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Innovative Propulsion Systems and CFD Simulation for Fixed Wings UAVs

Esteban Valencia and Victor Hidalgo

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Abstract

Nowadays, mobile applications demand, in large extent, an improvement in the overall efficiency of systems, in order to diversify the number of applications. For unmanned aerial vehicles (UAVs), an enhancement in their performance translates into larger payloads and range. These factors encourage the search for novel propulsion architectures, which present high synergy with the airframe and remaining components and subsystems, to enable a better UAV performance. In this context, technologies broadly examined are distributed propulsion (DP), thrust split (TS), and boundary layer ingestion (BLI), which have shown potential opportunities to achieve ambitious performance targets (ACARE 2020, NASA N+3). The present work briefly describes these technologies and shows preliminary results for a conceptual propulsion configuration using a set number of propulsors. Furthermore, the simulation process for a blended wing body (BWB) airframe using computational fluid dynamics (CFD) OpenFOAM software is described. The latter is examined due to its advantages in terms of versatility and cost, compared with licensed CFD software. This work does not intend to give a broad explanation of each of the topics, but rather to give an insight into the state of the art in modeling of distributed propulsion systems and CFD simulation using open-source software implemented in UAVs.

Keywords: unmanned aerial vehicles, CFD, distributed propulsion, boundary layer ingestion, blended wing body, OpenFOAM

1. Distributed propulsion

Distributed propulsion has been studied as a way of improving propulsive efficiency by increasing the bypass ratio of the turbofan engines, without any design constraints of large engines' fan radius. Distributed propulsion has been explored since the 1960s, for commercial aviation; however, the design complexities involving energy transmission, maintenance, and fluctuant oil price during the past decades have limited its research. Recently, the growing environmental awareness has again motivated initiatives for the search of more efficient

propulsion systems. Numerous renowned institutions [1–3] have taken the leap to study concepts with distributed propulsion and observed an achievable 8% benefit in terms of thrust specific fuel consumption (TSFC) compared with today's aircraft [2]. However, for civil aviation, the implementation of this technology is still a challenge, due to mechanical design constraints and safety issues. For unmanned platforms, this technology has been implemented successfully on multicopters [4], where multiple rotors are used for propulsion and flight control. The latter application has arisen as a consequence of suitable and reliable electrical power, control, and transmission systems, which enable to control pitch, torque, and rotational speed, to describe the flight envelope. Although distributed propulsion has been well examined in multicopters, unmanned aerial platforms, using fixed wing configurations, are not well documented. For fixed wings, the distributed propulsors could be arranged over the airframe [5], and they could present boundary layer ingestion, which could bring 7% reduction for civil aviation concepts in TSFC compared with today's aircraft [6]. Since highly integrated propulsion configurations have a high synergy with BWB airframes, the latter has been selected for the assessment of the propulsion configurations, and hence to set the thrust required at cruise conditions, the aerodynamic characteristics are based on a BWB airframe. A plot of the BWB airframe selected for this work is shown in **Figure 1**, and as observed, its selection obeys the multiple advantages for DP and BLI, such as (i) its uniform planform area in the spanwise direction, which enables the allocation of an array of propulsors; (ii) the large airframe space to embed the propulsors at the trailing edge of the airframe, which is beneficial when BLI is implemented, as more airframe drag is ingested. In the CFD simulation presented in this work, the BWB configuration is tested using the OpenFOAM open-source software. The aerodynamic
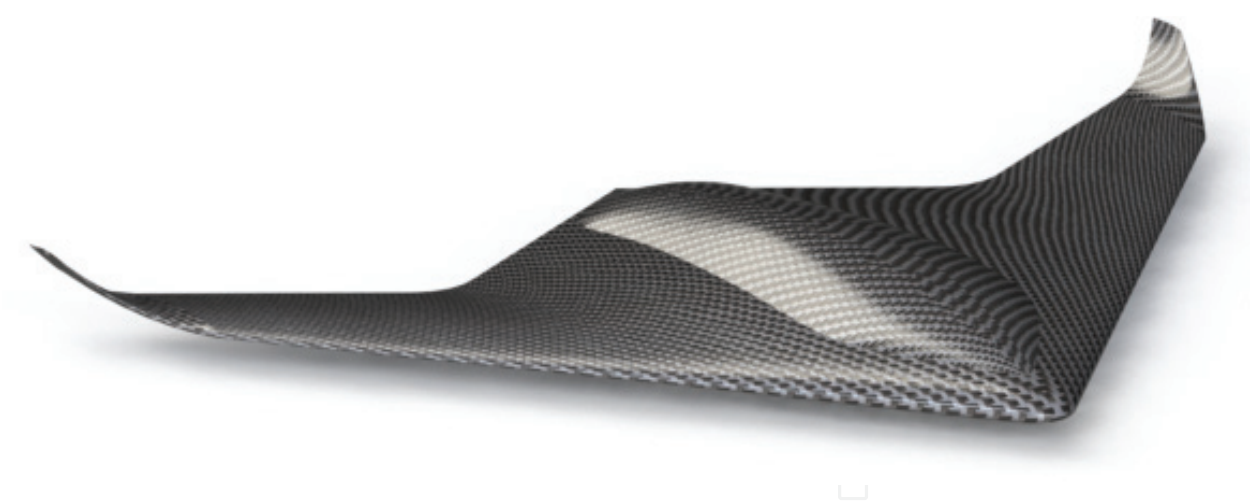

Figure 1. BWB model selected [7].

