Investigating an optimal aeroelastic design for aircraft wings with distributed propellers made of composites

Abouhamzeh M. [1], Ma Y. [2]

[1]Assistant Professor of Aerospace Engineering, School of Engineering and Mathematical Sciences, University of Wolverhampton, United Kingdom

[2] Postdoctoral Researcher at Visionary Aircraft Concepts, Bauhaus Aviation Research Institute, Willy-Messerschmitt-Straße 1, 82024 Taufkirchen, Germany; yiyuan.ma@bauhaus-luftfahrt.net

Abstract

Promoting novel technologies to exclude carbon emissions from civil aviation has initiated research on distributed propulsion. Specifically, features needed for electric aviation can benefit from a distributed propeller wing technology in terms of aero-propulsive efficiency which is crucial regarding the space needed for the battery cells. In order to have a structural design tool in preliminary phases, this paper presents the development of a coupled aeroelastic optimization tool for structural sizing of the wing. The structural modelling implements the geometrically nonlinear response of the composite material. The formulation is based on thin to moderately thick composite wings. Transverse shear deformations and moderate twist angles are considered, making it proper for the preliminary design of such structures. The aeroelastic response of the distributed propeller wing structure is obtained and results are illustrated. Having accomplished the coupling of the aerodynamic and structural fields for optimization, tailored layout can be obtained as follow-up research.

1 Introduction

The distributed propulsion concept has the advantage of improving wing aerodynamic efficiency with the need for electricity and hydrogen powered aviation which has been under investigation in recent years [1-3]. This is towards achieving targets for a zero-carbon emission in the civil aviation set by the United States, European Union, and United Kingdom [4-6]. The strategies are defined in some routes including but not limited to the Aircraft and Engine Technology. In this regard, improvements in fuel efficiency together with novel propulsion systems as electric and/or hydrogen are under considerations for the goals set for 2050. Targeting these goals, in this research, facilitating the application of distributed propulsion systems in the aircraft wings added to the optimised utilisation of composite structures are considered. Composite and hybrid materials, besides their high strength/weight ratios, allow changes in the material configuration for an optimal design with high structural performances like fatigue life, residual strength, and damage tolerance. The lightweight construction of composites together with the aerodynamic performance of the wing, can be optimised to enhance the flight performance even further. The selected approach will be applicable especially to electric and hydrogen types of energy.

There have been various configurations for the distributed propeller wing design from which a demonstrator developed by Airbus can be seen in Figure 1. For sizing wing structures in the preliminary design phase, optimization frameworks generally use lower fidelity panel methods and beam finite element (FE) structural models. Due to their limitations in terms of accuracy, they are typically useful in the preliminary design phase to minimize the structural mass. For future studies involving highly flexible wings with high aspect ratios, a geometrically nonlinear structural model must be used to estimate the aerodynamic load distribution over the wing accurately [7].

Figure 1- A distributed hybrid-propulsion demonstrator aircraft by Airbus (EcoPulse) [8]

