# Aerodynamic Analysis of Box Wing Configuration for Unmanned Aircraft System (UAS) – Student Design Project

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**Abstract** – As part of a summer research project, a second year undergraduate minority student designs a box wing model aircraft using Computer Aided Design (CAD). In addition to learning CAD, the student also learns the basic aerodynamic concepts. Computational Fluid Dynamic (CFD) analysis is performed on the CAD model. The box wing design has tremendous potential for improving aerodynamic characteristics of slow flying aircraft. The mission chosen for this project is to vary a few design parameters to improve the aerodynamic performance of a box wing aircraft as applied to Unmanned Aircraft Systems (UAS). Results obtained from the CFD analysis are presented and student learning within the span of two months as a result of this project is discussed.

*Keywords:* Minority Student, Summer Research, Computer Aided Design (CAD), Computational Fluid Dynamics (CFD), Unmanned Aircraft System (UAS)

## INTRODUCTION

In this paper a student summer design project is discussed. The project is designed for undergraduate minority students. A student is competitively selected based on their interest and PSLSAMP (Peach State Louis Stokes Alliance for Minority Participation) qualification criteria [1]. The student works for two months in the summer with a research advisor, gets credit for the research study and gets paid for the work. The research study for this project involves the CFD (Computational Fluid Dynamics) analysis for a box wing aircraft with specific application to UAS (Unmanned Aircraft Systems). Computer Aided Design (CAD) software, SolidWorks® is used in this project to create the model and perform the CFD analyses. A baseline fuselage is designed and used for a comparative study. The fuselage design and dimensions and other design parameters are not changed during the design process. Changes are only made to the aircraft wing parameters. These changes include wing aspect ratio, winglet to wing span ratio, taper ratio, and angle of incidence. Results obtained by the variations in the winglet height and taper ration are shown in this paper. The calculations are performed at various angles of attacks and free stream velocities. Lift and drag calculations are performed for different configurations at different flight conditions and compared to determine the optimal design. In this paper, in addition to the results of the analysis, the pedagogical aspects of the summer study, including its advantages and challenges are discussed.

Box wing aircraft conceptual design has been studied by Jemitola and Fielding [2]. They found that a box wing design, due to its superior aerodynamics characteristics compared to a conventional aircraft, can help reduce the operating cost of a medium range aircraft. Schiktanz and Scholz perform a systematic and general investigation about box wing aircraft including aerodynamic and performance characteristics. They discovered that because of its high span efficiency, the box wing aircraft has a glide ratio of 20:4. The downside of the box wing is that the wing is heavier compared to a conventional wing. Khan investigated the capability of a box-wing design to reduce induced

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drag [4]. Khan also discussed different potential advantages for the aviation industry and discussed if a box wing commercial aircraft should be made a reality. Various studies are being conducted to investigate the efficacy of box wing design for UAS.

In addition to the technical aspects of the project, the pedagogical dimension of this summer research is of paramount importance. The challenges associated with getting undergraduate students involved in research studies are similar to those of graduate level research. Often time's undergraduate students are less prepared for a research study. They are looking for an experience as a means to determine career path. This complexity is compounded by the fact that in summer, students are often interested in getting paid jobs and internships to augment of cost of attending college or to gain industry experience. The support mechanisms, evaluation structure, and reward systems for undergraduate students are not well established or well defined and are still being developed in many institutions and disciplines. In addition, funding mechanisms have not truly figured out how to properly evaluate and fund undergraduate research students. Given those challenges, it is still important to get them motivated and interested in research in the discipline of their choice. Students who get involved in research at the undergraduate level are more likely to pursue graduate studies [5].