C_{DO} (zero lift, drag coefficient)	C_L (Lift coefficient)	e (wing span efficiency)	AR (aspect ratio)	Flight velocity	Wing span
0.015	0.1	0.72	5.9	20 (m/s)	3 (m)

Table 1. Airframe and aerodynamic data at cruise conditions [8].

characteristics of the BWB airframe are described in **Table 1**, which correspond to the UAV case study. Since agriculture is one of the main applications for this sort of aerial platforms, the operating conditions are selected based on UAVs used in precision agriculture [5].

In order to clarify the structure of the distributed propulsion configuration, an illustrative diagram for the electrical propulsion system utilized in this work is shown in **Figure 2**. As observed in this figure, the electrical and control system units take the place of the gas turbine in common turbo-electric distributed propulsion arrangements [9], and hence they supply the electrical power to the propulsor's electrical motor. For the sake of clarity, in **Figure 2**, only one propulsor (NF = 1) is depicted; nevertheless, this is a design space variable for the UAV concept.

For the case of study previously mentioned and using the methodology developed in Valencia et al. [5], the power consumed by the distributed propulsion arrangement using an electrical power system is shown in **Figure 3**. The figure shows the power requirement per fan to achieve the set thrust at cruise condition for four propulsion configurations. In this case, each configuration uses a different number of propulsors (NF). To calculate the mass flow through the propulsors, an inner control volume approach is selected [10]. Through this approach, the propulsor mass flow can be defined based on the set thrust for cruise condition, which is calculated as a function of the aircraft drag. Eq. (1) is used to calculate the propulsor's mass flow. The latter variable enables to calculate the fan diameter through mass conservation and the fan power based on the isentropic thermodynamic relations for incompressible flow. This process is further explained in [3]
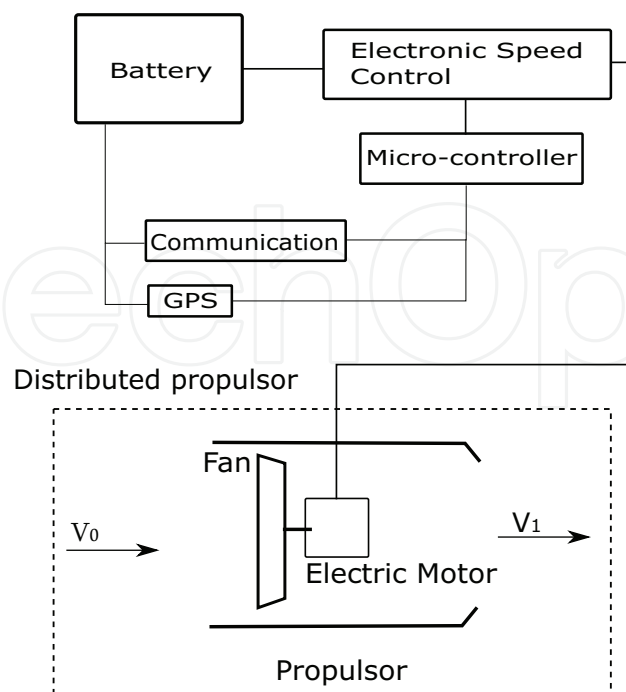
$$F_{N} = \dot{m}\left(V_{j} - V_{0}\right) \tag{1}$$

Figure 2. Distributed propulsion array for an electric-powered UAV.