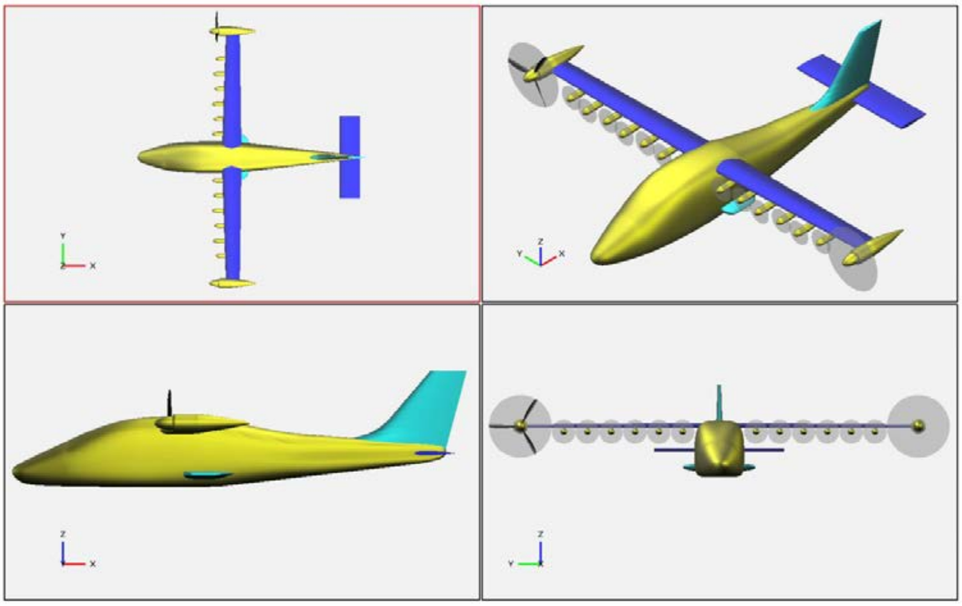

Figure 2- NASA SCEPTOR concept showing tip-mounted cruise propellers and leading-edge high-lift propellers [9]

The focus of this paper is to develop a coupled numerical model for aeroelastic design of Aircraft wings made of composite materials and having distributed propeller system mounted on it. An optimal robust and sustainable design is foreseen with such a tool. The aerodynamic pole of the model relies on the coupled Blade Element Momentum (BEM) theory and VLM method of aircraft aerodynamic simulation and the structural pole uses a geometrically nonlinear model developed for composite beams standing for the wing cross sectional properties. The description of the mentioned parts of the coupled model are described here briefly of which the details will be left to be presented in the full paper. Finally, this research makes it possible to extend the application of optimal composite designs of the current aircraft wings to the novel ones for hydrogen and electric aviation having a distributed propeller system.

In this study, investigations are performed on different types of composite panels and laminates for the wing-box structure. Synthetic composite panels are conventionally used in aircraft wing structure including carbon fibre and glass fibre epoxy composites. The mentioned composites, despite their high specific strength and stiffness, are vulnerable to the environment as they are not neither bio-degradable nor recyclable. Therefore, future trends in the aerospace materials industry would be the development and implementation of bio-degradable constituents [10]. After developing the aero-structural design/optimisation tool, different design options would be possible to examine with bi-based composite materials by which a comparison of overall weight and failure criteria with the traditional synthetic composites would provide the research community with new research-design opportunities.

2 Structural model for a composite wing

For the evaluation of the structural response of the wing under aerodynamic loads and the interference with the distributed propeller systems, a beam-type finite element model is developed accurate and fast enough for conceptual and preliminary phases of the aircraft wing design. The three-node beam element formulation is prepared to work for thin to moderately thick composite parts. The beam model will incorporate the properties of different parts of the wing structure, including upper and lower skin panels, trailing/leading edges, and the reinforcing spar webs.

The material is assumed to deform in its elastic phase for the constitutive equations. Considering the strain-displacement relationship, Von-Karman type strains are considered in which in-plane warping is not considered meaning that the cross-section may not deform in its plane but can go under arbitrary large twists. Additionally, being consistent to a geometrically nonlinear deformation, nonlinear transverse shear strains have been neglected. The formulation is made based on this assumption for bending analysis of wings. However, if other loading types of buckling and post-buckling are going to be investigated, corresponding nonlinear strains can be readily added to the current derivations. The model is also capable of deriving the natural frequencies of the wing.

2.1 Kinematics

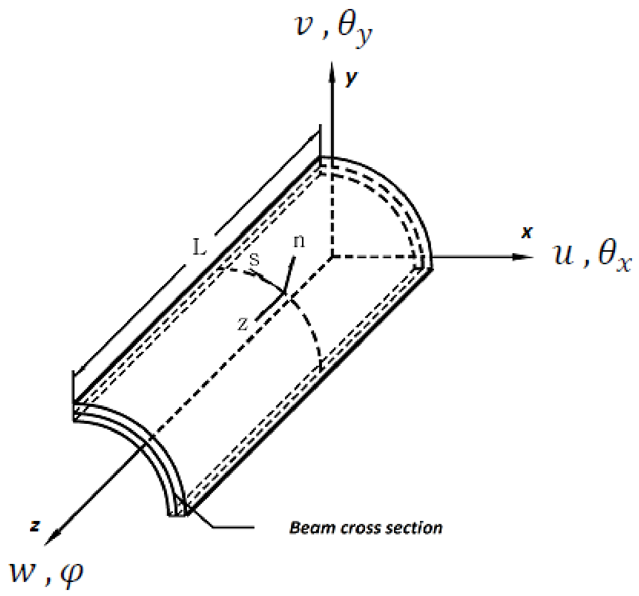

Figure 3. Coordinates for a typical thin-walled beam

The displacement field of the thin-walled wing is formulated as [11]:

