Evaluation of the Applicability of the Vortex Lattice Method to the Analysis of Human Powered Aircraft

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Evaluation of the Applicability of the Vortex Lattice Method to the Analysis of Human Powered Aircraft

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The applicability of the vortex lattice method to the design of human powered aircraft is investigated. Aerodynamic data such as coefficients of lift, drag, and moment are calculated for the Gossamer Albatross using VLAERO+©, a vortex lattice method commercial computer program, and compared to flight test data . The differences are analyzed and explained. Although the computations display similar trends to the experimental data, there exist discrepancies that can be explained by the inherent limitations of the method, such as being linear and inviscid. However, the program allows for certain calibration, through additive and multiplication factors. The Gossamer model, once calibrated, can be used with confidence for the calculation of aerodynamic properties and stability analysis for the range of Mach numbers between 0.016 and 0.0248, and angles of attack between -2 to 10 degrees.

Nomenclature

α	=	angle of attack
c	=	chord
C_D	=	drag coefficient
C_L	=	lift coefficient
C_m	=	moment coefficient
M	=	Mach number
μ	=	dynamic viscosity
Re	=	Reynolds number
ρ	=	density
V	=	velocity

I. Introduction

I NTEREST for human powered aircraft (HPA) in universities and among aviation enthusiasts has grown in recent years. Since Dr. Paul MacCready won the first Kremer Prize in 1977 with the Gossamer Condor, new designs and technology improvements have resulted in better performance. The Royal Aeronautical Society continues to foster research and development in this area with new prizes, such as the Kremer International Marathon Competition, for an HPA that can fly the distance of a marathon (26 mi 385 yd) in a pre-determined circuit and specific meteorological conditions, within an hour, and the Kremer International Sporting Aircraft Competition, for the design of an aircraft suitable for athletic competitions. It would therefore be beneficial to count on aerodynamic design tools that are, at the same time, reliable, reasonably accurate and low cost, both in terms of computational time and detailed input data

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requirements. Thus, the vortex lattice method (VLM) appears as a good candidate for this task. The purpose of this study is to evaluate its accuracy, limitations and, therefore, its applicability for the preliminary design of HPA.

VLAERO+© is the VLM computer program selected for this work. Among some of its features, it can be listed that it allows half-models analyses, the generation of aerodynamic and stability derivative coefficients, total forces and bending moments and a fully automated calculation of trim conditions.

In the present study, the data generated with VLAERO+© is compared to published experimental values for the Gossamer Albatross [4] with the objective of determining the applicability and limitations of the VLM applied to HPA. The Albatross, an improved version of the Gossamer Condor, is the first HPA to cross the English Channel, giving MacCready and his team their second Kremer prize in 1980.

II. Methodology

A. VLM Analysis

The VLM was first introduced in the 1930's and it was also one of the first methods to be implemented on computers [3]. A detailed explanation of the VLM is beyond the scope of this report but the following will describe its basic properties and capabilities. An in depth analysis of the VLM can be found in [3]. The VLM represents the wing as a surface on which a grid of horseshoe vortices (from lifting-line theory) is superimposed. The velocities induced by each horseshoe vortex at a specified control point are calculated using the Biot-Savart law. A summation is performed for all control points on the wing to produce a set of linear algebraic equations for the horseshoe vortex strengths that satisfy the boundary condition of no flow through the wing. The vortex strengths are related to the wing circulation and the pressure differentials between the upper and lower wing surfaces. The pressure differentials are integrated to yield the total forces and moments [1]. This method ignores viscous effects as well as thickness and, thus, it cannot calculate parasite drag.

VLAERO+© allows three main calculations: total forces, stability derivatives and trim analysis, all for a given airspeed (Mach) and angle of attack.

B. The Gossamer Albatross

The evaluation of the VLM is performed by comparison to the published flight test data of the Gossamer Albatross [4]. The main characteristics are presented on Table 1. The Albatross design builds on the experience gained with the Gossamer Condor, the winner of the first Kremer Prize. However, in this case the objective was to opt for the second Kremer Prize in 1979, namely, to cross the English Channel solely using human power.