(a) Power (P_f) per fan

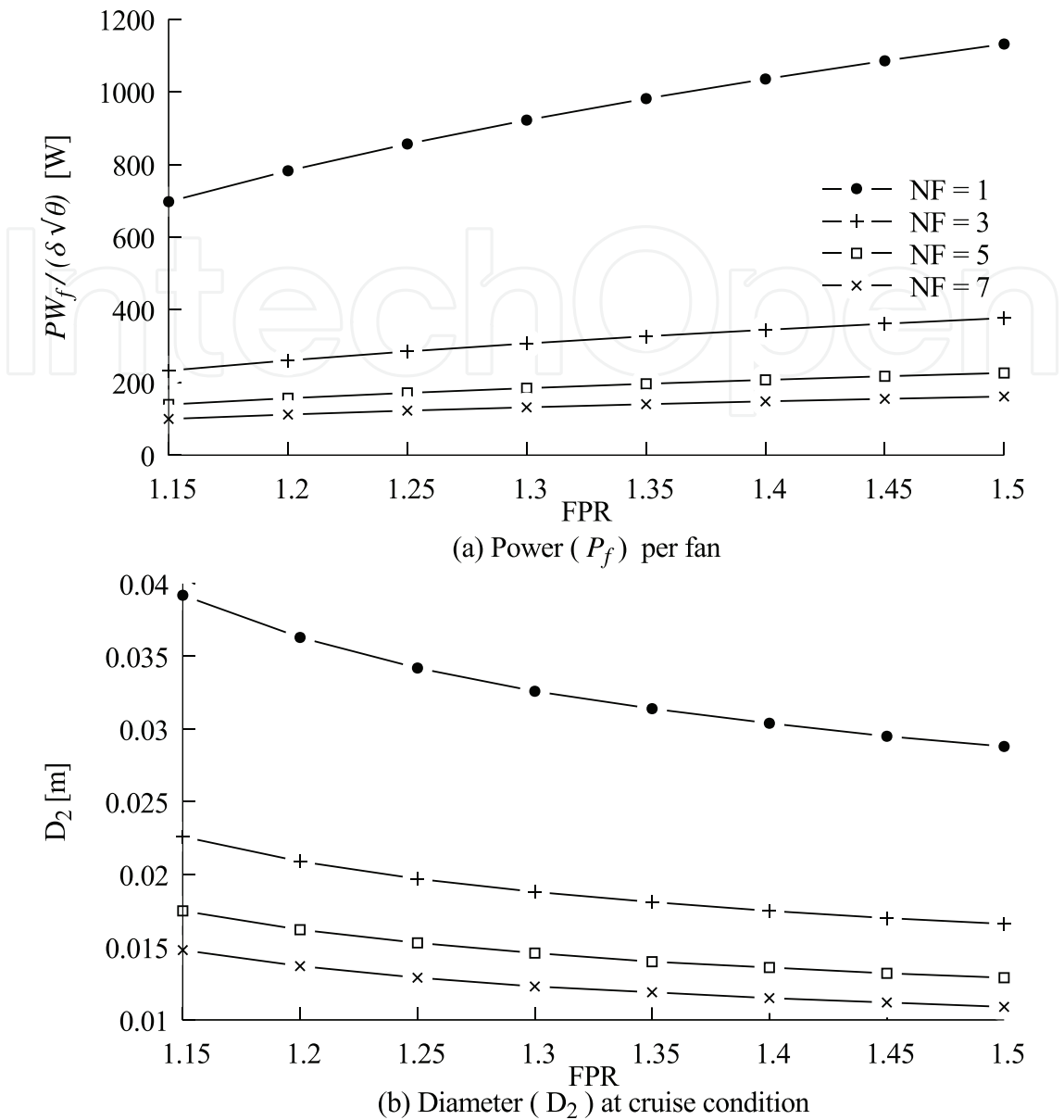(b) Diameter (D_2) at cruise condition

Figure 3. Power required per fan and fan diameter at cruise condition.

In **Figure 3(a)**, the total power remains the same, as it is assumed that the aircraft drag remains constant (this assumption, however, will depend on the distributed propulsion array); furthermore, for the calculation of the propulsor power, it is assumed that the flow entering the distributed propulsors presents the same velocity for all the propulsors. In **Figure 3(a)**, it is observed how the power required per fan reduces as more fans are implemented in the distributed arrangement and additionally shows the benefit of working with low fan pressure ratios. In this case, the intake pressure losses assumed are 1%, which is low and hence they do not restrict to operate at low fan pressure ratios. This, however, will highly depend on the duct design. It can also be observed from the figure that the total power of the distributed arrangement remains constant for all the configurations. In **Figure 3(b)**, the fan diameter for each arrangement is plotted and, as expected, a large number of propulsors will reduce their size,

due to the lower mass flow per propulsor. Also, it is important to note that insofar as the pressure ratio is increased, the fan diameter decreases; this is attributed to the larger energy that is delivered by the fan to produce the thrust set for cruise condition. To summarize, the benefits that distributed propulsion brings are (i) enhancement in the distribution of loads along the spanwise of the airframe, due to the reduction in size and therefore weight of the propulsors; (ii) suitability of small fans embedded into the airframe to improve its aerodynamic performance.

In the case of using turbo-electric distributed propulsion, where the energy source is a gas turbine/turbofan, the propulsive efficiency will improve, due to the increment of energy transferred to the low momentum flow (cold flow), and hence, the reduction of velocity in the high speed flow [11]. The latter, also, will contribute to a reduction in noise [12].

BLI configurations having a distributed propulsor array over the airframe sucking the boundary layer induce certain challenges in terms of boundary layer treatment, stability issues, aerodynamic integration effects propulsors-airframe, among others. It is usually a problem to deal with the boundary layer around the airframe, as highly coupled configurations ingest the boundary layer, and hence, the propulsors operate under combined radial and circumferential distortion patterns, which detriments to large extent fan performance [2, 5]. **Figure 4** shows the total pressure patterns at different radial and circumferential positions for a clean fan and for the BLI case. As observed, the change in flow properties of each rotational cycle would affect the fan performance, since blades are designed only for radial distortion, where a set flow conditions is expected at the design point. There are novel techniques to deal with boundary layer ingestion and take advantage of a reduced momentum drag for the propulsors. These alternatives either enhance control of the incoming flow or shift the blade position based on the
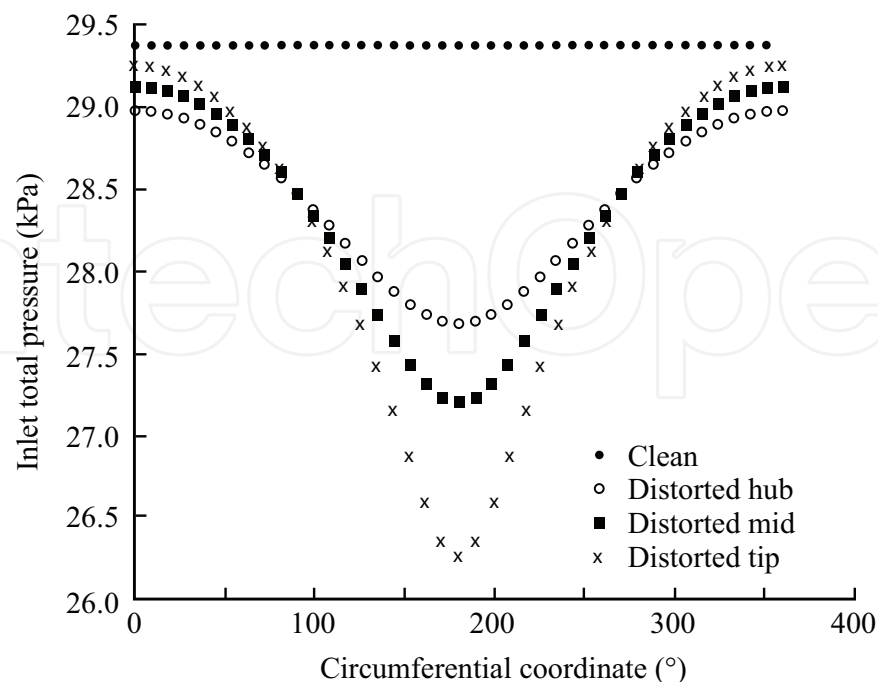

