

LOW-FIDELITY STATIC AEROELASTIC ANALYSIS FOR JIG SHAPE OPTIMIZATION OF A SOLAR-POWERED HALE AIRCRAFT WING

Pamela Bugała*  0000-0001-7186-7830

Łukasiewicz Research Network – Institute of Aviation, 110/114 Krakowska Ave., 02-256 Warsaw, Poland

ABSTRACT

This study investigates the static aeroelastic behavior of a lightweight, high-aspect-ratio wing designed for a solar-powered High Altitude Long Endurance (HALE) aircraft. The primary objective is to demonstrate that simplified, low-fidelity models can be effectively used to define the wing's jig shape and stiffness distribution, ensuring optimal aerodynamic performance during cruise flight. High-aspect-ratio wings (HARWs) are susceptible to significant deformations under aerodynamic loading, which can alter the lift distribution and compromise performance. Therefore, accurate modeling of aeroelastic effects is essential, particularly in the early stages of the design process. The numerical analysis presented in this work uses a low-order, two-way fluid–structure interaction (FSI) method, combining the Vortex Lattice Method (VLM) and the Euler–Bernoulli beam model. This approach offers a balance between computational efficiency and physical accuracy. Validation was carried out by comparing simulation results with wind tunnel data, confirming the method's ability to predict lift coefficients and structural deformation with satisfactory accuracy. The study also introduces an innovative flat-upper-surface airfoil, optimized for solar panel integration and evaluated for static aeroelastic effects. Results show that, with a known distribution of stiffness and mass, the jig shape can be tailored to achieve the desired in-flight geometry. The proposed method provides a fast, reliable, and practical tool for early-stage wing design and is well-suited for engineering applications.

Keywords

aeroelasticity, static aeroelasticity, HALE, UAV, solar-powered.

Abbreviations

HARW – high-aspect-ratio wing
HALE – high altitude long endurance
UAV – unmanned aerial vehicles
FSI – fluid structure interaction
VLM – Vortex Lattice Method

DLM – Doublet Lattice Method
CFD – computational fluid dynamics
AoA – angle of attack
WTT – wind tunnel test

* Corresponding Author. Email address: pamela.bugala@ilot.lukasiewicz.gov.pl

Received 12.03.2025 • Revised 08.04.2025 • Accepted 21.05.2025

© 2025 Author[s]. Article category: research article



1. INTRODUCTION

Recent advancements in battery and photovoltaic panel technology have spurred the development of Solar High Altitude Long Endurance Unmanned Aerial Vehicles (HALE UAVs) [1]. According to a report by Allied Market Research [2], the market for solar-powered UAVs is expected to grow at an average annual rate of 7.26% from 2025 to 2035. These UAVs offer a cost-effective alternative to geostationary satellites and can perform missions requiring more flexibility while being closer to the ground.

Solar HALE UAVs have numerous potential uses, including surveillance, communication, and scientific research. Their ability to operate at high altitudes for extended periods makes them ideal for tasks requiring long-term monitoring or data collection. Additionally, they are powered by solar energy, making them an environmentally friendly and stealthy option compared to conventional aircraft, as they do not produce emissions or noise.

Since the 1970s, various solar-powered UAV projects have been in development, including Sunrise [3], Helios [4], Zephyr [5], and Solar Impulse [6]. Designers frequently adopt wing-tail [5], and flying-wing [4] configurations for solar UAVs, but some teams have started to explore alternative concepts, including tandem-wing [7,8] and joined-wing [7,9,10] configurations. These emerging designs offer new possibilities, but also present additional engineering challenges.

One key requirement for HALE is to reduce vehicle-induced drag and lift loss caused by the wingtip vortex. Therefore, HALE wings are usually designed with a high aspect ratio (HAR). However, the structure of the HAR wings itself becomes more elastic, which can cause large deformations when aerodynamic loads are applied. The challenge with HAR wings is that their relatively large deformations can significantly affect wing performance by changing the aerodynamic load. This makes it essential to account for aeroelastic effects in the modeling of high-aspect-ratio wings.

As solar HALE platforms evolve, the need for accurate modeling of highly flexible aircraft becomes even more critical. Their exceptionally high aspect ratios and low structural rigidity result in large wing deflections, as illustrated in Figure 1.



Fig. 1. NASA Helios [11] and Arbus Zephyr Solar High Altitude Platform System [5].

HAR wings are usually made of modern composite materials. Such materials offer superior strength-to-weight ratios compared to traditional metals, enabling substantial weight reduction. This translates into operational cost savings by increasing payload capacity, extending flight range, and reducing maintenance needs. However, designing composite wings is inherently complex, as many parameters need to be considered [12].

Recent advancements in material science have also enabled the development of lightweight and flexible structures that can withstand the harsh environments encountered at high altitudes. These structures, combined with advanced control systems, allow solar-powered aircraft to maintain stable flight and optimize energy efficiency. With the increasing significance of aeroelasticity in HAR wings, it is crucial to consider these effects as early as possible in the design process [13].

To simplify modeling, especially in the early stages, equivalent structural models such as the beam model are often used. These enable aeroelastic analysis without detailed knowledge of the wing's internal structure, relying instead on simplified equivalent stiffness distributions and a limited set of input parameters. Reduced-order models help lower computational costs while maintaining acceptable accuracy [14].

