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Topology Optimization of an Aircraft Wing

David Walker[1] David Liu[2] and Alan Jennings[3]
Air Force Institute of Technology, Wright-Patterson AFB, OH, 45433

Topology optimization was conducted on a three-dimensional wing body in order to enhance structural performance and reduce overall weight of the wing. The optimization was conducted using commercial software on an aircraft wing with readily available schematics, allowing a stress and displacement analysis. Optimizations were accomplished with an objective of minimizing overall compliance while maintaining an overall design-space volume fraction of less than 30 percent. A complete wing segment was post processed and 3D printed. Future analysis involves the optimization of a complete wing body with comparison to the baseline structure. The resulting designs will be 3D printed and wind-tunnel tested for process verification. A design will also be manufactured using metallic additive manufacturing techniques as a proof of concept for future aircraft design. The final optimized solution is expected to provide a weight savings between 15 and 25 percent.

Nomenclature

C_p	Pressure Coefficient
ft	Feet
in	Inches
p	Pressure, Pa
p_∞	Atmospheric pressure, Pa
v	Velocity, m/s
α	Angle of attack, deg
ρ	Density, kg/m^3

I. Introduction

Current aircraft wing design, which relies on internal struts and spars for aerodynamic load bearing, is limited primarily by traditional manufacturing techniques. If manufacturing constraints are removed, the design focus shifts towards providing an improved distribution of loads throughout the structure, subsequently eliminating unnecessary material. To design an optimized component, an increasingly more common method in structural design is the implementation of Topology Optimization (TO). TO is considered a mathematical approach to finding an optimized material distribution over a given design space. In other words, only material vital to the support structure is used. The process entails iteratively determining the load bearing components from individual elements within the structure. The TO is limited by set design constraints and is driven by a series of objective functions. This process was not feasible in the past since there was not a practical means to fabricate the TO design.[1] However, advances in Additive Manufacturing (AM) have made this concept a seemingly more viable approach to aircraft design. An optimized design produced through AM techniques is not limited in shape by traditional manufacturing constraints, allowing for a design which truly enhances the performance of the component. Furthermore, AM has the potential for weight savings which can significantly reduce the number of connectors traditionally used to hold components together.[2]

An additional benefit of AM is its logistical advantage, notably for the Department of Defense as applied by this research. AM of aircraft components can potentially create the capability to produce structures without the infrastructure required in order to ship and store a multitude of parts. Rather, a single machine, along with the stock

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[1] Graduate Student, Department of Aeronautical and Astronautical Engineering, Student Member AIAA.
[2] Assistant Professor, Department of Aeronautical and Astronautical Engineering, Senior Member AIAA.
[3] Assistant Professor, Department of Aeronautical and Astronautical Engineering, Member AIAA.

material, can produce whichever component is needed in a relatively short period of time. In this scenario, Computer Aided Design (CAD) files are then modified and transmitted anywhere in the world in order to produce the most up to date part available. Doing so has the potential to significantly streamline the process of aircraft maintenance. As AM technology grows, the ability to manufacture these parts has the potential to impact the manufacturing process as well.[2]

II. Methodology

Initially, this research was intended for use on Unmanned Aerial Vehicles (UAVs) due to the relaxed air-worthiness requirements when compared to traditional manned-aircraft. Applying the optimized wing on a operational aircraft would therefore require less intricate consdierations when trying to employ on a UAV. In addition, UAVs are generally much smaller than a traditional aircraft. This would allow for ease of manufacturing when considering AM techniques. However, due to the difficulty in obtaining detailed plans for a baseline analysis of a modern UAV, a Van's RV experimental aircraft wing was examined. Most Van's aircraft are also relatively high performing, requiring a wing structure capable of supporting acrobatic loading. Since all RV aircraft are homebuilt; detailed plans are readily available from the manufacturer. Specifically, the RV-4 was selected due to the aircraft being constructed virtually in its entirety by the customer, resulting in more detailed schematics being available. The final objective of this research is to focus entirely on the main wing body structure, disregarding the control surfaces and wingtip flange. However, current results take into consideration a complete airfoil. Internal components such as fuel tank, electronics, and cables were disregarded. Thus all analysis was conducted considering only the structural support provided by spars, ribs, and skin of the wing.