Figure 4. Inlet total pressure for distorted BLI case [15].

flow conditions [13, 14]. The discussion of these alternatives is beyond the scope of the present work.
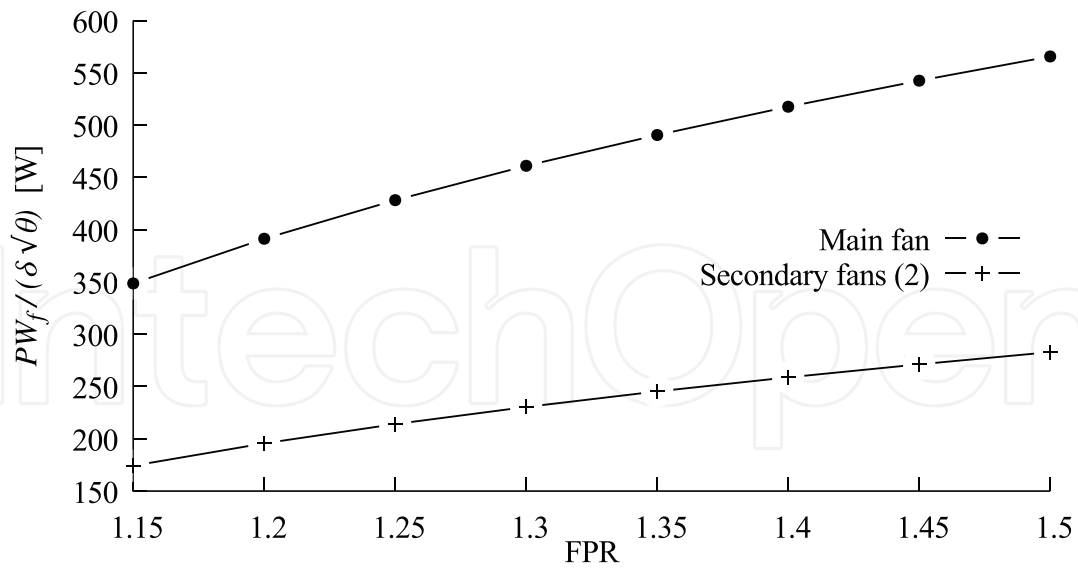
1.1. Thrust split

The concept of thrust split has been well explored in many different manned aerial concepts, such as the N3-X [1, 6] and Cranfield [3, 16, 17]. This technology, for manned concepts, which presents distributed propulsion, was observed as a way of enhancing propulsive efficiency and fuel consumption, while reducing the high transmission losses (electrical transmission systems) and integration aerodynamic effects between propulsion and airframe [10]. The mentioned benefits are achieved in civil aviation, by reducing the amount of power required by the distributed propulsion arrangement, and hence decreasing the amount of losses and increasing weight, which comes from the cryocooling system of the high-temperature superconducting (HTS) electrical propulsion [18]. Regarding BLI systems, it was observed that ingesting a larger share of boundary layer freestream determines the performance benefits from BLI [16] and thus, it is better to have smaller propulsors, which ingest only the boundary layer. The improvement in propulsive efficiency and energy consumption comes from the lower momentum drag entering the distributed propulsor array. Furthermore, the latter aspect can have other positive effects with regard to intake pressure losses and distributed array allocation. The first aspect is due to the reduced mass flow required by the propulsor array operating with BLI, and hence, less wetted area at the intake. The second aspect is related to the small size of the propulsors and hence less geometrical constraints for their allocation in the distributed propulsor unit. Thrust split (T_S) is defined by Eq. (2).

$$T_S = \frac{F_{DP}}{F_N} \tag{2}$$

where F_{DP} is the thrust delivered by the propulsor array and F_N is the net intrinsic net thrust [3].

In case of battery-powered aerial platforms, which have the configuration presented in **Figure 2**, thrust split is an extra design space variable for the configuration of distributed propulsion systems with BLI. This variable could help heterogeneous fan distributed propulsors arrangements, where geometric, aerodynamic, and structural constraints can be satisfied. **Figure 5** shows a conceptual configuration of the UAV described in **Table 1**, with a thrust split of 50% and 75%. In this case, the main engine is located at the centerline to reduce stability problems in case of one engine is put off. It is observed from the figures how the heterogeneous configurations for UAVs could help to better the distribution of loads (propulsors) within the airframe, versatility in configurations and better aerodynamic design (smaller propulsors embedded in the airframe). In **Figure 5**, the main fan power corresponds to the airframe centerline fan shown in **Figure 6**.