Table 1. Gossamer Albatross II parameters

Wing Span	96 ft
Wing Area	488 ft^2
Gross Weight	222 lb
Wing Loading	0.455 lb/ft^2
Aspect Ratio	18.89

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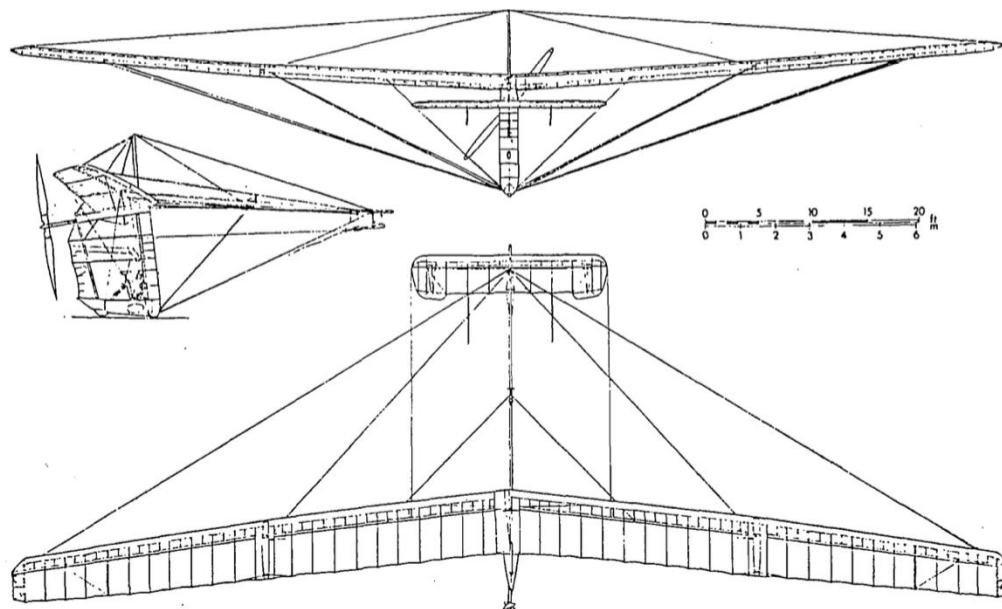American Institute of Aeronautics and   Astronautics

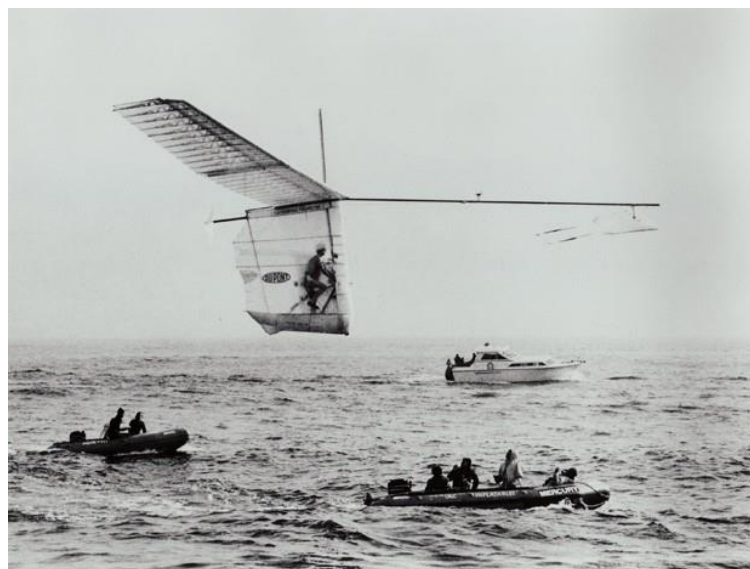*Figure 1. Gossamer Albatross 3-view [4]*

Figure 2. Gossamer Albatross crossing the English Channel
http://www.avinc.com/img/media_gallery/Gen_GossamerAlbatross_lg.jpg

The flight test campaign was carried out jointly by AeroVironment Inc.[2] , Systems Technology Inc. (in charge of most of the stability and control work), and NASA Dryden Flight Research Center [2]. The aircraft used in the flight test campaign was the Gossamer Albatross II, in all equal to the original Albatross with the exception of some minor modifications incorporated to facilitate the tests, such as the addition of an electric motor to drive the propeller and other equipment for data collection. Thus, for the purposes of this report, the Gossamer Albatross II, for which the flight test data was available, will be referred to as Gossamer Albatross or simply the Albatross.