In recent years, numerous computational studies have addressed fluid-structure interactions and static aeroelasticity. The literature features simplified aerodynamic methods like the Vortex Lattice Method (VLM) [7,15–17] and Doublet Lattice Method (DLM) [18–21], as well as advanced CFD methods [17,22,23]. Structural modeling methods include the Bernoulli beam model [20,24] and CSD methods [19,25]. However, each method has its own advantages and limitations.

The present study focuses on the static aeroelasticity of a very light solar-powered aircraft at high altitudes. The objective is to showcase the potential of using basic models (VLM and Bernoulli Beam Model) for predicting optimal wing shape (jig shape) during cruise conditions. A lightweight UAV described in [26] was selected for the analyses. Its design specifications include a flat upper surface of the airfoil, which is necessary to accommodate solar panels and ensure efficient operation. Although flexible solar panels do exist, they only tolerate bending in one direction. Applying solar panels to wings with a conventional curved profile exposes them to bending in two directions, which often results in damage. Thus, the profile used in this study is a flat-upper-surface airfoil proposed by Galiński [27], who also highlighted the importance of aeroelastic analysis in subsequent design steps and presented a complete method for airfoil shape optimization.

The results of this study provide valuable insights for designing and optimizing solar-powered aircraft for high-altitude operations. Simulations were performed across a range of bending and torsion stiffness values, representing different wing structures and different dihedral angles.

2. METHOD

This study demonstrates a methodology for the preliminary aeroelastic analysis of a wing. The analysis was conducted using XAVEL(X-Foil & AVL wing aeroELasticity software) [28], an in-house tool prepared by Adam Sieradzki, based on low-cost computational models such as the Beam Model and Vortex Lattice Method VLM. The aerodynamic module was implemented using the open-source programs AVL and XFOIL. The VLM method is based on potential flow theory, and it provides a satisfactory level of accuracy for flight speeds with a Mach number below 0.6. A detailed formulation of the steady-state and the unsteady variant of VLM can be found in [29].

The proposed approach to the aeroelastic analysis of a wing adopted a simplified structural model – the Euler-Bernoulli beam model. This choice balances computational efficiency with sufficient accuracy for evaluating flexible wing behavior.

The analysis focused on a HALE wing with a flat-upper-surface airfoil. Three configurations were considered:

- rigid with zero dihedral angle;
- flexible with zero dihedral angle;
- flexible with a negative dihedral angle;

The goal was to assess these three high-altitude wing configurations by evaluating the static aeroelastic response for each case. As such, the study sought to demonstrate the potential of using simple models to propose a jig shape and stiffness distribution of the wing that results in an optimal in-flight shape under cruise conditions.

Numerical Method Overview

Aeroelastic analysis is one of the most computationally intensive stage in the optimization process due to its iterative nature, as shown in Figure 2. Starting from an initial wing geometry and operating conditions, AVL & XFOIL calculates the aerodynamic loads. Using the Beam Model, these forces are then used to determine wing deflection and twisting.

This updated, deformed wing geometry is then reintroduced into AVL for a new round of aerodynamic calculations. The updated aerodynamic forces are used again to recalculate the wing's deformation, repeating the process iteratively. This loop of aerodynamic load calculation (AVL) and structural deformation analysis (Beam model) continues until convergence is reached. Convergence is defined as the point where the relative change in the angle of attack or wing geometry between iterations becomes negligible.

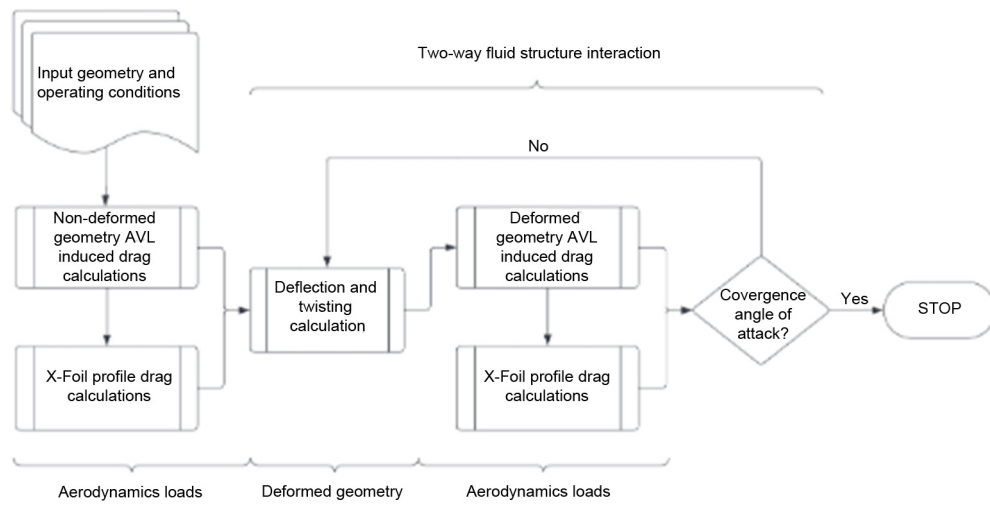


Fig. 2. Diagram of two-way fluid-structure interaction implemented in XAVEL (from [28]).