Illustrative configurations for the three thrust split configurations presented in **Figure 5** are shown in **Figure 6**. As observed in the figure, insofar as thrust split is reduced, the size of the main propulsor increases, which is attributed to the large share of thrust that needs to be delivered by the main propulsor to keep the thrust at cruise condition.
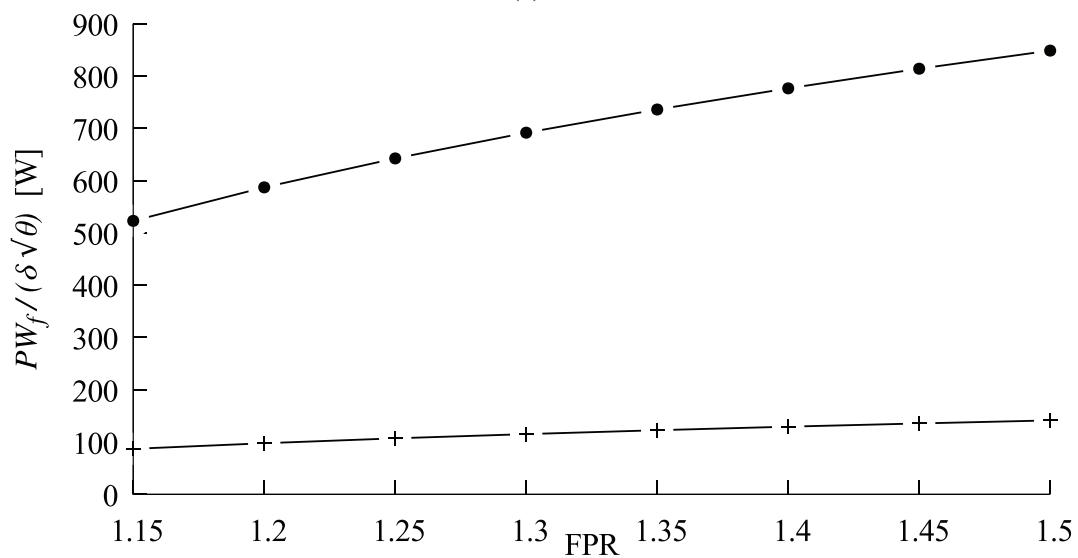
Figure 5. Propulsion system configurations for 50 and 75% thrust split.
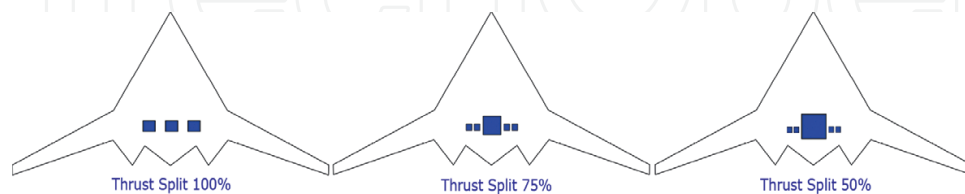

Figure 6. Illustrative configurations for different thrust splits.

In unmanned aerial vehicles, which use distributed propulsion, gas turbines or internal combustion engines work as the main power source. These previously mentioned benefits need to be verified and adapted for the different power settings that UAVs required [5]. First, most of unmanned systems do not employ turbofans, due to increased cost and complexity of these

systems; therefore, the benefit in propulsive efficiency accrued from using large by pass ratio turbofans in high thrust split configurations will not be present. Nevertheless, UAVs that have gas turbines and distributed propulsion may have structural issues that come from the load distribution within the airframe. This latter aspect could be solved by introducing thrust split as main power source, and the propulsion system (main and distributed) could be sized based on a thrust schedule where the main engine and the propulsor array can cooperate with a share of the thrust required at each flight condition during the flight envelope looking for an optimum in terms of weight and overall performance.

2. CFD simulation

The fixed-wing UAVs can be examined using CFD simulation to reduce cost in investigation [19, 20]. For that purpose, OpenFOAM have been used to carry out a numerical simulation for a general shape of UAVs' wing. OpenFOAM means Open Field Operation and Manipulation and it is not only a software but also a library of C++ solvers for CFD simulations. The main code is free and open-source software, which allows to modify and to implement equations and functions without any commercial restriction [20]. In this context, OpenFOAM is an important tool to carry out numerical simulations for CFD.

2.1. Description of the mathematical model

The turbulence model of $SST\ k - \omega$ has been selected to carry out the numerical simulation to capture the effects of the boundary layer [21] over the airframe, which in this case presents geometrical complexity. The adverse pressure gradient and the separating flow can be captured fairly well with considerations of $SST\ k - \omega$ properties in regions far away from walls [21]. Moreover, a general expression of the turbulence model is indicated in the filtered Eq. (3).

$$\rho \frac{\partial \overline{\phi}}{\partial t} + \rho \overline{u}_j \frac{\partial \overline{\phi}}{\partial x_j} - \frac{\partial}{\partial x_j} \left[\Gamma_{\phi,\,\mathrm{eff}} \frac{\partial \overline{\phi}}{\partial x_j} \right] = S_\phi \tag{3}$$

where ϕ represents variables, $\Gamma_{\phi,\mathrm{eff}}$ represents the effective diffusion coefficient, and S_ϕ represents the source term of the equation, which is according to [21].

The OpenFOAM solver called simpleFoam has been used for solving the steady-state Reynolds-averaged Navier-Stokes equations with the $SST\ k - \omega$ turbulence model [22]. For that, the coupling between velocity and pressure is treated using the SIMPLE method [23].

2.2. CFD domain

The selected geometry of UAVs for numerical simulations has been based on the design of the BWB airframe [24, 25] shown in **Figure 1**. The analyzed 3D model is depicted in **Figure 7**.