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[2] Paul MacCready's company which developed and built the aircraft

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III.   Validation of VLAERO+©

Figure 3 shows the Albatross modeled in VLAERO+©. For this study only the total forces, and trim analysis jobs were considered. For the trim analysis the entire moveable canard was used as control surface.
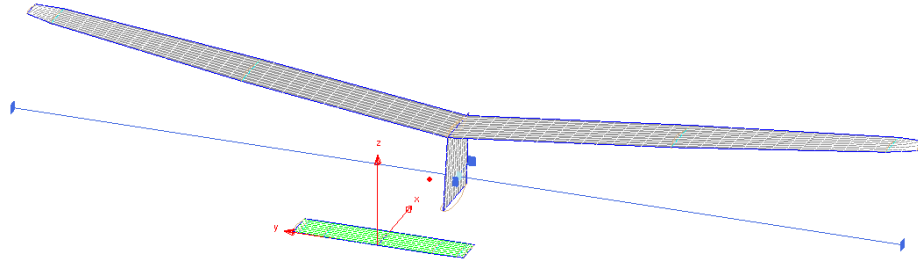

Figure 3. Gossamer Albatross model in VLAERO+©

The lift and drag coefficients for the four Mach numbers and angles of attack in the NASA flight test report of 1982 [4], shown on Table 2, were calculated in VLAERO+© for the trimmed condition and then compared to the flight test data.

Table 2. Flight test data from Reference [2] used in the VLAERO+© analysis

Mach	α (° Trimmed)	C_L (Trimmed)
0.0160	8.5	1.16
0.0177	5.3	0.96
0.0214	2.5	0.66
0.0248	0.9	0.48

Figures 4 to 7 present the VLAERO+© results together with the reference experimental data. It can be appreciated that, in all cases, both curves display the same general behavior but that the calculations do not match the flight test data: VLAERO+© consistently over-predicts the lift coefficients and the difference increases with the velocity. Contrarily, the canard C_L's are consistently under-predicted. These discrepancies are carried over to the total C_L curve (Fig. 6) and could be explained by the method limitations such as its neglect of airfoil thickness, viscosity and possible flow separation.
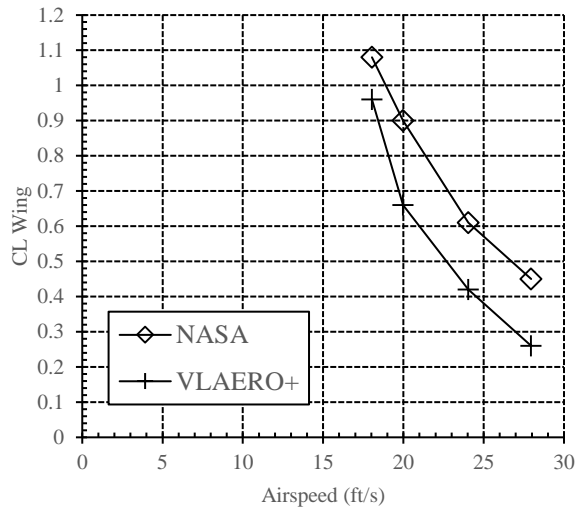
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Figure 4. C_L wing vs. airspeed for NASA and VLAERO+ values
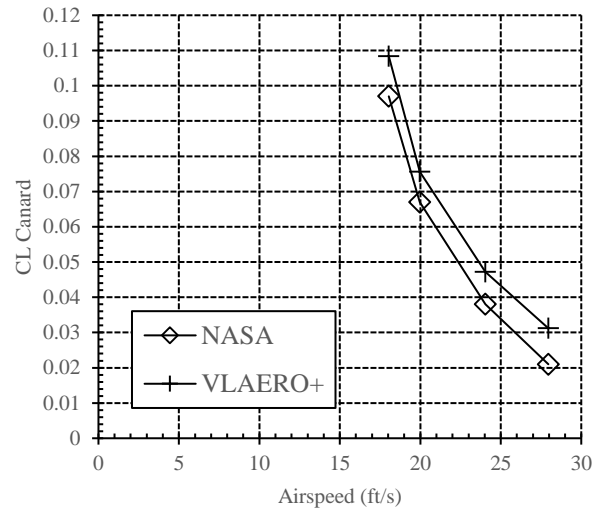