The RV-4 wing is a modified NACA 23015.5 airfoil with a 7.01 m (23 ft) overall wingspan. Each wing is 2.82 m (9.25 ft) from root to tip, not considering the wingtip flange. Each stock main wing structure contains 2 spars and 14 ribs (disregarding the in-wing fuel tank). The ribs are either 20 (.032 in thickness) or 22 (.025 in thickness) gauge 2024-T3 aluminum alloy. The spars are 18 gauge (.040 in thickness) 2024-T3 aluminum and used to mount the wing to the fuselage. A 20 gauge skin thickness was used for all baseline calculations; actual RV-4 aircraft skin thickness ranges for 20-22 gauge depending on the spanwise location. The wing does not have a taper or sweep, but it does have a small dihedral which was disregarded for this study. Figure 1 is an engineering drawing of the Van's RV-4 Aircraft.[3]

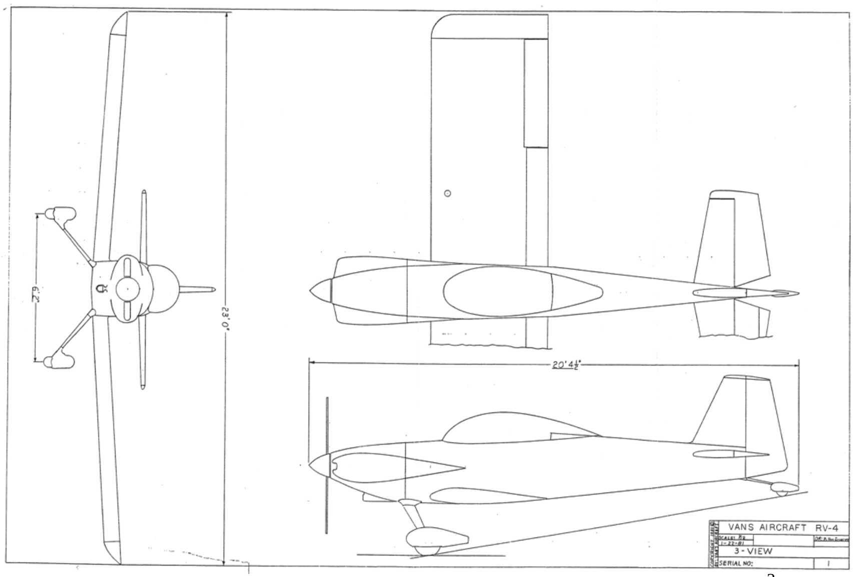

Figure 1. Van's RV-4 Experimental Aircraft 3-view drawing.[3]

All wing designs were constructed as 2D or 3D CAD models and imported into Altair Hypermesh software package and analyzed using the Optistruct toolkit. Optistruct utilizes finite-element analysis and optimization algorithms in order to develop topology optimized designs. Similar studies have been conducted by Airbus Aeronautical Company in recent years applying both Altair and in-house developed software. Airbus optimized the design of individual spars and wing-box structures for large commercial aircraft. They considered a hybrid global/local approach in a semi two-dimensional manner to modify the existing spar and ribs. A considerable material savings was noticed in their updated designs. However, fatigue testing and machine trials are ongoing[4].