Undergraduate Peach State LSAMP (Louis Stokes Alliance for Minority Participation) student participated in this summer research project. This program is designed for underrepresented minority students. It is a collaborative effort sustained by several higher education institutions in the state of Georgia [1]. At SPSU, it provides scholars supplemental instruction and an opportunity for academic enrichment. It promotes learning communities among fresh engineering students. It also provides opportunities for tutoring, financial support, peer and faculty mentoring, STEM conferences, research opportunities, summer bridge program, leadership development, outreach initiatives and internships [1]. The project also exposes students to topics not covered elsewhere in the curriculum. For this particular project, the selected student is introduced to the basics of aircraft design and aerodynamics. The student learns to use commercial design software and performs preliminary analyses.

## BOX-WING DESIGN

For the purpose of this research study, the student designs a Computer Aided Design (CAD) model of a multi-planar wing aircraft, also known as the box-wing design. The box wing design increases the aspect ratio of a conventional aircraft as shown in Figures 1 and 2 [2].

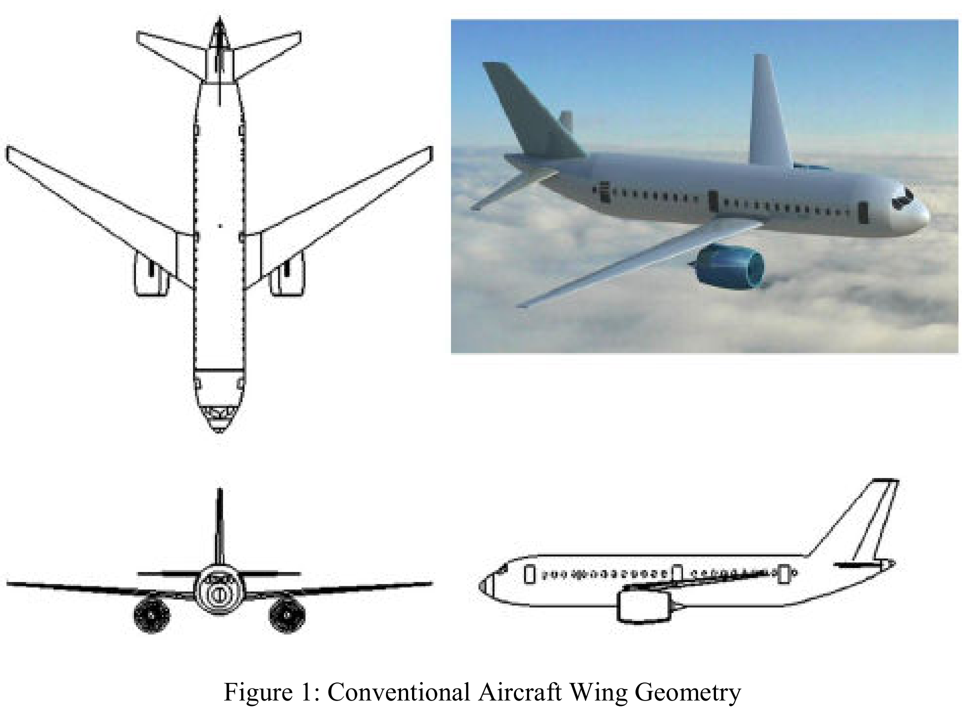

Figure 1: Conventional Aircraft Wing Geometry

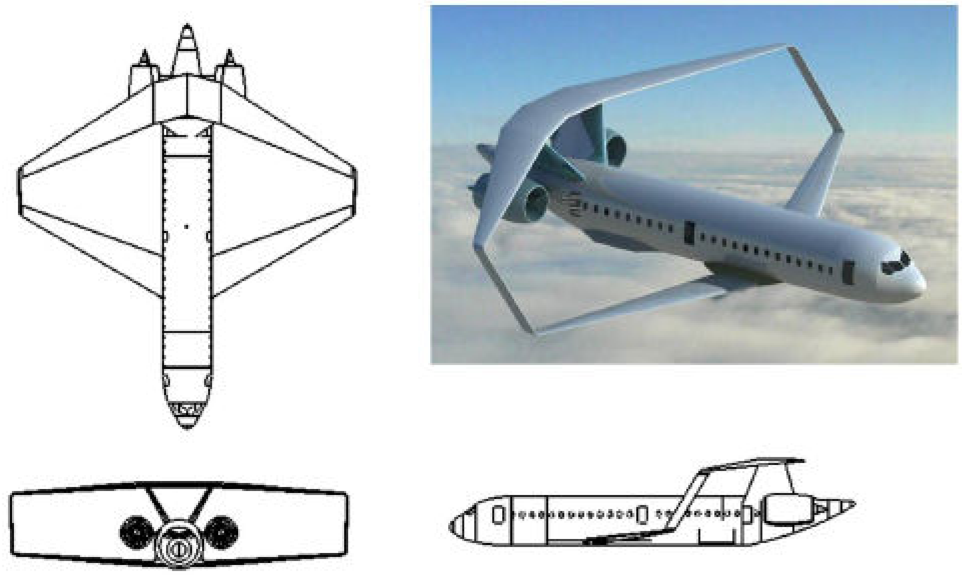

Figure 2: Box-Wing design Wing Configuration