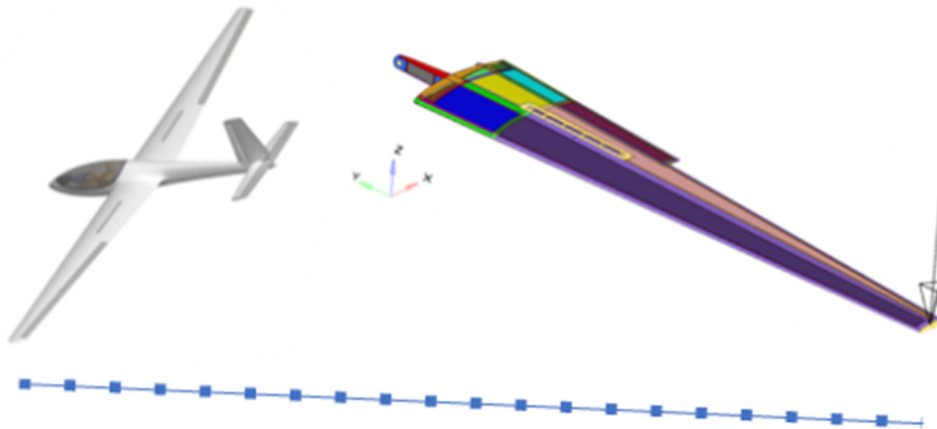


Fig. 3. Different levels of structure modelling.

Researchers are increasingly exploring models that require less computational power while still producing reliable and consistent results, in pursuing more cost-effective analysis. In parallel, a method for developing equivalent stiffness models (ESM) has been introduced to reduce the model from a complex 3D geometry to a simpler one [30–32]. Figure 3 shows different levels of structure modelling. In the initial design phase, simplified beam models used to perform static and dynamic aeroelastic analyses to obtain preliminary results without incurring high costs [33]. Detailed 3D FEA models are used for design validation and analysis in the final design stages. Equivalent beam finite element models, or stick models, are

often used for static or dynamic aeroelastic analysis and optimization. These stick models are usually generated when the wing structure has been defined and sized.

Such models are well described in the literature [34–37]. The Euler-Bernoulli beam model is widely used in engineering due to its simplicity and ability to provide accurate predictions for many practical applications. A brief overview will be given here.

Bending deformations of the beam model:

The shear force in cross-section y is given by:

$$F_{shear}(y) = \int_y^b [L(\rho) + Q(\rho) d\rho] \quad (1)$$

where: F_{shear} – shear force [N], L – lift force [N], Q – [N], and b – half span [m].

The shear moment in cross-section y is:

$$M_{shear}(y) = \int_y^b F_{shear}(\rho) d\rho \quad (2)$$

where: M_{shear} – shear moment [Nm].

The curvature in cross-section y is given by:

$$k(y) = \frac{M_{shear}(y)}{EI(y)} \quad (3)$$

where: k – curvature [1/m] and EI – bending stiffness [Nm²].

The slope in cross-section y is:

$$\beta(y) = \int_0^y \kappa(\rho) d\rho \quad (4)$$

where: β – slope [rad].

The deflection in cross-section y is:

$$z(y) = \int_0^y \beta(\rho) d\rho \quad (5)$$

where: z – deflection [m].

Torsional deformations of the beam model:

The twisting moment about point (0,0) in cross-section y is given by:

$$M_0(y) = \int_y^b [F_{shear}(\rho) \cdot x_{CP}(\rho) + Q(\rho) \cdot x_M(\rho)] d\rho \quad (6)$$

where: M_0 – bending moment about point (0,0) [Nm], x_{CP} – center of pressure [m], x_M – center of mass [m].

The twisting moment about center of shear forces in cross-section y is:

$$M_{SC}(y) = M_0(y) + T_{shear}(y) \cdot x_{SC}(y) \quad (7)$$

where: M_{SC} – torque about shear center [Nm] and x_{SC} – shear center [m].

The torsion angle in cross-section y is:

$$\theta(y) = \int_0^y \frac{M_{SC}(y)}{GI_S(y)} d\rho \quad (8)$$

where: θ – angle of torsion [rad], GI_S – torsional stiffness [Nm²].

Wing specification & flight conditions

This section presents the typical solar-powered UAV configuration used for the present study. The simulations were performed using various bending and torsion stiffness values, representing different wing configurations and different dihedral angles. Figure 2 shows sketches of the airplane under analysis, whose design is inspired by current F1A FAI flyers [38,39]. The general specifications of this class of UAV are shown in Table 1. Aircraft of this type could be as light as 0.4 kg, with wingspan as long as 3 m and wing area on the order of 0.51 m².

Table 1. Gross specifications of current F1A FAI flyers [38,39].

Code Class	General Type	Brief Description
F1A	Gliders (A2 'Nordic')	Surface area: 32–34 dm ² Minimum weight: 410 g Max length of launching cable: 50 m at 5 kg load with minimum cable pennant area of 2.5 dm ² World Championship Class

Figure 4 shows the jig shape of the solar UAV selected for analysis. The jig shape of a wing refers to the nominal, stress-free geometry defined during the manufacturing and assembly process, typically in the production jig, prior to the application of any aerodynamic, inertial, or structural loads. It serves as the undeformed reference

configuration for finite element and computational fluid dynamics analyses and for aeroelastic simulations. The jig shape is used to compute structural deformations and assess the differences between the manufactured geometry and the in-flight, loaded configuration (commonly called the cruise shape).

This study deliberately introduces a negative dihedral angle in the jig shape to account for the elastic behavior of high-aspect-ratio wings. Due to their flexibility, such wings exhibit significant upward bending under aerodynamic loading. As a result, the actual in-flight geometry (the cruise shape) tends to have a greater dihedral angle than the unloaded configuration. By designing the jig shape with a slight negative dihedral, it is possible to compensate for this deformation so that the wing achieves the intended geometric and aerodynamic characteristics during cruise flight.