Differentiating from the Airbus report, this research involves the optimization of the entire global wing body, rather than a localized component of the wing. A baseline wing body was adopted from the existing RV-4 platform and acted as the design space in order to maintain a desired aerodynamic shape. The wing was structurally constrained at the wing root and aerodynamic forces for the specified conditions were applied. The “design space” is considered the volume in which Optistruct can manipulate to provide the best load support. Load paths are analyzed and material is iteratively removed until the TO objective function is met while maintaining the optimization constraints. For all optimizations in this case, the objective function was to minimize compliance, or maximize stiffness, of the overall structure. The optimization constraint was to maintain a volume fraction of the overall design space of less than 30 percent. All models currently completed in this study used two small structural constraints near the center of the design space to simulate wing-box attachment. Figure 2 is an illustration of the initial design space for the TO. The blue indicates the design space which is manipulated during the optimization. Both the red skin and pink supports are considered non-design space; volumes which are not considered for TO. The skin was considered a non-design space so the aerodynamic shape of the wing was maintained. Structural constraints for the 3D model were applied on the wing supports only at the root of the wing.

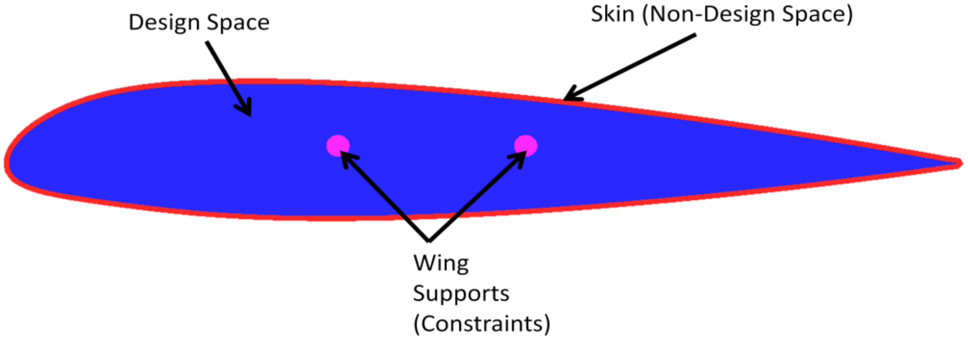

Figure 2. Initial design space example for wing topology optimization.

For this research effort, low-speed aerodynamic loading was applied to the wing. The preliminary investigation discussed in this research focused on a flight profile of maximum cruise speed at a zero angle of attack (α). Depending on the gross weight of the aircraft, a zero α is not necessarily steady level flight, but is relatively close. In a study conducted by Luo, Yang, and Chen, a missile body was topology optimized in a similar manner. The authors examined the loading on the missile resulting from the most extreme flight characteristic. This was to ensure compliance during all phases of flight[6]. Future analysis for the wing structure will consider a broader spectrum of flight conditions which result in increased wing loading.

Wing loading was determined using the MIT (Massachusetts Institute of Technology) developed X-Foil airfoil analysis program [5]. X-foil outputs pressure coefficient (C_p) values for small iterations along the airfoil surface for a given angle of attack. The C_p values were then converted to actual pressure values using the specified conditions. In this case, the RV-4 gross weight top speed of 212 mph (94.8 m/s) and a cruise altitude of 10,000 ft (ρ=0.958 kg/m^3) were used for analysis[8]. The differential from atmopshereic pressure (p-p_∞) was calculated in order to determine the actual loading on the wing surface. The pressure conversion equation is shown in Eq. (1) as a function of density (ρ) and velocity (v).

$$p - p_\infty = C_p\left(\frac{1}{2}\rho v^2\right) \tag{1}$$

A significant consideration in topology optimization is variable density material. Since an optimization process can consider variable density, a density fraction must be selected as a point to have material versus a void. Generally this determination is left to engineering judgment and a detailed analysis of the optimization results. In most cases for this research, a density fraction of 50 percent was selected as the point in which material will be shown. In other words, any volume in which density is greater or equal to 50 percent is considered as solid material whereas anything less is considered a void. The process of penalizing a density fraction towards material or void is discussed in detail by Bendsoe and Sigmund[7]. The process is also discussed by Krog, Tucker, and Rollema in regard to designing optimized wingbox ribs for commercial aircraft[4]. The resulting TO should also be interpreted towards a final realistic design and not taken literally as a stand-alone result. In the case of the Airbus wingbox optimization, the TO was used to determine where the voids should be for a tranditionals manufactured rib, rather than creating a complete truss-structure[4]. Optistruct has the added capability to post-process results using an "OSSmooth" option which generates solid material based on an input density fraction and joins any unconnected branches from the resulting optimization. However, the results are not necessarily perfect and must be analyzed for practicability.