The Computational Fluid Dynamics (CFD) analysis is performed using the SolidWorks® software. A virtual wind tunnel is created for the scaled model. This analysis is performed for comparative purposes. The results presented in this paper do not represent absolute values. For consistency, comparative simulations are performed by varying the free stream velocity and angle of attack. The baseline aircraft design variables are listed in Table 1.

Table 1: Baseline aircraft design variables

| **Design Variable** | **Value** |
|---|---|
| Wingspan | 1.7m |
| Taper Ratio | 1:1 |
| Winglet / Wingspan ratio | 0.1:1 |
| Root chord length | 0.2m |
| Angle of incidence | $0^o$ |

The baseline design parameters listed in table 1 are kept constant for this study. Variations in the lift and drag are calculated as a function of the angle of attack at $0^o$ and $5^o$ by varying the free stream velocity. Lift and drag are also calculated as a function of winglet height to wingspan ratio. Similar calculations are performed for variations in taper ratio. Lift and drag are also calculated by increasing the angle of attack and keeping the taper ratio and winglet height parameter at baseline values. These calculations help determine the direction of improvement in lift and drag as a function of the design parameter values. The design begins with conceptual sketches of the model as shown in Figure 3. After a few iterations, several design parameters are fixed and a CAD model is developed. The baseline CAD model designed for this project is shown in figure 4.