Figure 5. C_L canard vs. airspeed for NASA and VLAERO+ values
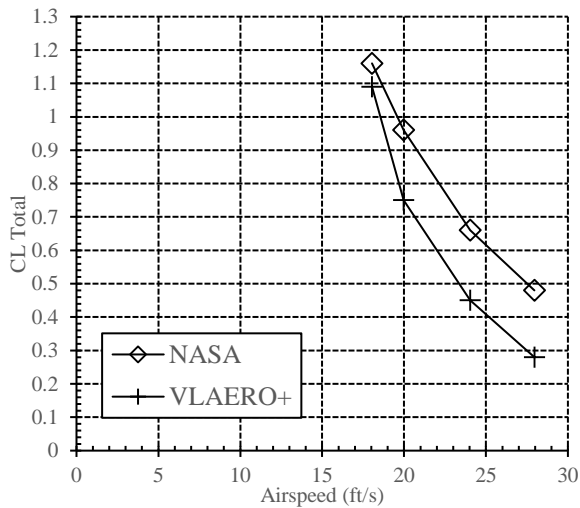

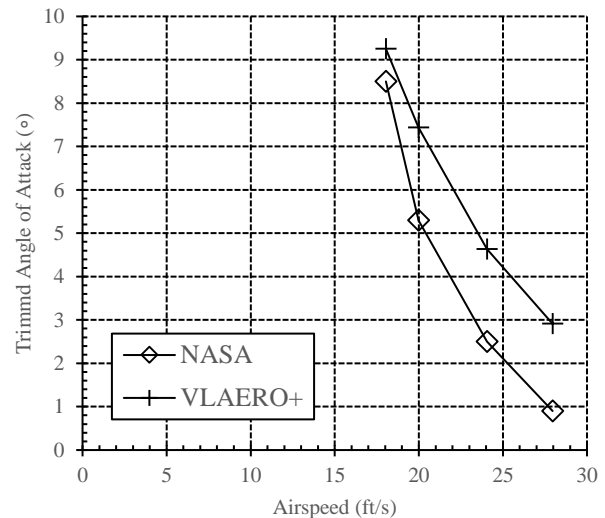*Figure 6. C_L total vs. airspeed for NASA and VLAERO+ values*

Figure 7. Trimmed angle of attack vs. airspeed for NASA and VLAERO+ values

VLAERO+© allows the user to apply calibration factors to a model. There are three types of calibration factors: circulation, incidence and camber. The circulation factor multiplies the perturbation solution redefining the lift curve slope. For example, a circulation factor of 0.95 will reduce the lift-curve slope by 5%. The incidence factor corrects solutions with no perturbation (relating to angle of attack), it is applied uniformly throughout all panels in the component, and has units of degrees. For example, an incidence calibration of 2 degrees would increase the lift at zero angle-of-attack by the equivalent of 2 degrees of angle-of-attack, while leaving the lift-curve-slope unchanged. Lastly, the camber factor multiplies the camber line contribution (airfoil and twist definitions) and redefines the mean camber while the lift curve slope is unchanged. For example, a camber factor of 0.90 will reduce the lift at zero angle of attack by the

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equivalent of a 10% reduction in mean camber without affecting the lift-curve slope. The calibration factor has a similar contribution to the incidence factor but performs the calibration based on reducing the mean camber in the airfoil rather than based on the angle of attack variation at zero lift [6].

The calibration parameters can be specified as a function of Mach number or as a single value. The user has also a choice of interpolation and extrapolation for calculations at Mach numbers not specified in the calibration table. Each table can be assigned to one or more aircraft components, convenient for calibrating a surface composed from multiple components. For example, a wing divided into several chord-wise components can be calibrated using a single calibration table. Determining the calibration factors can be done in several ways: using a 'guess and interpolate' iterative process or by inverting a sensitivity matrix [6].