III. Results

For process verification purposes, a 2D test case was conducted and compared to results from the publically available 99 line topology optimization MatLab code written by Ole Sigmund. Sigmund's code generates TO in a similar manner to Optistruct; load paths are examined and material is iteratively removed until an objective is met[9]. The desired volume fraction (optimization constraint) is input while the objective function is to minimize compliance. The test case was completed for a simply supported beam with a single load force. The x and y pixel count for both runs is 60 and 20, respectively. Similar to an example completed by Sigmund, a half-beam was analyzed using structural constraints along the center of the structure[9]. Figure 3 shows the loading conditions of the analysis. The red area is the design space with constraints located along the left wall and at the lower right corner. A single vertical force, F, is applied on the uppermost left point of the design space. Both optimizations were accomplished with a desired volume fraction of 30 percent. Figure 4.a. is the "99 Lines" result and Figure 4.b. is the Optistruct result. As seen in Figure 4, both optimization processes output have very similar results. Even though "99 Lines" does not work for 3-dimensional optimizations, the 2D analysis delivers confidence in the TO process with Optistruct.

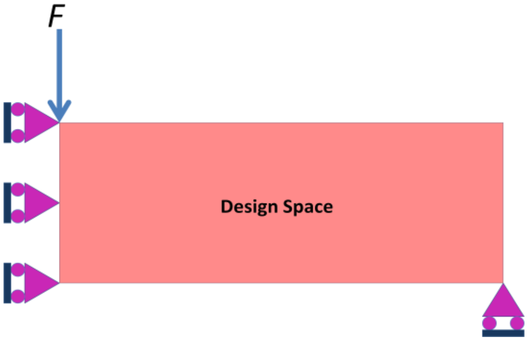

Figure 3. Schematic for test case topology optimization for "99 Lines" and Optistruct comparison.

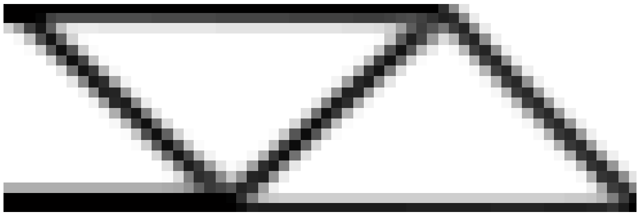

Figure 4.a. 99 lines topology optimization result for simple bending beam.[6]

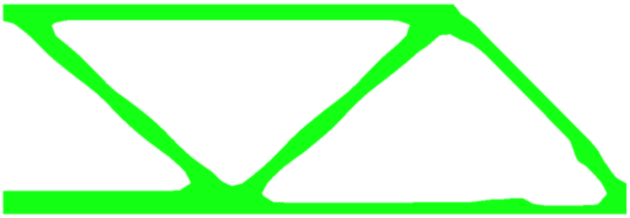

Figure 4.b. Altair Optistruct optimization result for simple bending beam.

A 2D NACA 23015 airfoil was optimized in a similar fashion to the simple bending beam. For simplicity, forces were applied to nodes solely in the horizontal and vertical directions. In addition, a loose estimation of forces was applied for the preliminary investigation. In general, a negative vertical force was applied to the top and bottom of the wing with a positive horizontal force along the nose. A thin "skin" was employed in order to maintain the aerodynamic shape of the airfoil and to have only the internal design space considered. The design space is in blue with two green supports where the airfoil was constrained. The optimization was conducted with an objective to minimum compliance and an optimization constraint limiting the volume fraction to less than 30%. Figure 5.a is the optimization design space followed by the resulting TO in figure 5.b. As shown, the optimization resulted in a general "truss-like" structure supporting the top and bottom of the airfoil. A density fraction of 50 percent is shown. This results in the discontinuity of some of the struts near the rear of the airfoil. Once again, the determination of what density fraction should be used is left to engineering judgment. Application of OSSmooth would connect these points for a better output.