This design strategy is particularly relevant in aeroelastic optimization, where the aerodynamic performance depends on the interaction between the structural flexibility and the loading conditions. The jig shape, therefore, is not purely a matter of structural convenience but a key factor influencing the final in-flight shape and performance of the wing.

Wing geometry

The configuration mainly comprises a high-aspect-ratio wing, a vertical tail, a horizontal tail, and the fuselage. The main geometric parameters of the wing are shown in Table 2. Figure 4 shows sketches of the jig shape of the solar UAV under analysis with dihedral angle: 0 deg, -3 deg.



Fig. 4. Sketches of the jig shape of the solar UAV under analysis.
Dihedral angle: 0 deg, -3 deg.

As can be seen, the wing features an airfoil with a flat upper surface, which is maintained consistently from the root to the tip along the span, with no geometric twist. The airfoil design process and its results are presented in [27]. Figure 5 shows the shape of the MOD-42 airfoil with a flat-upper surface – selected to facilitate easier installation of solar panels and to minimize curvature-induced stress.

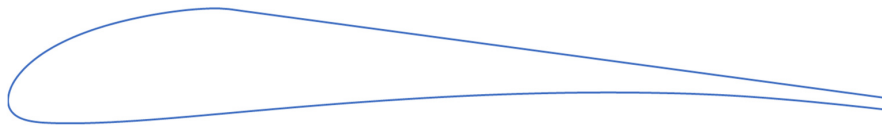


Fig. 5. The shape of the MOD-42 airfoil with a flat-upper surface, adopted from [40].

Table 2. Wing geometry parameters.

Parameter	Value
Span [m]	3
Reference area [m ²]	0.51
Aspect ratio	17.65
Mean aerodynamic chord [m]	0.17

Structural properties

The wing under analysis consists of a D-shaped torsion box construction, with a spar, ribs, a trailing edge beam, and a polymer elastic skin. In F1A models, wings of this type usually weigh approximately 0.350–0.500 kg. For the purposes of this analyses, it was assumed that the mass of half the wingspan is 250 g. XAVEL does not need detailed data on the internal geometry of the structure; instead, information about the structure's mass and flexural and torsional stiffnesses is sufficient for analysis. Mass and stiffness are approximated as functions of the wingspan, based on structural estimates. Figure 6 shows the D-box build technology, and Figure 7 shows the uniform structure of the wing along the span.

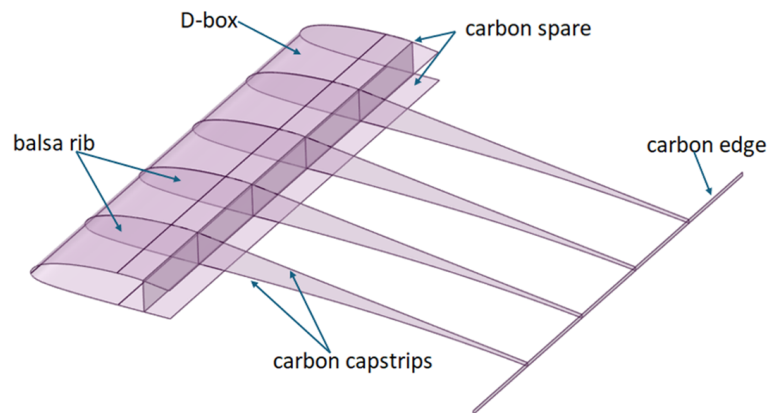


Fig. 6. Explanation of The D-Box build technology.



Fig. 7. Uniform structure of the wing along the span.

Flight conditions

The maximum flight altitude was taken to be 20 km, as HALE platforms are designed to operate in the lower stratosphere. The average wind speed at the specified altitude is minimal. Figure 4 shows average wind speed vs altitude. Values vary with season and location. Table 3 shows flight conditions under analysis, including a determination of the required lift coefficient.

Table 3. Flight conditions under analysis and required lift coefficient.

Altitude [km]	Air Density [kg/m ³]	Speed [m/s]	Design total lift [N]	Angle of attack [deg]	Coefficient of Lift
20	0.089	18	4,9	4	0.67

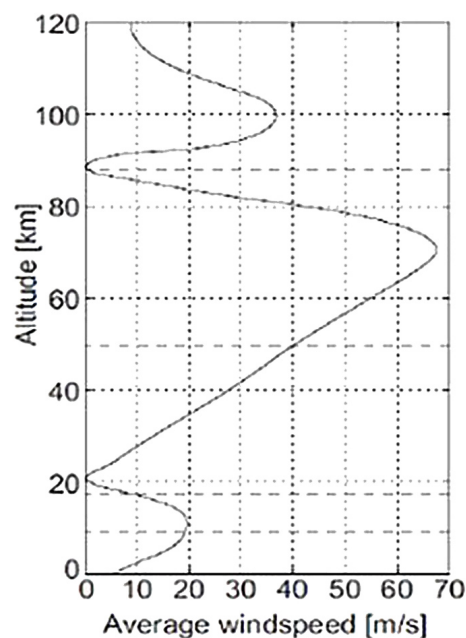


Fig. 8. Average wind speeds in m/s vs. altitude in km (figure adapted from [41]).

3. RESULTS AND DISCUSSION

Numerical calculations of the two-way fluid–structure coupling were carried out to obtain the deformation characteristics of the wing structure. The angle of attack was varied in the range of -2° to 13° . The following section presents the results obtained from these static aeroelastic calculations.