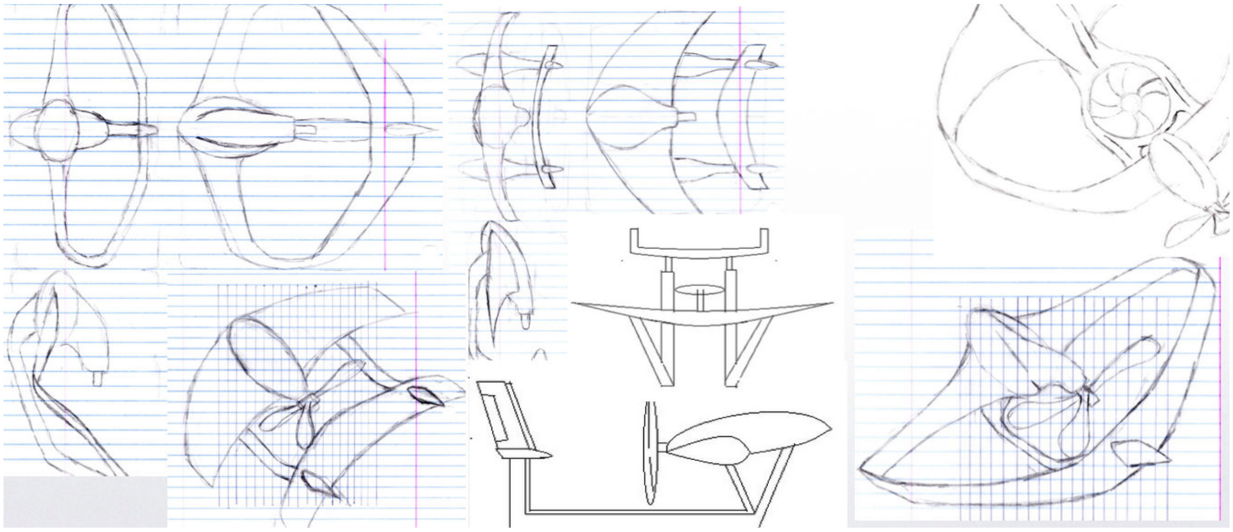

Figure 3: Conceptual design of box-wing aircraft

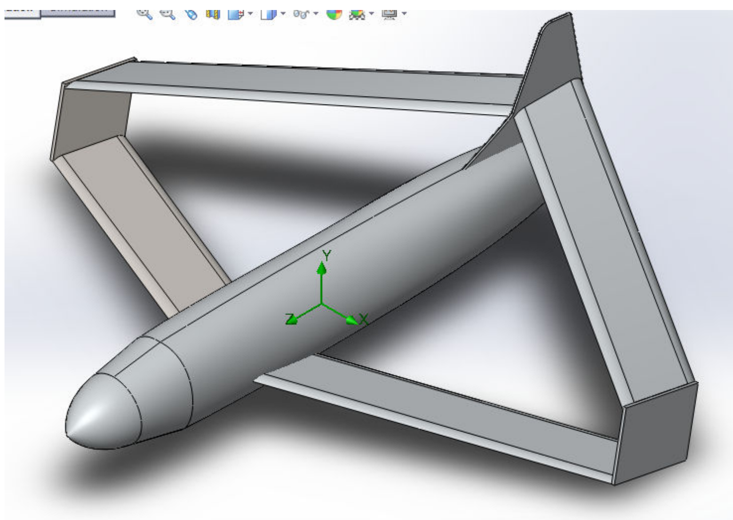

Figure 4: Baseline CAD Model

## RESULTS AND DISCUSSIONS

CFD analysis is performed by changing one variable at a time. Streamlines depicting changes in pressure are shown in figure 5. High pressure regions are observed near the nose and vertical tail sections. Low pressure regions are observed near the top of the wing indicating drop in relative pressure and increase in lift. For the student, the visual depiction of the pressure profile and the streamlines help understand the variations in lift and drag as a function of various design variables. The CAD model is parametrically designed. Changes in the model are made varying the design variable settings for each successive CFD analysis. It is important to note that the results obtained as part of this study are for comparative purposes. A thorough validation study needs to be performed to understand the true lift and drag values. This study provides sufficient detail to demonstrate the undergraduate student a basic understanding of the aircraft aerodynamic design process, CAD and CFD analyses.

The free stream velocity is increased from 50km/hr to 200 km/hr and the corresponding lift and drag values are calculated and plotted. It is observed that the relative drag and lift coefficients increase with the increasing free stream velocity. Both lift and drag curves, as shown in Figure 7 follow a quadratic increase as a function of velocity. Theoretical lift and drag relationships are shown in equations 1-4. As part of this project, in addition to learning these aerodynamic relations, the student also visualizes them and verifies the theory by virtual experimental results.

$$L = \frac{1}{2}\rho V^2 C_L S \qquad (1)$$

$$L \propto V^2 \qquad (2)$$

$$D = \frac{1}{2}\rho V^2 C_D S \qquad (3)$$

$$D \propto V^2 \qquad (4)$$

The winglets help reduce the wing tip vortices – thereby reducing the drag. The winglet height to wingspan ratio parameter is varied from 5% of the wingspan to 25% of the wingspan. Changes in the pressure profile are depicted in figure 6. Corresponding lift and drag graphs are shown in figure 8.