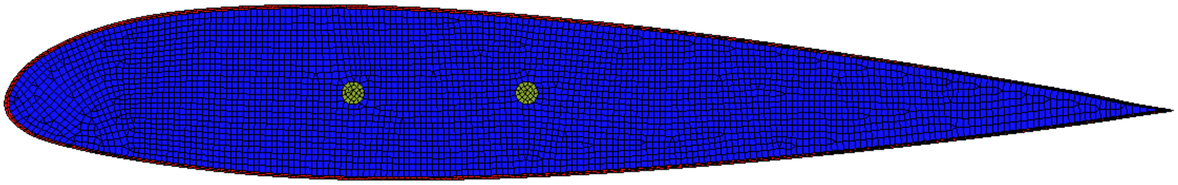

Figure 5.a. Topology optimization design space for 2D airfoil test case.

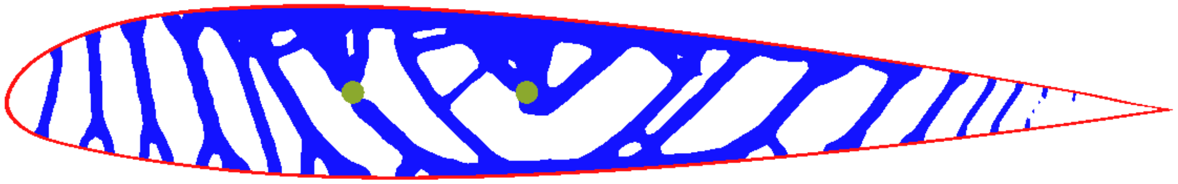

Figure 5.b Topology optimization results for simple 2D airfoil test case.

An analysis on a 3D wing segment was conducted with the appropriately applied pressures for a 212 mph steady level cruise at 10,000 ft density altitude based on realistic flying conditions of the RV-4 aircraft. Once again, the optimization was conducted with an objective of minimizing compliance with a volume fraction of less than 30%. Material properties for standard 2024 aluminum alloy were applied. Figure 6 is the output for the topology optimization. Figure 6.a is the initial design space for the problem. Only the blue design space was considered for optimization whereas the red skin and pink supports are non-design components. Pressures were applied normal to all nodes on the surface of the skin. Constraints were applied along the face of the pink support structures only on the left hand side of the wing segment. Figure 6.b is the Optistruct output set at a 38 percent density fraction. In this case, the lower density fraction was selected to reduce the disconnect between trusses at various locations in the output. This determination was made after examination of the resulting TO. The color-coding in the figure is for various density fractions, from 0 to 1. Finally, figure 6.c is the final product post-processed using the OSSmooth option.