In this study, the calibration was carried out in the following manner. First, incidence calibration factors were applied to the wing only in order to match the flight test data, which was conveniently provided in the NASA report for the entire aircraft and also for the isolated wing and the canard (Figs. 4, 5 and 6). Then the canard was calibrated using circulation factors. The circulation factor on the canard is important because by changing the lift-curve slope, the downwash affecting the wing was also taken into consideration. Table 3 shows the final incidence and circulation factors applied on the model. The calibrated model results are presented together with the flight test data in Figs. 8 to 11.

Table 3. Calibration factors applied to the VLAERO+© model of the Gossamer Albatross

Mach Number	Incidence Wing	Circulation Canard
0.0160	0.99	0.85
0.0177	2.26	0.80
0.0214	2.15	0.57
0.0248	2.05	0.002
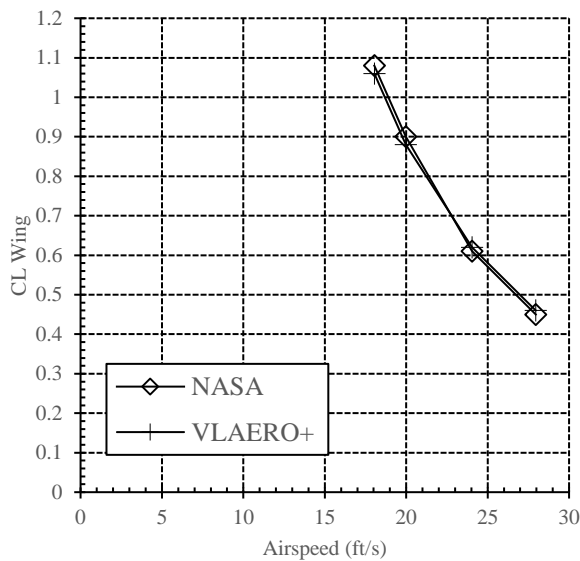
Figure 8. C_L wing vs. airspeed after calibration *Figure 9. C_L canard vs. airspeed after calibration*
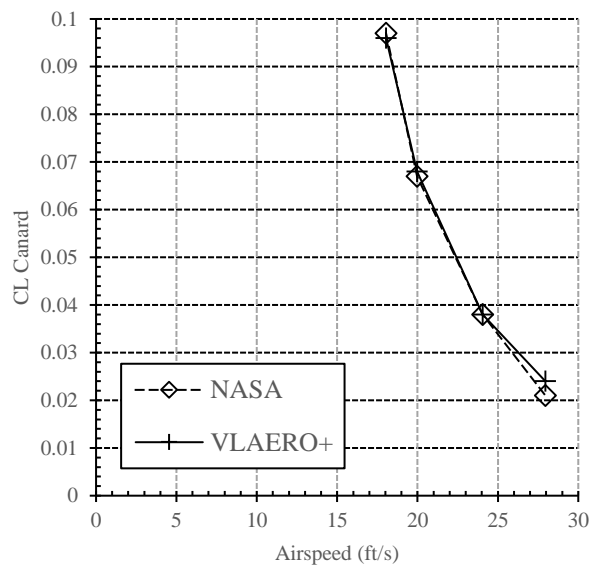
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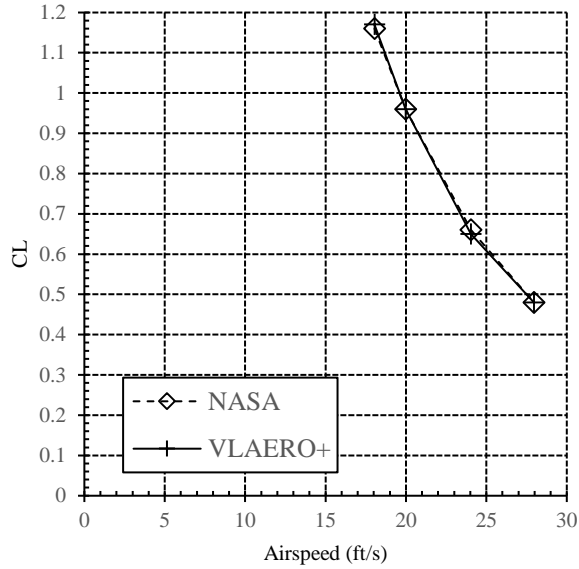
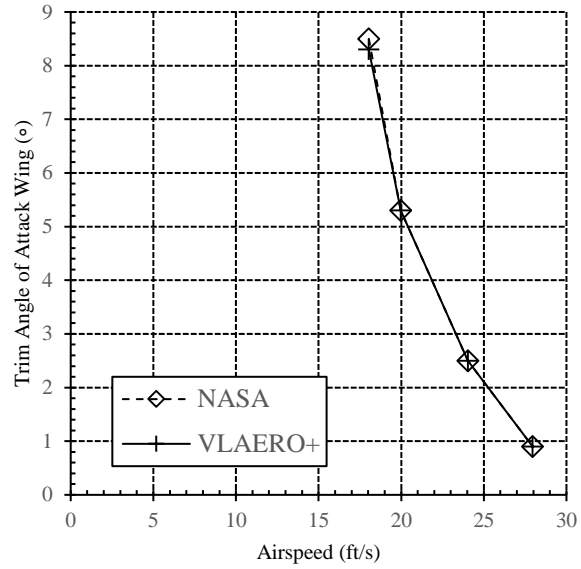*Figure 10. C_L total vs. airspeed after calibration*