Flexible wing -0 deg dihedral

The results obtained from the XAVEL program were compared with wind tunnel tests. Although the tests published by [27] showed a deflection of the wing during loaded conditions, the actual deflection values were not quantified. Instead, validation was performed by comparing the lift coefficient results, shown in Figure 9. The results are satisfactory and show the verification of the method and the determined stiffness distributions.

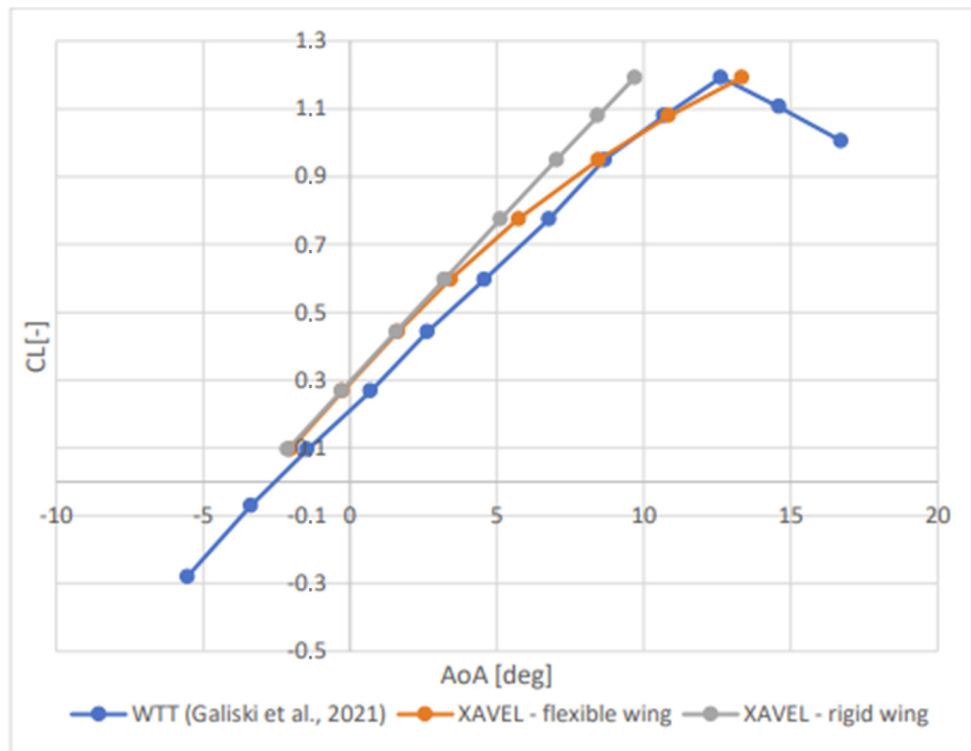


Fig. 9. Lift coefficient vs angle of attack: comparison XAVEL and wind tunnel test (WTT) (from [27]).

The difference in aerodynamic characteristics between rigid and elastic is quite obvious owing to the static aeroelastic effect. As the aerodynamic load increases, the static aeroelasticity exerts a great influence on the aerodynamic force. Figure

10 shows the results of the structural deformations at a flow velocity of 8 m/s. The normalized deflection Δz , with respect to the wingspan, is plotted against the normalized spanwise coordinate y/b . Note that this deformation sequence is valid only for an airspeed of $V = 8$ m/s. As the deformation of the wing depends on the forces and moments applied to the wing surface, the corresponding deformed shape will be different for a different airspeed.

As the angle of attack increases, the deformations become increasingly positive, which is in line with expectations. At an angle of attack of 13 degrees, the wing tip displacement in the z direction reaches a maximum of approximately 4.5%.

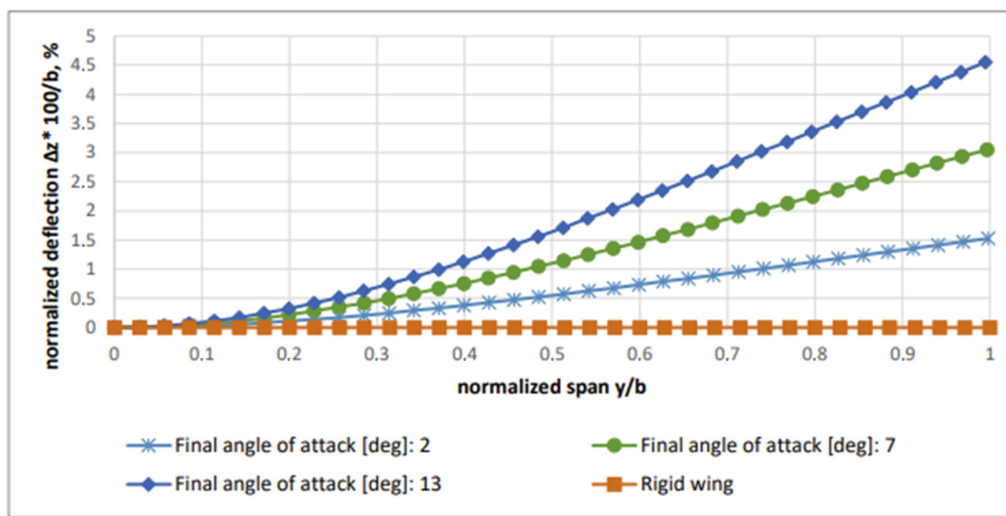


Fig. 10. Geometry normalized deflection of wing at 8 m/s at sea level.