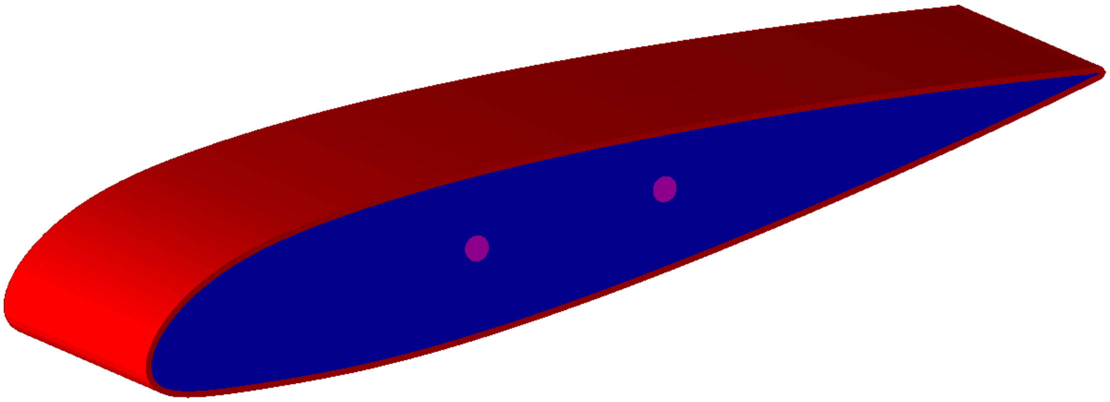

Figure 6.a. Initial design space for topology optimization problem of Van's RV-4 wing segment. *Red and pink volumes are considered non design space. The blue volume is the design space for the topology optimization*

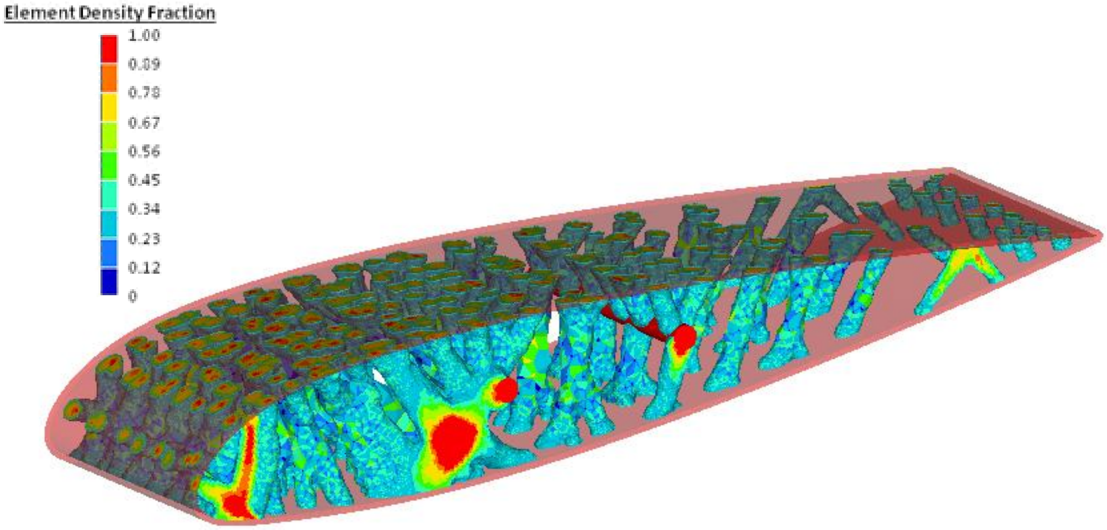

Figure 6.b. Topology optimized RV-4 wing segment with density fraction set to 38 percent.

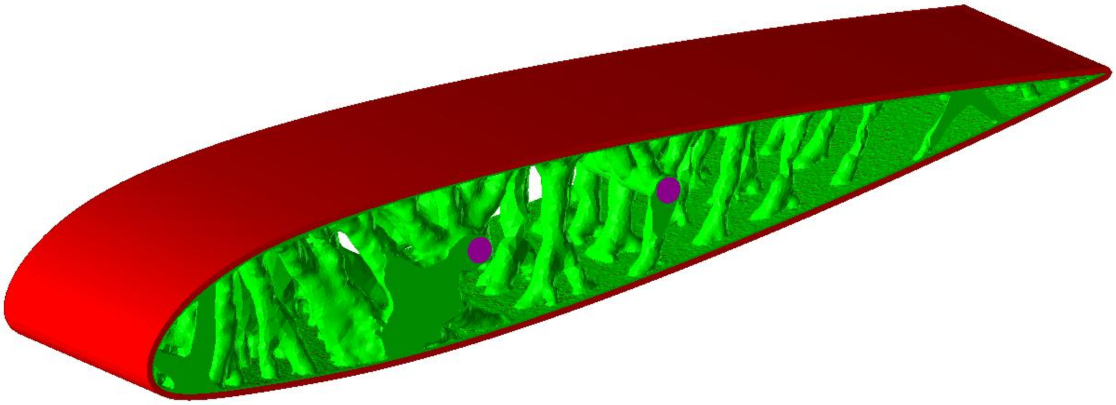

Figure 6.c. Post-process topology optimized RV-4 wing segment with density fraction set to 38 percent.