Figure 11. Trim angle of attack vs. airspeed after calibration

Being an inviscid calculation, the VLM analysis can only calculate induced drag. Figure 12 presents the drag from VLAERO+© together with the total drag curve from flight test data. The difference between the two can be considered the parasite drag and has also been included on the graph.

With this information and the calibration factors, a complete aerodynamic model that faithfully represents the behavior of the Gossamer Condor is completed and it is presented in Figs. 13 to 15.
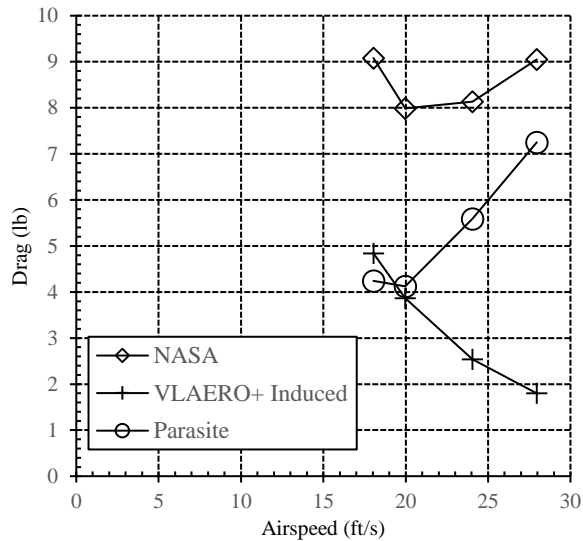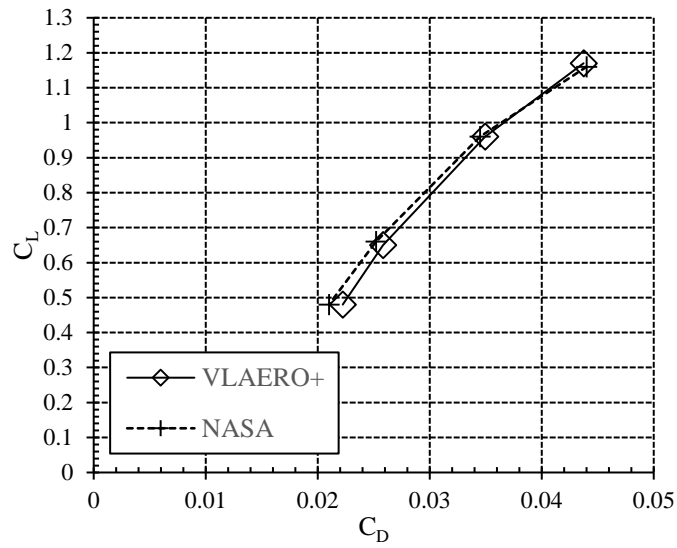