Flexible wing with -3 deg dihedral

The final stage of the study involved analyzing the wing shape with a negative dihedral angle for different angles of attack. Figure 11 shows the geometry of the wing at 18 m/s for different angles of attack taking into account deflections and twists of the wing. Subfigure A presents the vertical deflection of the wing, while subfigure B displays the angle of twist for each wing section.

As the load increases, the wing tends to level out the dihedral angle. By assuming a known distribution of stiffness and weight of the wing, it is possible to design the wing's jig shape to achieve the desired shape during cruise conditions. In particular, to obtain a straight wing without a dihedral, the jig shape must be carefully optimized.

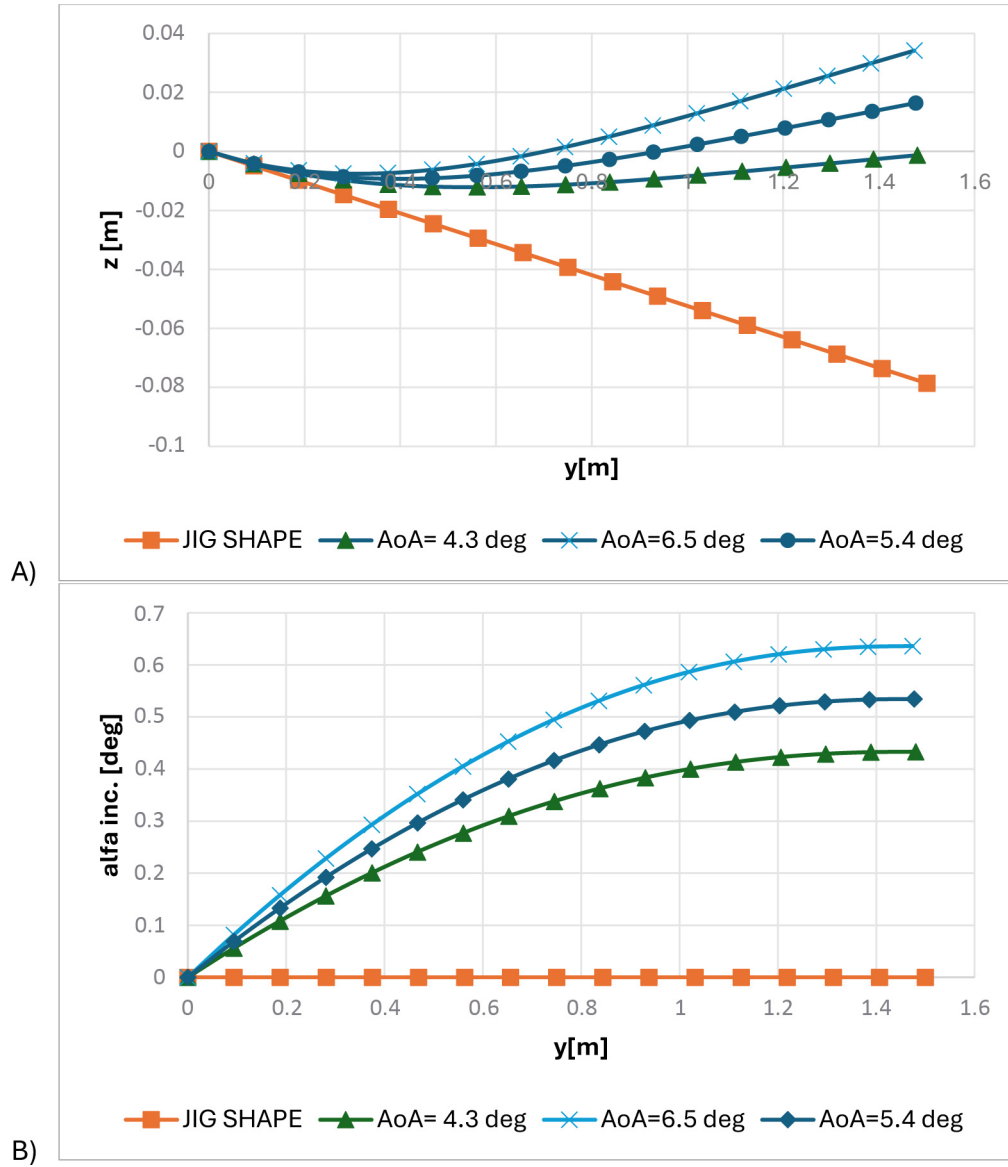


Fig. 11. Wing geometry at 18 m/s at 20 km for different angles of attack: Deflection (A) and Angle of inclination (B).

4. SUMMARY

This study has investigated the static aeroelastic behavior of a very light, high-aspect-ratio solar-powered aircraft wing operating at high altitudes. The primary objective was to evaluate the effectiveness of a simplified, low-cost numerical method – based on the Vortex Lattice Method (VLM) and the Euler–Bernoulli beam model – to accurately simulate the aeroelastic response of flexible wings. By integrating these models in a two-way fluid-structure interaction (FSI) loop, the proposed

method enables efficient determination of the required jig shape and the stiffness distribution to achieve the desired in-flight (cruise) geometry.

The method was validated against wind tunnel test data, confirming its reliability for predicting aerodynamic performance. Simulations demonstrated how varying the wing's bending, torsional stiffness, and jig shape (e.g., dihedral angle) impacts the aeroelastic response. In particular, introducing a slight negative dihedral in the jig shape compensated for elastic deformation, enabling the wing to reach a flat or positively dihedral cruise shape under aerodynamic loading.