Once the resulting optimization shown in Figure 6.c was complete, the design was 3D printed on an Objet Eden500V printer at Air Force Institute of Technology (AFIT). Figure 7 is a photograph of the printed wing section. The chord of the wing section is 0.21 m (8.27 in) with a width of .062 m (2.44 in), demonstrating the entire design to build process.

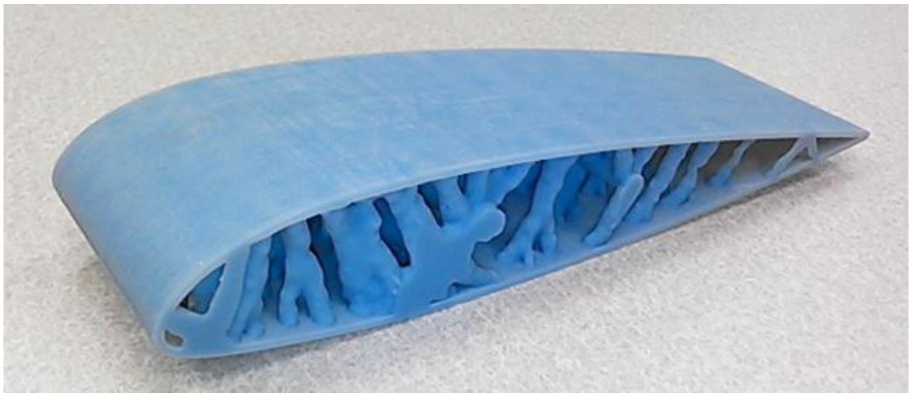

Figure 7. 3D printed wing section for a NACA 23015 airfoil.

IV. Future Analysis

A baseline analysis was conducted on the standard RV-4 wing structure at the specified loading conditions for comparative purposes of the finalized topology optimized design. Current baseline Finite Element Analysis (FEA) estimations show an empty wing body (ribs, spars, and skin) weigh approximately 18 lbs per wing with a wingtip deflection of approximately 0.020 m (0.79 in). Once a complete optimization is conducted on the entirety of the wing, the results will be compared. Optimizations will also be conducted with an objective to minimize volume while constraining to the maximum material stress found in the baseline analysis. This will be done for a multitude of flight profiles to ensure the design is compatible for all stages of flight. In addition, a complete stress and buckling study will also be completed for all flight profiles once an optimized design is generated. Since an Optistruct optimized design does not necessarily provide a finalized product, an interpretation of the results will be conducted and applied to a working CAD model. The final wing design will be wind-tunnel tested for verification of the analytical results. A successful design will provide equal or improved structural support with a lower volume fraction/weight than the baseline design. Final output will be aluminum AM model developed for further structural testing. Results will determine the feasibility of producing a topology optimized wing using AM techniques.

Research conducted by Locatelli, Mulani, and Kapania optimized a wing using curvilinear spars and ribs. They were able to reduce the weight of a generic fighter wing by 19 percent while maintaining or enhancing stress and buckling[10]. The research conducted by Luo, Yang, and Chen concluded an estimated missile body weight savings of 37 percent using their optimization techniques[4]. Therefore, it is expected a topology optimized design will save between 15 to 25 percent from a baseline model while maintaining or improving structural integrity. The weight saving from the elimination of fasteners within the structure will also be considered.

A further study will be completed to determine the possibility of using internal components, such as fuel tanks, as load bearing structures. It is expected the implementation of components external to the aerodynamic structure as load bearing elements will provide a noticeable weight savings compared to components which are constructed as individual structures. An effective use of AM enhances this possibility, along with the ability to simply produce improved aerodynamic designs previously limited by manufacturing constraints.

Acknowledgments

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