The main dimensions of the domain are indicated in **Figure 8**, which was based on previous work focused on drag estimations using CFD [26]. The largest dimension is 15 times the chord
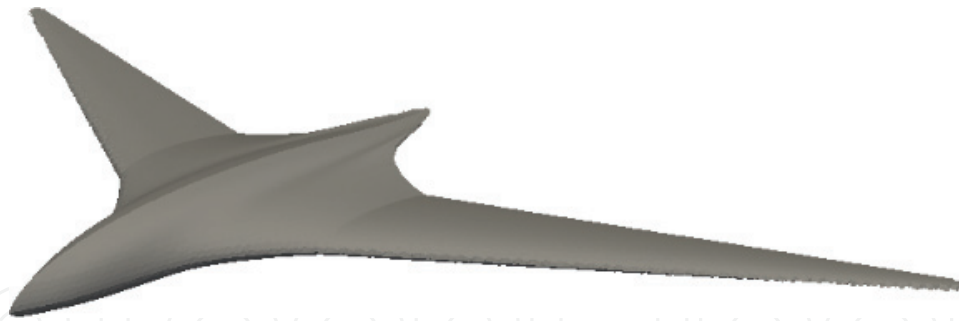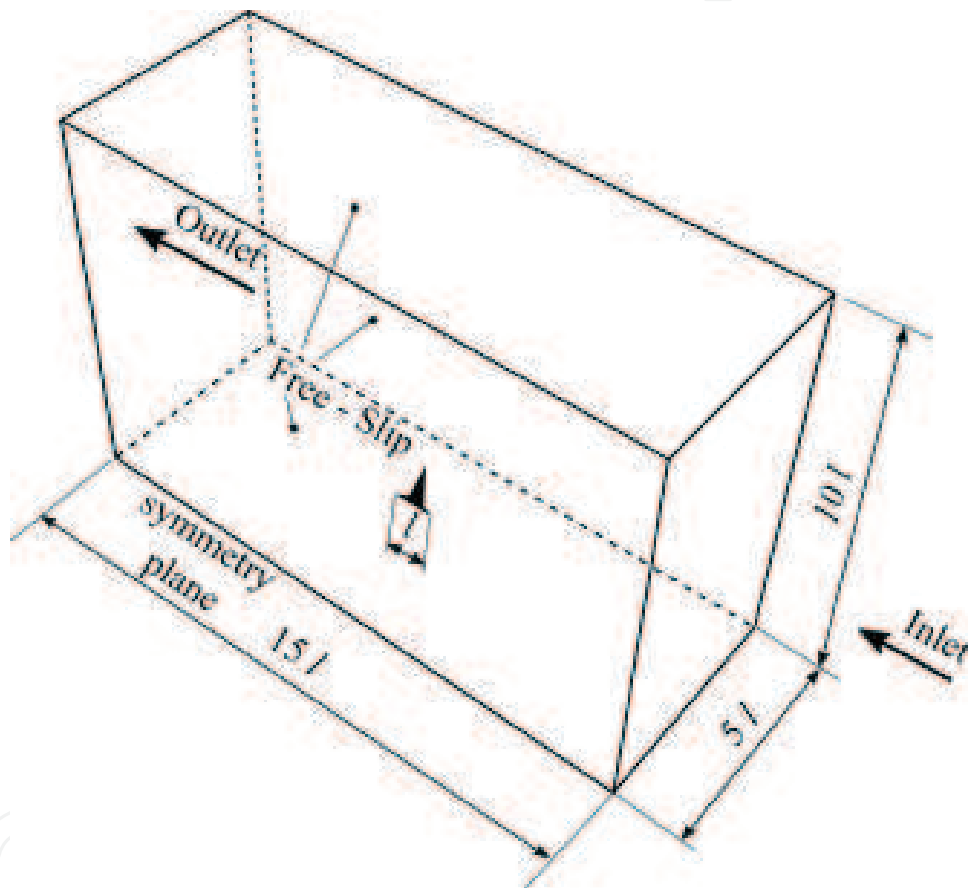
Figure 7. 3D model of BWB Mark 2 [24, 25].

Figure 8. Main computational domain.

length, *l*, in the axial direction and the shortest length is 5 times *l* in the spanwise direction. The aforementioned configuration was used for the CFD simulation.

2.3. Mesh generation and boundary conditions

The mesh in **Figure 9** was obtained using the OpenFOAM tool snappyHexMesh [27] with 1.3 million cells. Based on previous research [19, 28], the mesh has been divided in two zones, refined and no-refined, to capture special characteristics of the phenomenon and fluid development, respectively. Furthermore, the refined zone close to the wing walls presents a special
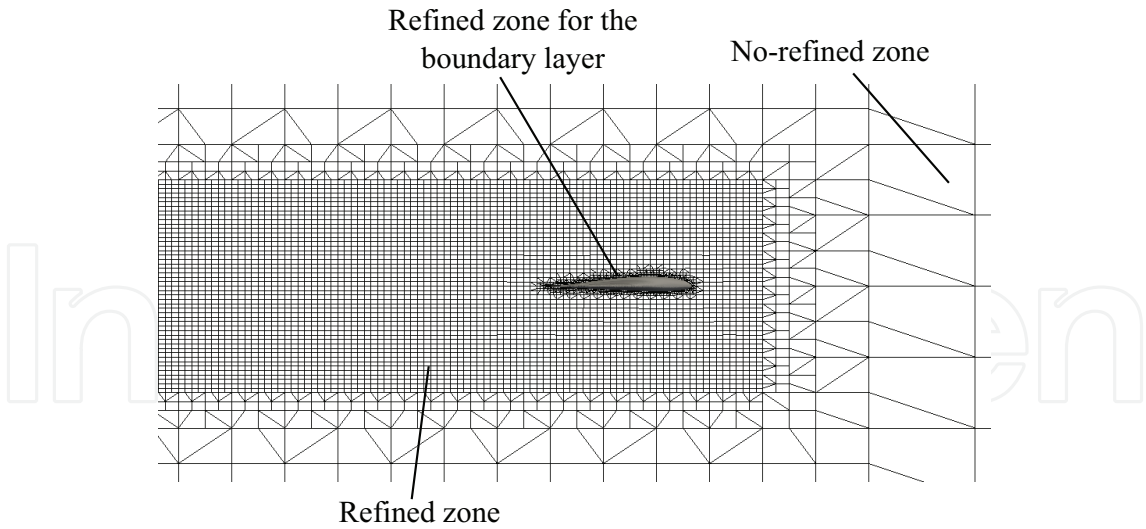
Figure 9. Mesh around the BWB Mark 2 model.