$$
\begin{aligned}
u(x,y,z) &= u_c(z) - (x - x_c)(1 - \cos\varphi(z)) - (y - y_c)\sin\varphi(z) \\
v(x,y,z) &= v_c(z) + (x - x_c)\sin\varphi(z) - (y - y_c)(1 - \cos\varphi(z)) \\
w(x,y,z) &= \mathrm{w}_c(\mathrm{z}) + (\mathrm{y} - y_c)\theta_x + (\mathrm{x} - x_c)\theta_y - \varphi_{,z}\omega(s)
\end{aligned}
\qquad (1)
$$

s is the circumferential coordinate as shown in Figure 3.) is the twist angle, and $\omega(s)$ is the warping function for closed contour cross-sections which will take the following for the wing aerofoil:

$$\omega(s)=\int_0^s r ds-2A_c\frac{\delta_{0s}}{\delta};\delta_{0s}=\int_0^s\frac{ds}{\overline{G}_{sz}(s)t(s)};\delta=\oint\frac{ds}{\overline{G}_{sz}(s)t(s)} \qquad (2)$$

In the above equation, *r* is the normal radial vector as shown in Figure 3 from the origin to the point on the contour. $\overline{G}_{sz}(s)$ is the average transverse shear modulus and $t(s)$ is the thickness over the contour of the aerofoil. A_c denotes the cross-sectional area swept by the vector *r* over the mid-line contour.

It must be noted that if the flexural and torsional shear flexibilities are neglected, transverse shear simplifications may be applied as: $\theta_x = \frac{\partial v}{\partial z}$, $\theta_y = \frac{\partial u}{\partial z}$.

The kinematic, strain-displacement, equations of the geometrically nonlinear bending of the beam, counting for the transverse shear strains, can be written as:

$$\begin{aligned}\varepsilon_z &= \frac{dw}{dz}+\frac{1}{2}\left[\left(\frac{du}{dz}\right)^2+\left(\frac{dv}{dz}\right)^2\right]\\ \gamma_{sz} &= \frac{dw}{ds}+\frac{dv}{dz}\\ \gamma_{nz} &= \frac{dw}{dn}+\frac{du}{dz}\end{aligned} \qquad (3)$$

Together with the stress components as:

$$\begin{Bmatrix}\sigma_{zz}\\ \tau_{sz}\end{Bmatrix}=\begin{bmatrix}Q_{11} & Q_{16}\\ Q_{61} & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_{zz}\\ \gamma_{sz}\end{Bmatrix}\ ;\ \tau_{nz}=Q_{55}\gamma_{nz} \qquad (4)$$

Qij are the transformed material coefficients of the composite beam. As observable from the above, the formulation accounts for the transverse shear strains. The stiffness matrix of the (wing) beam elements are derived and the corresponding bending equations, through a weak formulation, are formulated and solved using beam finite element method. The derivation of the finite element equations are provided in the previous papers published by the authors [12, 13].

The accuracy of the developed model is examined through some results available for prismatic composite laminates. The test case results are reported by Minguet & Dugundje in 1990 [14] and Cesnik & Hodges in 1997 [15]. The laminate strip is 560mm long and 30mm wide and is loaded at 550mm from the root. The deformations are large concerning the beam length and this makes it possible to evaluate the model's accuracy in predicting geometrically nonlinear deflections (see Figure 4).