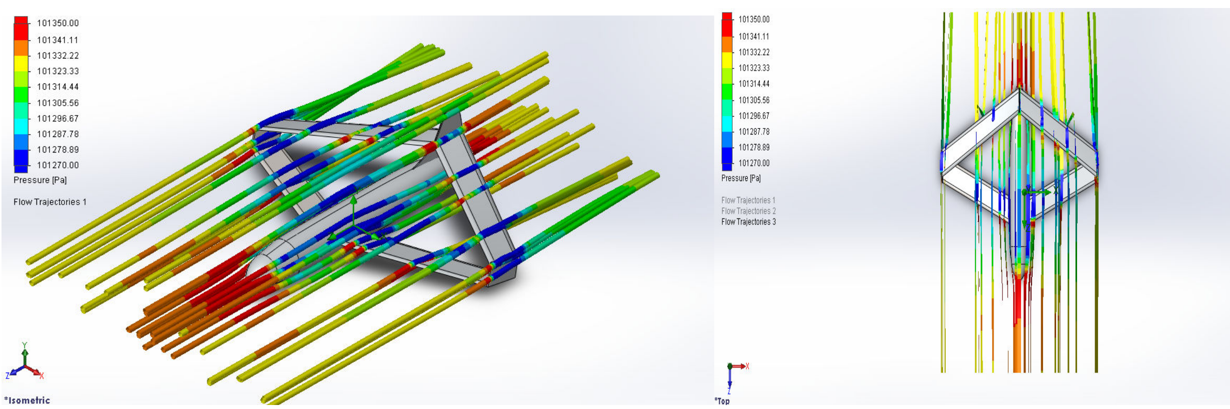


Figure 5: Streamlines on the baseline box-wing aircraft from CFD analysis

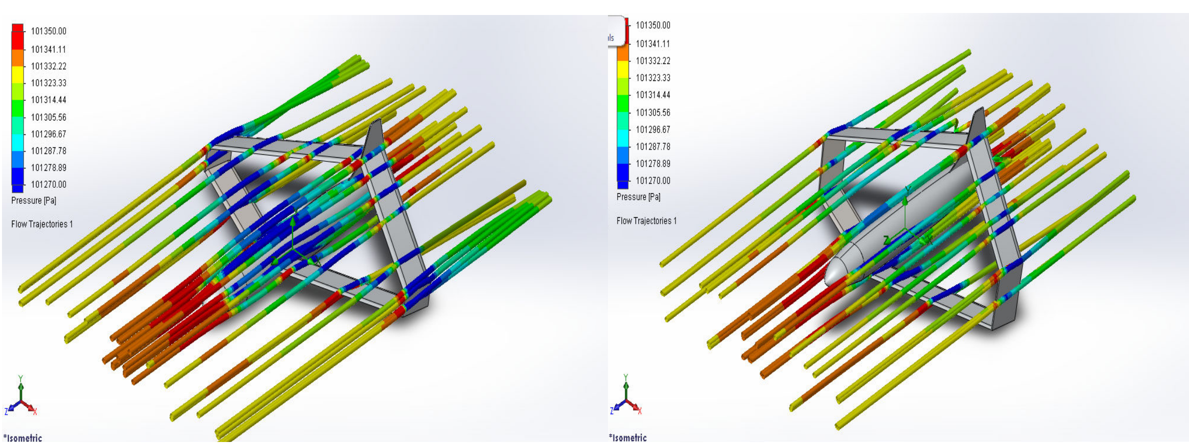


Figure 6: Variations in the winglet height parameter

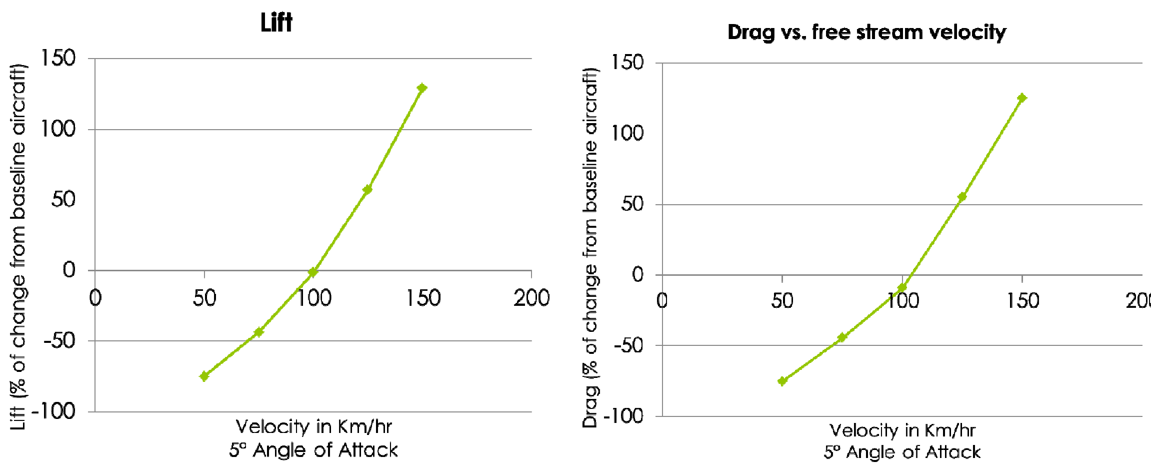