U_{in}	p_{out}	ρ_∞	μ_∞
[m/s]	[m²/s²]	[kg/m³]	[kg/(ms)]
50	0	0.5895	1.561×10^5

Table 2. Boundary conditions.

treatment to improve the simulation of the boundary layer, which has a y^+ equal to 50 according to the requirements of the *SST $k - \omega$* model [19, 27].

The boundary conditions are based on previous studies for BWB [29] and indicated in **Table 2**, where U_{in} is the inlet velocity, p_{out} is the static pressure in the outlet, ρ_∞ is the estimated density of the air, and μ_∞ is the dynamic viscosity.

2.4. Results and discussion

Figure 10 shows that the numerical simulation converge after 200 iterations for the pressure and components of the velocity, *U*, in the respective axes; hence, 300 iterations can be acceptable for steady-state results.

According to **Figure 11(a)**, the pressure coefficient (C_p) distribution of the BWB Mark 2 model changes from the leading edge to the trailing edge. The upper part indicated in **Figure 11(b)** shows the C_p decreasing downstream and the lowest C_p was found close to the quarter chord of wings, maintaining the trends as expected for BWB airframes [8, 26]. Downstream, the minimum C_p increases in the direction of the trailing edge. The bottom view shows similar C_p distribution to the upper surface with higher values to give the lifting characteristics of this component.

Furthermore, the C_L and C_D were calculated in OpenFOAM using the forces library called libforces. The estimated values are 0.216 and 0.014 for C_L and C_D, respectively, which matched fairly well the values obtained by Cisneros [29] using XLFR5. Since the aim of the present work
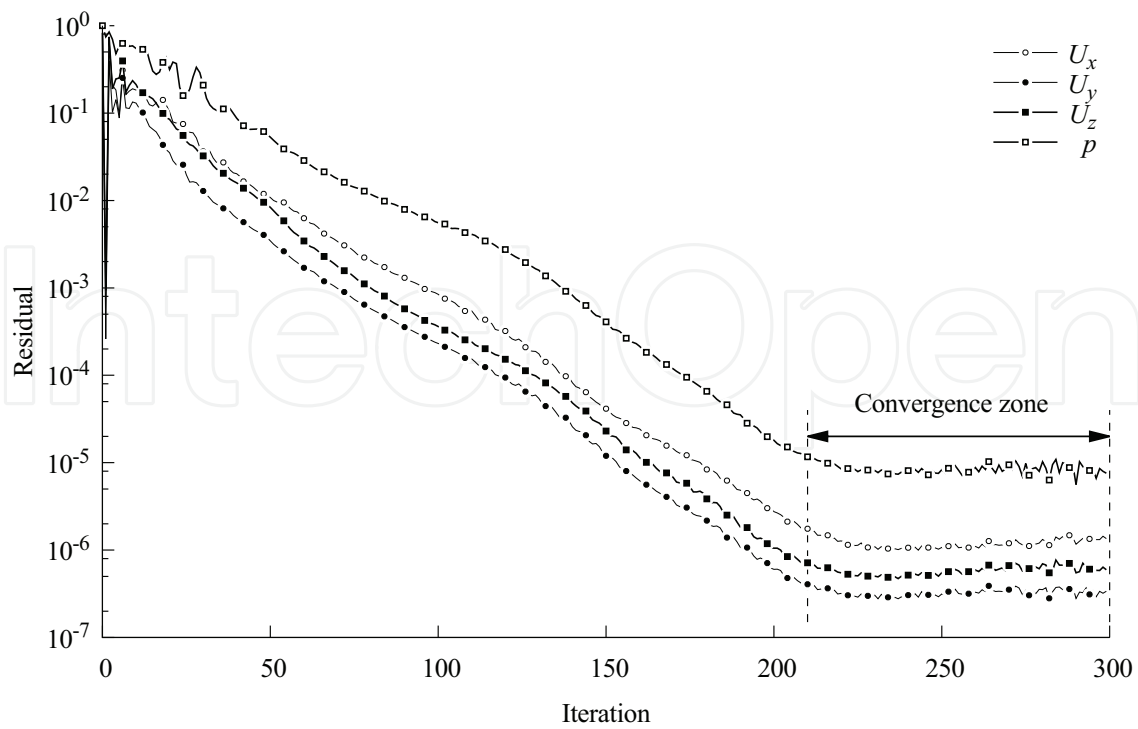
Figure 10. General residuals of the BWB Mark 2 simulation.