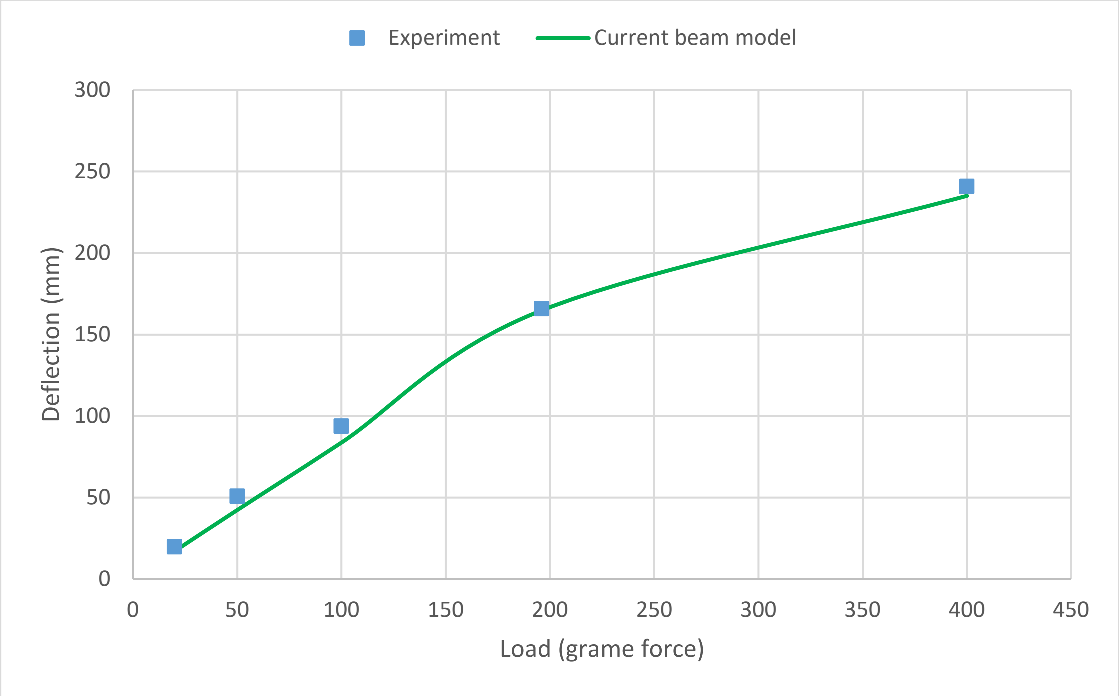

Figure 4- Deflection of the $[0/90]_{2s}$ composite beam under tip load ([14][15])

2.2 Finite element solution

As long as shear deformations are taken into account, we have only the first derivatives of the degrees of freedom in the generalized strains, which helps to simplify the analytic derivations of the finite element equations. The general displacement degrees of freedom (in total six: three translations and three rotations) are approximated by appropriate shape functions. The nonlinear algebraic equations are derived from the weak form of the governing equations. The governing equations are highly coupled and are solved using the iterative Newton-Raphson linearization method. The derivation of the finite element equations are skipped in this paper and will be left for a follow-up publication with more details.

3 Aerodynamic Solver

This section covers the approach to addressing the wing-propeller interaction.

3.1 Introduction to the Methodology

For the aerodynamic modelling of propeller-wing interaction effects, specialized techniques need to be devised, which can consider the impact of propeller wake on the wing aerodynamic characteristics, as illustrated in Figure 5. This work presents a complex procedure that draws upon existing aerodynamic analysis models to analyse the spanwise lift distribution for a wing with distributed propellers along its leading edge. These models are specifically designed to account for wing lift, slipstream, and propeller velocities, and 2D aerofoils.

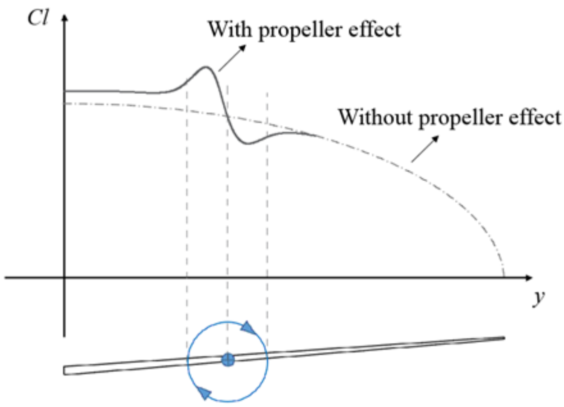

Figure 5- Distribution of wing spanwise lift coefficients with and without propeller influence

The first step is to perform an in-depth study of the lift and drag characteristics of the 2D aerofoil of the propeller blades. This preliminary analysis is performed using the XFOIL program [8], a sophisticated tool known for rapid and accurately calculating the aerodynamic characteristics of aerofoils under various flight conditions. The XFOIL analyses the flow around the aerofoil utilizing the potential flow panel approach and an integral boundary layer formulation.