Figure 7: Lift and Drag variation as a function of free stream velocity at baseline configuration and 5$^{o}$ angle of attack

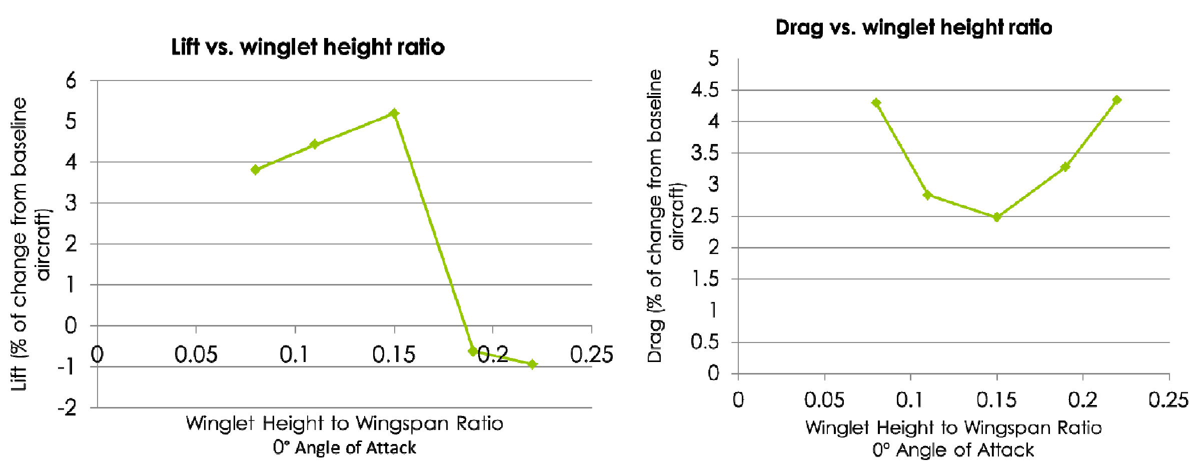


Figure 8: Lift and drag variation as a function of winglet height to wingspan ratio at 0$^{o}$ angle of attack