Figure 12. Drag vs. airspeed

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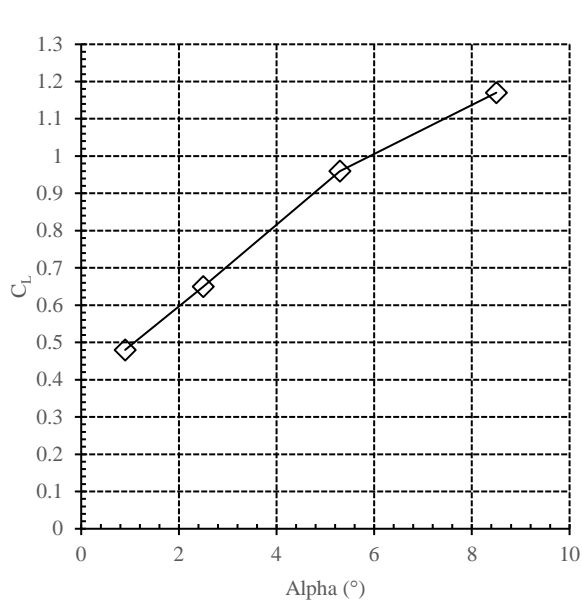American Institute of Aeronautics and   Astronautics

Figure 13. Drag polar

Figure 14. Lift coefficient vs. angle of attack from VLAERO+
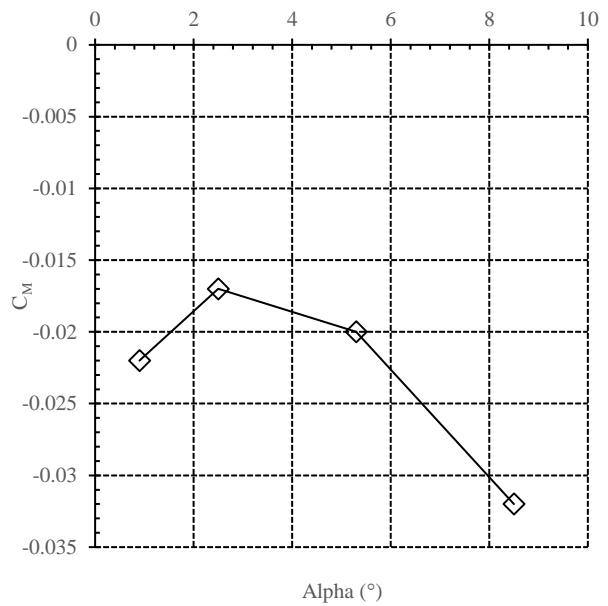
Figure 15. Moment coefficient vs. angle of attack from VLAERO+

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IV. Conclusion

A VLM of the Gossamer Albatross was created in VLAERO+© and the aerodynamic data such as lift, moment and drag coefficients for the trimmed condition were calculated and compared to flight test data. It was found that the program produces results that closely follow the trends of the experimental data but with certain offsets due to the inherent limitations of the method such as being linear, inviscid, incompressible and not considering airfoil thicknesses, for example. However, the program allows for the application of calibration factors that can result in a highly accurate model that, within the range of applicability, can be used with confidence to calculate lift and moment coefficients and, for example, to perform stability analyses. Since the parasite drag is close to being constant, that value can also be added to the drag obtained from VLAERO+©, which is the induced drag, and various drag polars can also be generated (for the range of Mach numbers and angles of attack for which the calibration is valid).

Thus, if experimental data for an aircraft is available, a VLAERO+© model for that aircraft or for one which is not significantly different, can be produced. Due to the calibration that model will be fairly accurate at very low cost. For an aircraft for which no other data exist or that is significantly different from the calibrated model, the calculations could be complemented with empirical formulations. However, results must be used with caution.

Therefore, it can be concluded that VLAERO+© can be a useful tool in the preliminary design of human powered aircraft and, at later stages of development, higher fidelity methods such as Navier Stokes computational fluid dynamics or wind tunnel measurements can be utilized.

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[3]DeYoung, J., "Historical Evolution of Vortex Lattice Methods," Vortex-Lattice Utilization., Rept. NASA-SP-405, Hampton, VA, May. 1976.

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[5]MacCready, P., "Flight on 0.33 Horsepower: The Gossamer Condor," AIAA 14th Annual Meeting and Technical Display, Washington, D.C., February, 1978.

[6]VLAERO+©, Vortex Lattice Method, Software Package, Ver. 2.2.5, Analytical Methods, Inc., Redmond, WA, 2007.

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