Following the 2D aerofoil analysis, the focus shifts to understanding the axial and transverse velocities that are induced by the propellers. This step is crucial for comprehending the aerodynamic interactions between the propellers and the wing. The analysis is performed utilizing XROTOR [9], a specialized tool designed to simulate the aerodynamic performance of rotors and propellers based on the Blade Element Momentum (BEM) theory.

Additionally, the impact of the analysis involves the application of a Vortex Lattice Method (VLM) [10]. This method is employed to analyse the aerodynamics of the wing. The VLM method provides a comprehensive view of the aerodynamic behaviour of a wing by considering the combined effects of the distributed propellers and the aerodynamic characteristics of the wing itself.

3.2 Wing-propeller interaction study

The developed aerodynamic model for propeller-wing interaction was utilized for the aerodynamic analysis of an aircraft with leading edge-installed distributed propellers. The wing with varying numbers of propellers, including no propeller, one propeller, two propellers, and three propellers (on the half wing), was investigated in this work. In order to compare and analyse the effects of DP more intuitively, the position of the propellers with respect to the wing was fixed, and when the number of propellers was increased, the newly added propellers were placed in the outer position of the previous propellers, as shown in Figure 6.

The aerodynamic analysis results for the four wing configurations shown in Figure 6 are presented in Figure 7. These lift loads will be applied to the representative beams of the wing structure for aeroelastic analysis. The analysis of wing-propeller configuration employing BEM and VLM reveals significant impacts on spanwise lift distribution, as shown in Figure 4. The configurations include a clean wing and wings with different number of leading-edge propellers. The clean wing exhibits a typical elliptical lift distribution, peaking at mid-span and tapering towards the wingtips. Introducing propellers alters this distribution, with one propeller increasing the local lift coefficient near its position, creating a peak in the lift distribution. Adding a second propeller produces two peaks, indicating more evenly distributed lift across the span. The three-propeller configuration achieves the most uniform distribution, resembling the clean wing's elliptical shape but with higher lift values at the propeller locations. These findings highlight the potential of distributed propulsion system to enhance and control lift distribution, improving aerodynamic efficiency. Optimizing the number and placement of propellers can lead to better performance in advanced aircraft designs. Therefore, there is a need for a deeper study of DP aircraft characterisation using coupled aerodynamic and structural aeroelastic analysis method.

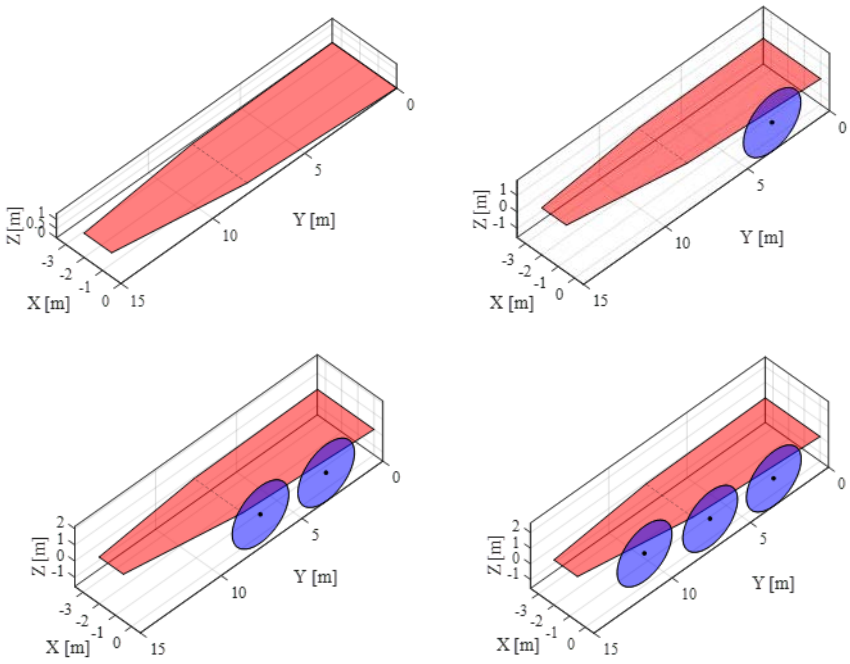

Figure 6- Configurations of wing with different number of leading-edge propellers