(a) The 3D model of BWB Mark 2

(b) BWB Mark 2 upper view   (c) BWB Mark 2 bottom view
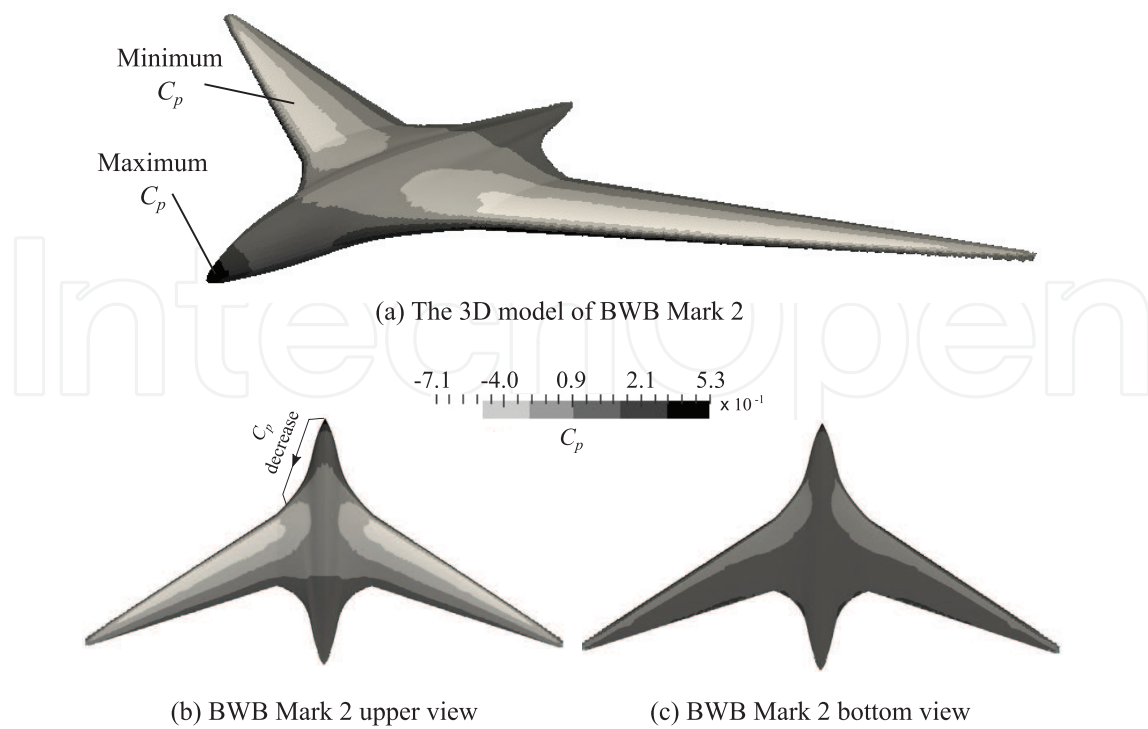
Figure 11. Pressure distribution around the BWB Mark 2 model.

is to give an insight on high-fidelity aerodynamic assessment using open-source software and demonstrate the suitability of OpenFOAM, the simulation for other flight conditions is beyond the scope of the present work.

3. Summary

This study assessed the suitability of alternative propulsion configuration for UAVs, using a blended wing body (BWB) airframe with distributed propulsion and thrust split. Since the airframe design influences in the propulsion system, a prototype configuration was tested for the aerodynamic performance assessment through OpenFOAM, which is a library of C++ solvers for CFD simulation under guidelines of the free and open-source software. In this context, it was demonstrated that distributed propulsion, together with thrust split, enables structural, aerodynamic, and performance benefits. The aforementioned was achieved through a better load distribution along the airframe spanwise and reduction of propulsors' size to allow embedding them to attain a low drag propulsion array. Furthermore, these latter configurations open the window for BLI installations, which bring important benefits in terms of propulsive efficiency and drag reduction, but represent challenges from the aerodynamic integration perspective.

Finally, the research demonstrated the suitability of using OpenFOAM as CFD platform for aerodynamic performance assessment, which presents significant advantages in terms of (i) freedom to adapt the main code to our needs and (ii) no license requirement, which is important to reduce simulation costs.

Acknowledgements

Abbreviations and nomenclature

UAV_S Unmanned Aerial Vehicle System

BLI   Boundary Layer Ingestion

DP   Distributed Propulsion

BWB   Blended Wing Body

TSFC   Thrust Specific Fuel Consumption

FPR   Fan Pressure Ratio

CFD   Computational Fluid Dynamics

HTS	High Temperature Superconducting
SST	Shear Stress Transport
LP	Low Pressure
HP	High Pressure
C_L	Lift Coefficient
C_D	Drag Coefficient
C_p	Pressure Coefficient
C_{Do}	Zero Lift Drag Coefficient
$\dot{m}^{\cdot}$	Mass Flow
AR	Aspect Ratio
e	Wing Span Efficiency
P_f	Power Per Fan
θ	Referred Temperature
δ	Referred Pressure
D_2	Fan Diameter
N_f	Number of Fans
T_S	Thrust Split
F_{DP}	Thrust Delivered by the Propulsor Array
F_N	Net Thrust
V_0	Velocity at Propulsor Intake
V_1	Velocity at Propulsor Outlet
U_{in}	Air Velocity at Inlet for CFD Simulation
p_{out}	Air Gaussian Pressure at Outlet
ρ_∞	Air Density
μ_∞	Air Viscosity
η_f	Fan Efficiency
ϕ	Variables
$\Gamma_{\phi,eff}$	Effective Diffusion Coefficient
S_ϕ	Source Term

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