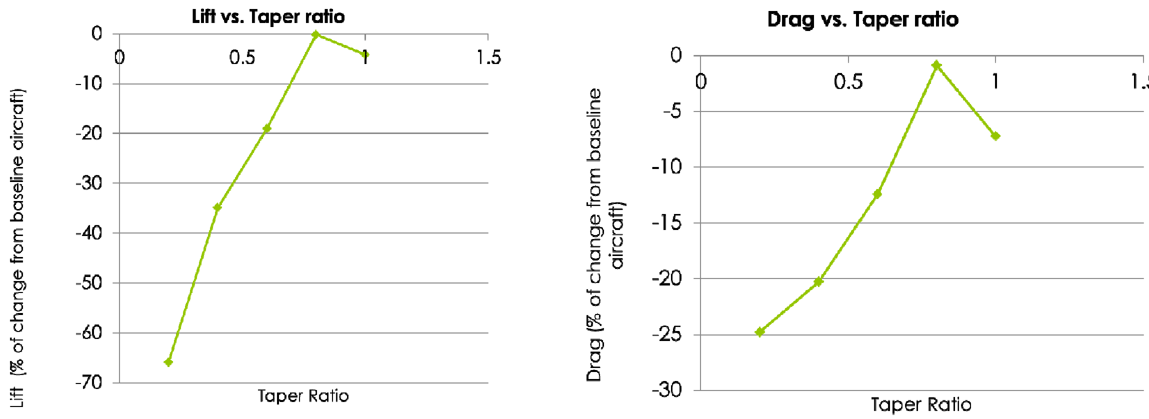


Figure 9: Lift and drag variations as a function of taper ratio

As shown in Figure 7, it is observed that the increase in the winglet height initially increases lift and decreases drag. This occurs up to the winglet height to wingspan ratio of 0.15. Beyond the ratio of 0.15, the lift starts to decrease and the drag begins to increase. This phenomenon shows that the advantage gained by the introduction of winglets in the box wing design, in terms of reducing the wing tip vortices, is only effective up to the winglet height of 15% relative to the wingspan. At 15%, the highest lift to drag ratio is obtained. The optimal winglet height for the baseline model aircraft is determined as a result of this analysis.

Similarly, as the wing root to tip taper ratio is increased, an increase in lift and an increase in drag is observed. The relative lift at a low taper is much higher than the relative drag compared to the baseline model. There is a lift advantage observed for increasing the taper ratio but a drag penalty is observed. A high taper ratio wing results is the decrease of the chord length of the wing tip and therefore a decrease in the chord length of the winglet. A relatively small chord length of the winglet causes the drag to increase, therefore reducing the tip vortex reduction advantage obtained from the winglets. The variations of the lift and drag as function of taper ratio are shown in Figure 9. The results indicate that a taper ratio of approximately 0.8 generates the highest lift. Un-tapered wing generates the least amount of drag. The lift to drag ratio is therefore highest at the taper ratio of 0.4. This taper ratio is applicable for both upper and lower wings of the box-wing aircraft.

## Conclusions

A box wing aircraft is studied in this research as part of a minority undergraduate summer research program. For the purpose of this study, the two variables optimized are the winglet height and taper ratio. A baseline model aircraft is designed. All the other variables are fixed at the baseline and only one variable is changed at a time. It is observed that the winglet height to wingspan ratio of 15% provides the highest increase in the lift to drag ratio. Similarly the wing root to tip taper ratio of 0.4 provides the highest lift to drag ratio for the given baseline aircraft. These results are only applicable to the model aircraft designed in this project. For a complete study, a more robust analysis needs to be performed and validated. The goal of this study is to get the selected LSAMP undergraduate student exposed to the concepts of aerodynamics and aircraft design, give them an opportunity to learn Computer Aided Design (CAD) before their counterparts and introduce them to more advanced concepts like Computational Fluid Dynamics (CFD) and its applications. This program provides students an opportunity to pursue research during the summer months. It is the hope of the author that the students who go through these summer research programs will get excited about engineering and continue the path of lifelong learning.

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**Brian Golson**

At the time of this writing, Brian Golson is pursuing a mechanical engineering degree at Southern Polytechnic State University and is in the third year of his education. Upon completion of his degree, he wants to work in an aerospace industry.