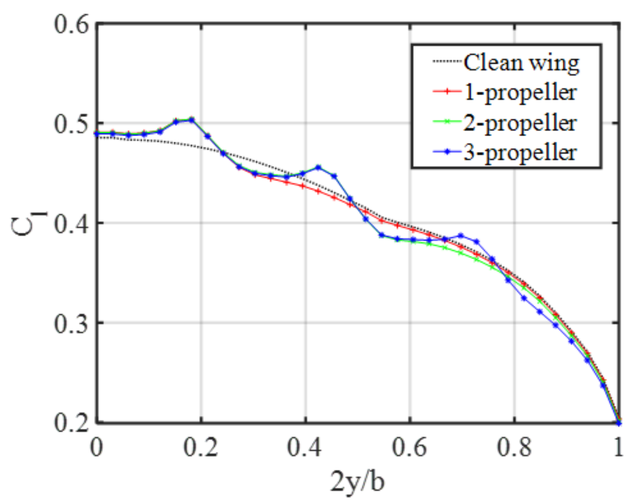

Figure 7- Comparison of wing spanwise lift distribution for different wing-propeller configurations

4 Aeroelastic coupling with the structural model

In the current stage, an aeroelastic analysis of the wing has been conducted. In other words, the aerodynamic loads, obtained from the aerodynamic model incorporating the interaction with the distributed propeller system were coupled and applied to the wing structure.

In the following, the deformation (vertical deflection) of the wing structure under applied lift load generated by the aerodynamic tool incorporating the interactions with and without the propellor system is illustrated. Again, four cases are reported: Clean wing, 1-propeller wing, 2 propeller wing, and 3-propeller wing (see Figure 6).

The composite material being used for the aeroelastic analysis is a T300/5208 graphite/epoxy having the properties presented in

Table 1. The layup of the laminate is also shown in the same table.

Table 1- Material properties for the composite (Layup: [0 / 45 / 0 / 45 /0 / 45])

E_1 [GPa]	E_2=E_3 [GPa]	G_{12}=G_{13} [GPa]	G_{23} [GPa]	ν_{12}=ν_{13}	Density ρ (Kg/m^3)
146.78	10.3	6.2	4.8	0.28	1600