These results show that an optimal balance between bending and torsional stiffness is key for maintaining aerodynamic efficiency in cruise conditions while minimizing unwanted deflections. Overall, then, this study highlights the practical utility of low-fidelity models in the early stages of aeroelastic design.

ACKNOWLEDGEMENTS

The author would like to thank Adam Sieradzki (Ł-ILOT) for providing the in-house software tools, XAVEL and MOPTAX, making this work possible, and helping with the software.

REFERENCES

- [1] G, Cestino E. Design of a High-Altitude Long-Endurance Solar-Powered Unmanned Air Vehicle for Multi-Payload and Operations. *Proc Inst Mech Eng G J Aerosp Eng* 2007;221:199–216. <https://doi.org/10.1243/09544100JAERO119>.
- [2] Mayank H, Katare LJ. Solar-Powered UAV Market Size, Share, Competitive Landscape and Trend Analysis Report, by Application, by Mode of Operation, by Type, by Range: Global Opportunity Analysis and Industry Forecast, 2025-2035. Allied Market Research; 2022. <https://www.alliedmarketresearch.com/solar-powered-uav-market-A08543>.
- [3] Boucher RJ. Sunrise, the world's first solar-powered airplane. *J Aircraft* 2012;22:840–6. <https://doi.org/10.2514/3.45213>.
- [4] Noll TE, Brown JM, Perez-Davis ME, Ishmael SD, Tiffany GC. Investigation of the Helios Prototype Aircraft Mishap Volume I. 2004.
- [5] Davey P. Zephyr HALE UAS (High Altitude Long Endurance Unmanned Aerial System). *Science & Technology Conference*, vol. 8, 2009.
- [6] Weiss G. Around the World in a Solar Plane. *IEEE Spectr* 2004;41:12–4. <https://doi.org/10.1109/MSPEC.2004.1270538>.
- [7] Cipolla V, Dine A, Viti A, Binante V. MDAO and Aeroelastic Analyses of Small Solar-Powered UAVs with Box-Wing and Tandem-Wing Architectures. *Aerospace* 2023;10:105. <https://doi.org/10.3390/aerospace10020105>.
- [8] Okulski M, Ławryńczuk M. A Small UAV Optimized for Efficient Long-Range and VTOL Missions: An Experimental Tandem-Wing Quadplane Drone. *Appl Sci* 2022;12. <https://doi.org/10.3390/app12147059>.

- [9] Rasmussen CC, Canfield RA, Blair M. Optimization process for configuration of flexible joined-wing. Collection of Technical Papers – 10th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, vol. 1, American Institute of Aeronautics and Astronautics Inc.; 2004, p. 358–66.
<https://doi.org/10.2514/6.2004-4330>.
- [10] Rasmussen CC, Canfield RA, Blair M. Joined-Wing Sensor-Craft Configuration Design. *J Aircr* 2006;43:1470–8. <https://doi.org/10.2514/1.21951>.
- [11] Nick Galante/PMRF. The Helios Prototype flying wing is shown over the Pacific Ocean during its first test flight on solar power from the U.S. Navy's Pacific Missile Range Facility in Hawaii. [Http://WwwDfrcNasaGov/Gallery/Photo/IndexHtml](http://WwwDfrcNasaGov/Gallery/Photo/IndexHtml) 2001.
- [12] Yanko T, Dmytrenko O. Prospects for the Implementation of New Materials and Technologies in the Aerospace Industry. *Transactions on Aerospace Research* 2021;2021:1–10. <https://doi.org/10.2478/tar-2021-0019>.
- [13] Hasan YJ, Roeser MS, Hepperle M, Niemann S, Voß A, Handojo V, et al. Flight mechanical analysis of a solar-powered high-altitude platform. *CEAS Aeronaut J* 2022. <https://doi.org/10.1007/s13272-022-00621-2>.
- [14] Kafkas A, Lampeas G. Static aeroelasticity using high fidelity aerodynamics in a staggered coupled and ROM scheme. *Aerospace* 2020;7:1–23.
<https://doi.org/10.3390/aerospace7110164>.
- [15] Grozdanov A. Transonic Static Aeroelasticity Using the 2.5D Nonlinear Vortex Lattice Method. <https://publications.polymtl.ca/2899/>. Mémoire de maîtrise, École Polytechnique de Montréal; 2017.
- [16] Mao S, Xie C, Yang L, Yang C. Static Aeroelastic Characteristics of Morphing Trailing-Edge Wing Using Geometrically Exact Vortex Lattice Method. *International Journal of Aerospace Engineering* 2019;2019.
<https://doi.org/10.1155/2019/5847627>.
- [17] Yang L, Xie C, Yang C. Geometrically exact vortex lattice and panel methods in static aeroelasticity of very flexible wing. *Proc Inst Mech Eng G J Aerosp Eng* 2020;234:742–59. <https://doi.org/10.1177/0954410019885238>.
- [18] Bordogna MT, Lancelot P, Bettebghor D, De Breuker R. Static and dynamic aeroelastic tailoring with composite blending and manoeuvre load alleviation. *Structural and Multidisciplinary Optimization* 2020;61:2193–216.
<https://doi.org/10.1007/S00158-019-02446-W/TABLES/5>.
- [19] Demirer HG. Static and dynamic aeroelastic analysis of a very light Aircraft. <https://open.metu.edu.tr/handle/11511/93190>. Middle East Technical University; 2021.
- [20] Kidane BS, Troiani E. Static aeroelastic beam model development for folding winglet design. *Aerospace* 2020;7:1–16. <https://doi.org/10.3390/AEROSPACE7080106>.
- [21] Kilimtzidis S, Kostopoulos V. Static Aeroelastic Optimization of High-Aspect-Ratio Composite Aircraft Wings via Surrogate Modeling. *Aerospace* 2023;10:251.
<https://doi.org/10.3390/aerospace10030251>.
- [22] Delavenne M, Barriety B, Vetrano F, Ferrand V, Salaun M. A Static Aeroelastic Analysis of an Active Winglet Concept for Aircraft Performances Improvement. *Lecture Notes in Mechanical Engineering* 2021:77–82.
https://doi.org/10.1007/978-981-33-4960-5_12/COVER.

