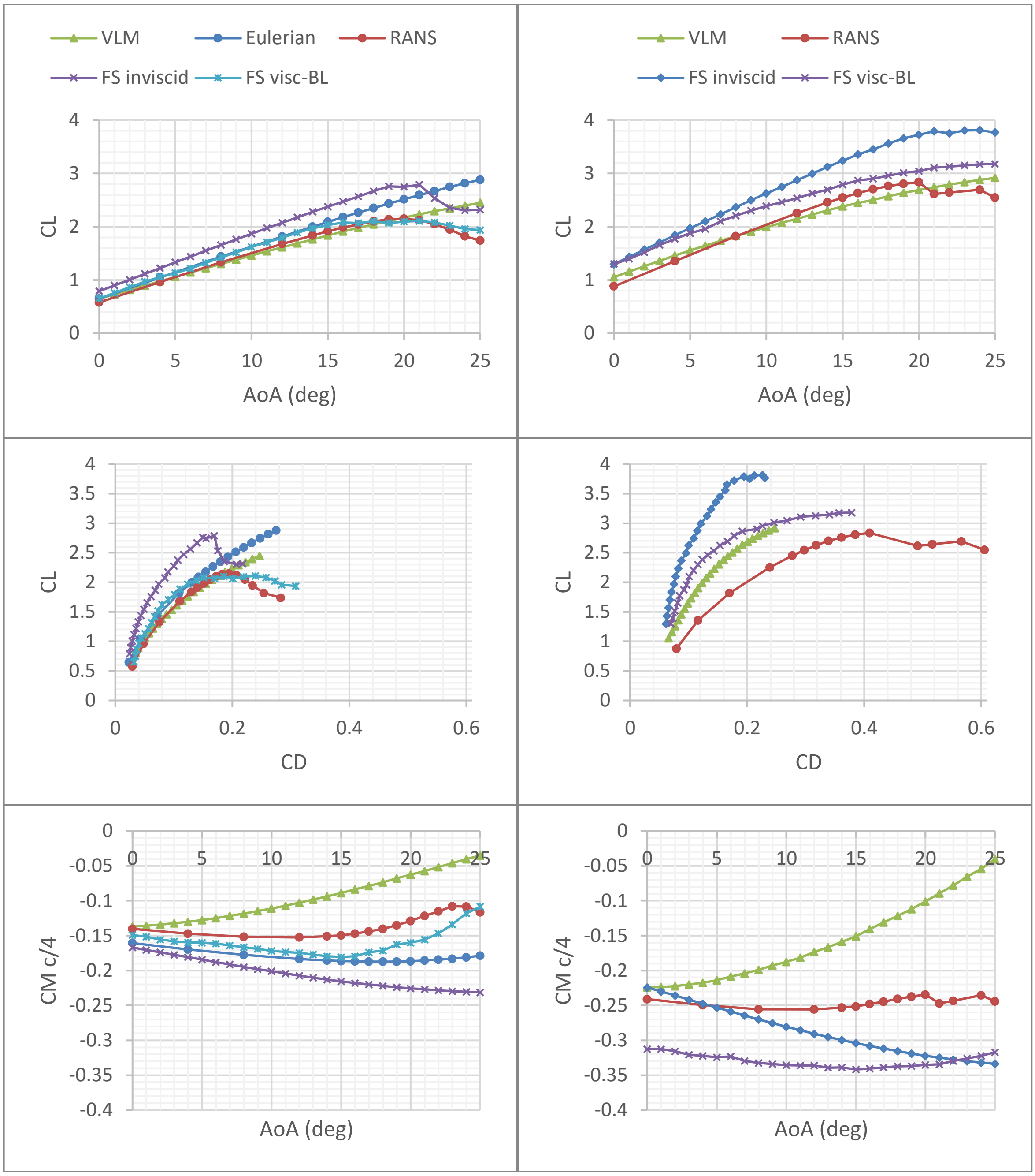

Figure 3. Comparison of different aerodynamic solvers solutions on the aerodynamic coefficients. Left: prop-OFF (unblown) conditions. Right: prop-ON (blown) conditions.

Wing load distributions at α = 16° are shown in Figure 4. The effect of single propeller-wing interaction mode of VLM and FlightStream is apparent, while CFD shows a benefit due to the two-way interaction mode. In fact, in the CFD solver the effect of propeller swirl is mitigated (propellers are rotating inboard up) and the local lift increment is more evenly distributed. FlightStream provides a sharper change between flapped and clean spanwise regions.