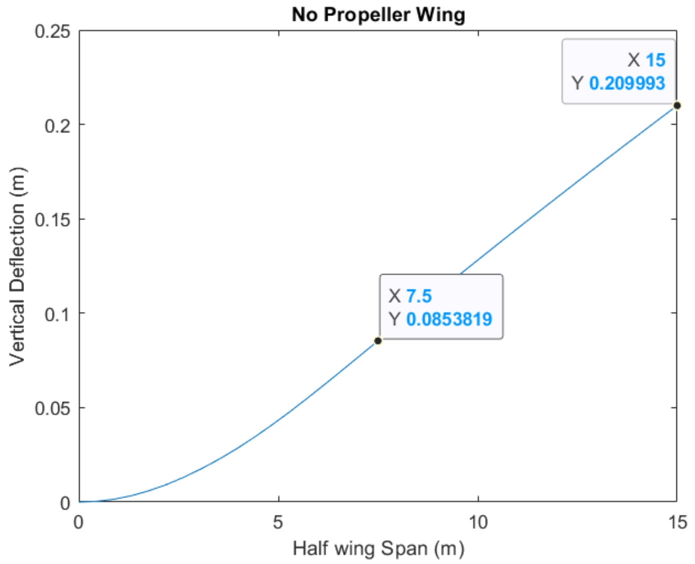

Figure 8- deflection of the composite wing under lift load without any propeller

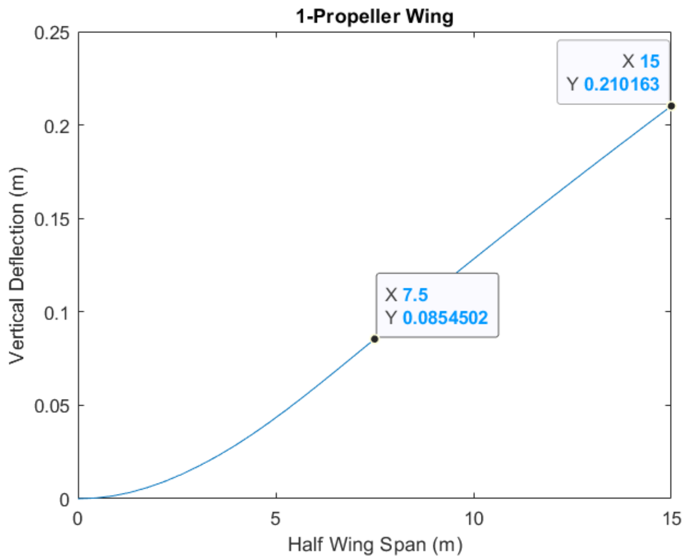

Figure 9- deflection of the composite wing under lift load with one propeller at the leading edge

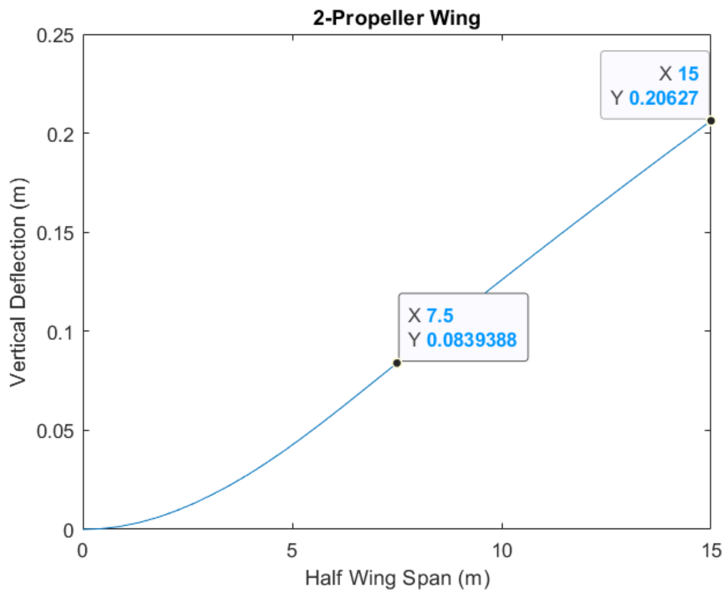

Figure 10- deflection of the composite wing under lift load with two propellers at the leading edge

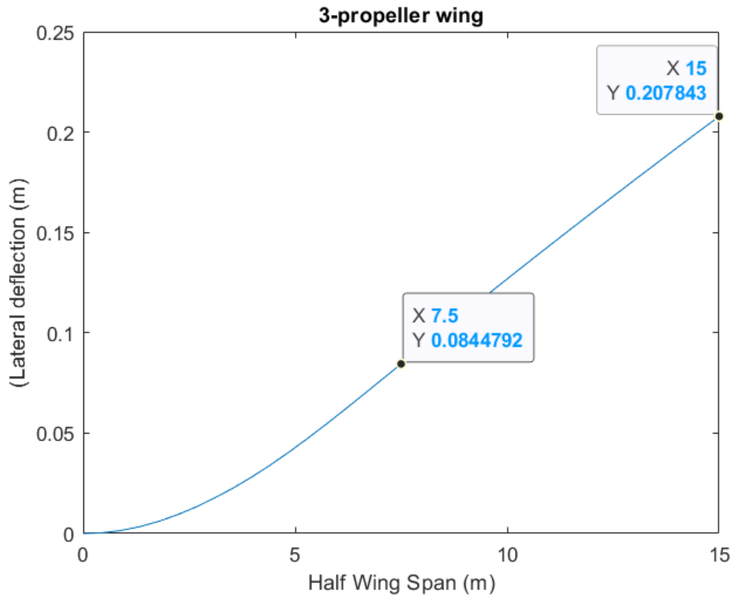

Figure 11- deflection of the composite wing under lift load with three propellers at the leading edge

As it can be seen from the deflection plots, the distribution of the deflection of the wing changes due to the interaction accompanied with the distributed propeller system. However, the maximum deflection at the wing tip is not significantly changing.