-
- [23] Lyrio JAA, Azevedo JLF, Rade DA, da Silva RG. Computational static aeroelastic analyses in transonic flows. AIAA Aviation Forum 2020;1 Part F. <https://doi.org/10.2514/6.2020-2718>.
 - [24] Vindigni CR, Mantegna G, Esposito A, Orlando C, Alaimo A. An aeroelastic beam finite element for time domain preliminary aeroelastic analysis. *Mechanics of Advanced Materials and Structures* 2023;30:1064–72. <https://doi.org/10.1080/15376494.2022.2124333>.
 - [25] Yang L, Xie C, Liang D, An C. Geometrically Nonlinear Static Aeroelastic Analysis Based on CFD/CSD Interaction Accelerated by Panel Method, 2023, p. 324–36. https://doi.org/10.1007/978-981-19-7652-0_31.
 - [26] Galiński C. Preliminary Study of an Airplane for Electric Propulsion Testing at High Altitudes. *Journal of KONES* 2018;25:167–74. <https://doi.org/10.5604/01.3001.0012.4328>.
 - [27] Galiński C, Gronowska M, Stalewski W, Gumowski K. Flat-upper-surface wing for experimental high altitude unmanned aerial vehicle. *Proc Inst Mech Eng G J Aerosp Eng* 2021;235:81–94. <https://doi.org/10.1177/0954410020925642>.
 - [28] Bugala P, Sznajder J, Sieradzki A. Numerical Modelling of Static Aeroelastic Deformations of Slender Wing in Aerodynamic Design. *Transactions on Aerospace Research* 2023;2023:52–70. <https://doi.org/10.2478/tar-2023-0023>.
 - [29] Ritter M, Hilger J. Dynamic Aeroelastic Simulations of the Pazy Wing by UVLM with Nonlinear Viscous Corrections. AIAA SCITECH 2022 Forum, American Institute of Aeronautics and Astronautics; 2021. <https://doi.org/10.2514/6.2022-0177>.
 - [30] Li X, Wan Z, Wang X, Yang C. Aeroelastic Optimization Design of the Global Stiffness for a Joined Wing Aircraft. *Applied Sciences* 2021;11. <https://doi.org/10.3390/app112411800>.
 - [31] Banerjee JR. A FORTRAN routine for computation of coupled bending-torsional dynamic stiffness matrix of beam elements. *Advances in Engineering Software and Workstations* 1991;13:17–24. [https://doi.org/10.1016/0961-3552\(91\)90041-2](https://doi.org/10.1016/0961-3552(91)90041-2).
 - [32] Dillinger JKS, Abdalla MM, Meddaikar YM, Klimmek T. Static aeroelastic stiffness optimization of a forward swept composite wing with CFD-corrected aero loads. *CEAS Aeronaut J* 2019;10:1015–32. <https://doi.org/10.1007/s13272-019-00397-y>.
 - [33] Crovato A, Almeida HS, Vio G, Silva GH, Prado AP, Breviglieri C, et al. Effect of Levels of Fidelity on Steady Aerodynamic and Static Aeroelastic Computations. *Aerospace* 2020;7:42. <https://doi.org/10.3390/aerospace7040042>.
 - [34] Andersen L, Nielsen SRK. Elastic Beams in Three Dimensions – DCE Lecture Notes No. 23. vol. 1. Department of Civil Engineering, Aalborg University; 2008.
 - [35] Bauchau OA, Craig JJ. *Structural Analysis With Applications to Aerospace Structures*. vol. 163. New York: Springer; 2009.
 - [36] Megson THG. *Aircraft Structures for Engineering Students*. Elsevier; 2021. <https://doi.org/10.1016/B978-0-12-822868-5.09989-7>.
 - [37] Roark RJ, Young WC, Budynas RG, Sadegh AM. *Roark's formulas for stress and strain*. McGraw-Hill Education; 2012.
 - [38] FAI Sporting Code, Common Section 7-1 st FAI Sporting Code Section 7-Class O Common Hang Gliders and Paragliders Classes1 to 5 2018 Edition Effective 1st. 2018.

- [39] Findahl P. My F1A Developments, *Free Flight Quarterly*, pp. 27-31, January 2008. n.d.
- [40] Galiński C, Gronowska M, Stalewski W, Gumowski K. Flat-upper-surface wing for experimental high altitude unmanned aerial vehicle. *Proc Inst Mech Eng G J Aerosp Eng* 2021;235:81–94. <https://doi.org/10.1177/0954410020925642>.
- [41] Limpinsel M, Kuo D, Vijn A. SMARTS Modeling of Solar Spectra at Stratospheric Altitude and Influence on Performance of Selected III-V Solar Cells. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), IEEE; 2018, p. 3367–73. <https://doi.org/10.1109/PVSC.2018.8547665>.