Figure 5 shows the pressure coefficient distribution for two sections around the first propeller (inboard and outboard) at α = 16°. It confirms the global results and load distribution values. VLM is not represented because of the degenerated geometry, i.e. there is no airfoil shape and therefore C_p is not available.

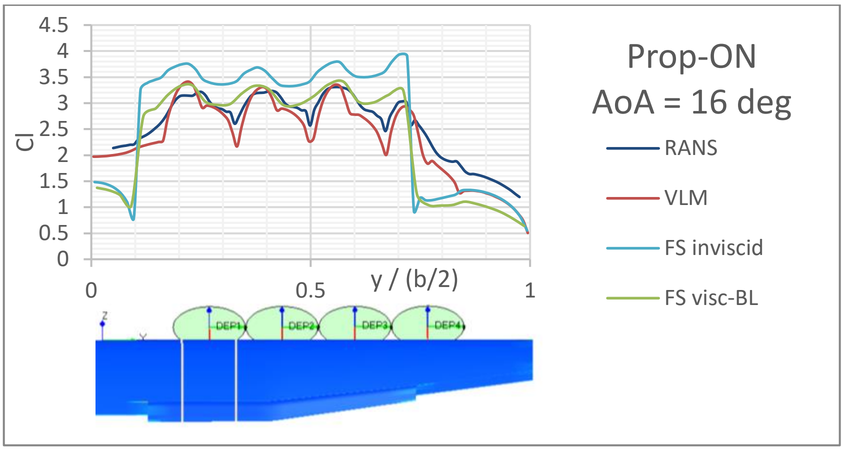

Figure 4. Comparison of lift distribution estimations at α = 16°.

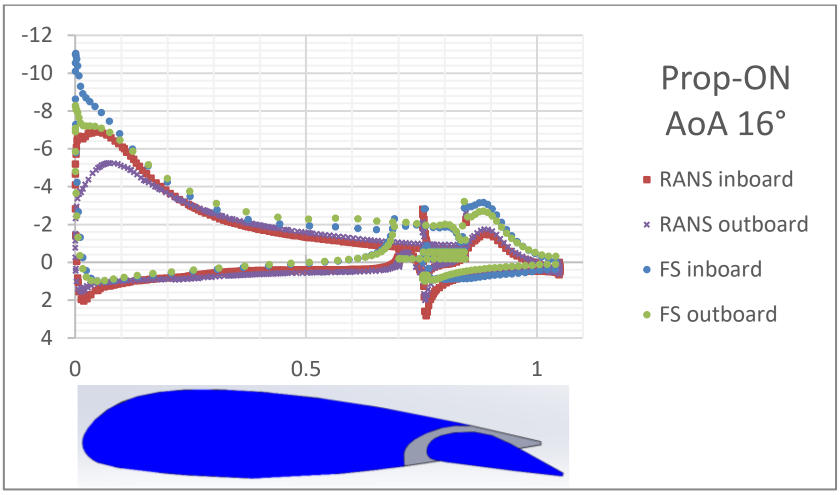

Figure 5. Comparison of pressure coefficient distribution estimations at α = 16°. FlightStream results are with the viscous – boundary layer coupling solver enabled.

5. Conclusion

Distributed electric propulsion is new technology that could increase the aerodynamic efficiency of aircraft. The aero-propulsive interactions must be accurately predicted to estimate the performance of DEP-powered aircraft. At this scope, numerical analyses could be effectively used to explore novel designs, where usually the faster is the solution the less accurate is the result. VLM solvers like VSPAERO are fast and useful to capture aerodynamic coefficients at low angles of attack but lack separation models (designers are also interested in $C_{L\max}$) and miss the C_M trend, which is related to longitudinal stability. However, the results of this test case make them very attractive. CFD solvers are more accurate, but computationally very expensive, with a drag polar sweep lasting many hours or even days. FlightStream is a new software half-way between VLM and CFD that tries to merge the speed of the former with the accuracy of the latter. Its new viscous – boundary layer coupling solver is an interesting feature that increase the accuracy of the results. Other test cases are necessary to further compare the performance and quality of the solvers. Here RANS have been used as reference values. DEP wind tunnel test data would be ideal.

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