5 Concluding remarks and follow-up steps of this research

The formulations for the wing structural model in detail together with some numerical examples to show the level of accuracy under various loading and performance conditions, were provided in this paper. Regarding the coupling between the wing and the propeller aerodynamics, details are provided in terms of the BEM and multi-lifting line method. Furthermore, the aeroelastic coupling between the structural and aerodynamic solvers has been achieved at this stage of research. The results show the influence of the distributed propellers on the aerodynamic and structural response of the wing. It can be concluded that the propeller effect should not be ignored and needs to be estimated as precise as possible at the conceptual design stage, otherwise the wing deflections are not accurate.

In the next stages, the optimisation framework through parametric inputs for structural and aerodynamic properties will be developed. Stress distribution together with prediction of failure modes need to be added to the model. After establishing the aeroelastic optimisation framework, results can be obtained for geometric parameters of the wing, i.e. wing-box thicknesses. Alongside, the use of bio-fibres, in order to improve sustainable designs, will be considered as a comparison. Improvements in the model, like flutter considerations and geometrically exact modelling would provide unique possibilities for designing future aircraft wings.

6 Copyright Statement

References

1. Clarke, M.A., et al., *Aerodynamic Optimization of Wing-Mounted Propeller Configurations for Distributed Electric Propulsion Architectures*, in *AIAA AVIATION 2021 FORUM*. 2021, American Institute of Aeronautics and Astronautics.
2. Gur, O. and A. Rosen, *Optimization of Propeller Based Propulsion System.* Journal of Aircraft - J AIRCRAFT, 2009. **46**: p. 95-106.
3. Resende, G.J., et al., *Wing's aerodynamic characteristics due to distributed propulsion over the wingspan.* Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2023. **45**(9): p. 495.
4. ATI, *Destination Zero: The Technology Journey to 2050*. 2022, Aerospace Technology Institute (ATI): UK.
5. Greitzer, E.M., et al. *N+3 Aircraft Concept Designs and Trade Studies. Volume 2; Appendices-Design Methodologies for Aerodynamics, Structures, Weight, and Thermodynamic Cycles*. 2010.
6. UNFCCC, *The Paris Agreement – Publication*, in *Paris Climate Change Conference – November 2015*. 29 November 2018.
7. Gray, A.C. and J.R. Martins, *Geometrically Nonlinear High-fidelity Aerostructural Optimization for Highly Flexible Wings*, in *AIAA Scitech 2021 Forum*. 2021, American Institute of Aeronautics and Astronautics.
8. *EcoPulse: A new approach to distributed propulsion for aircraft*. 2023, AIRBUS: https://www.airbus.com/en/innovation/low-carbon-aviation/hybrid-and-electric-flight/ecopulse.
9. Borer, N.K., et al., *Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator*, in *16th AIAA Aviation Technology, Integration, and Operations Conference*. 2016, American Institute of Aeronautics and Astronautics.
10. Andrew, J.J. and H.N. Dhakal, *Sustainable biobased composites for advanced applications: recent trends and future opportunities – A critical review.* Composites Part C: Open Access, 2022. **7**: p. 100220.
11. Librescu, L.a.O.S., *Thin-Walled Composite Beams: Theory and Application.* 2006, Springer.
12. Abouhamzeh, M., Y. Ma, and A. Elham, *A Geometrically Nonlinear Structural Model For Aerostructural Optimization of Ultra-High Aspect Ratio Composite Wings*, in *AIAA SCITECH Forum*. 2022.
13. Ma, Y., M. Abouhamzeh, and A. Elham, *Geometrically Nonlinear Coupled Adjoint Aerostructural Optimization of Natural-Laminar-Flow Strut-Braced Wing.* Journal of Aircraft, 2022: p. 1-20.
14. Minguet, P. and J. Dugundji, *Experiments and analysis for composite blades under large deflections. I - Static behavior.* AIAA Journal, 1990. **28**(9): p. 1573-1579.
15. Cesnik, C.E.S., R. Palacios, and E.Y. Reichenbach, *Reexamined Structural Design Procedures for Very Flexible Aircraft.* Journal of Aircraft, 2014. **51**(5): p. 1580-1591.