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Computational investigations for topology optimization of UAV and small-scale aircraft wings

Received 23 January 2024, Revised 21 April 2024, Accepted 27 April 2024, Published online 28 May 2024

Keywords: 4R-UAV, CFRP, SIMP method, SG6043mod airfoil, topology optimization

This study was conducted under the 4R-UAV project. The project is funded by the Latvian Council of Science with the goal of creating an innovative, aerodynamically improved, environmentally friendly, zero waste, and zero emission UAV. For the Circular Aviation 4R (Reduce, Recycle, Reuse, Redesign) concept, this paper covers two Rs (Reduce and Redesign) aspects of the 4R-UAV project. Topology optimization of structures has gained enormous potential with the advances in additive manufacturing techniques. However, it is still challenging when it comes to conventional manufacturing. Aircraft/UAV wings are conventionally hollow structures and leave almost little or no space for further material removal. It becomes even more complicated when conventional manufacturing limitations are further imposed. Nevertheless, topology optimization is indeed an excellent way of reducing the mass of the structures by keeping the mechanical strength intact. This computational study attempts to implement topology optimization on a small-scale aircraft aluminum alloy wing as well as on a carbon composite UAV wing. In order to ensure the feasibility of not only additive manufacturing but also conventional manufacturing, controlled/limited topology optimization was applied only to the ribs of the wings. It was found that topology optimized wing ribs (aluminum and carbon composite) demonstrated a 20% mass reduction while up to 10% overall mass reduction of the wings was achieved. Moreover, after the topology optimization, the wings demonstrated improved mechanical characteristics and factor of safety. The knowledge learned from this study will be implemented for the topology optimization of the future small-scale 4R-UAV wings which will be mainly manufactured using additive manufacturing.

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1. Introduction

This study presents the topology optimization of a wing structure for minimizing material use and mass reduction. The study was carried out on a ‘universal’ wing that can be used in small-scale general aviation aircraft or a military scale UAV. The main aim of the study is to investigate if topology optimization is useful in such wings, as the study is intended to offer the base for the future implementation of topology optimization in small-scale 4R-UAV.

4R-UAV is a project supported by the Latvian Council of Science to develop an aerodynamically efficient, zero waste, zero emission, environmentally friendly UAV. The fundamental research project addresses the unreadiness of the aviation industry to achieve the EU climate neutrality goal of 2050. Unfortunately, the existing 3R (Reduce, Recycle, Reuse) principle of circular economy is insufficient when it comes to the aviation industry; the secret to Circulation Aviation is 4R (Reduce, Recycle, Reuse, Redesign), which is only possible with improved aerodynamic and structural designs for future aircraft/UAVs. The 4R-UAV project is the small-scale implementation of the 4R circulation economy concept and intends to propose solutions for the full-scale aviation industry. While the 2 Rs (Recycle and Reuse) are relatively known and are largely in practice these days, the rest of the 2Rs, i.e., Reduce and Redesign, are the most significant as well as the challenging aspects of the 4R implementation concept that requires out of the box solutions for the aviation field. While the 4R-UAV studies so far were mainly focused on aerodynamic design improvements (Redesign), this study mainly focuses on ‘Reduce’ (the material) by ‘Redesign’ the structure geometry.

Aviation is an extremely ‘weight sensitive’ industry and over the years, many scientific developments were denied (heat recovery, compressor casing treatments, etc.) due to excessive weights associated with these systems. On the other hand, weight reduction, by any means, is always highly regarded (lightweight composites, etc.) that eventually improves aerodynamic performance and fuel efficiency. One R (Reduce) can contribute largely to facing environmental concerns by (directly) minimizing the use of material for manufacturing and (indirectly) improving the aerodynamic performance of aircraft by decreasing the overall weight of the structure.

Topology optimization of structures for weight reduction using computational simulations is not a new concept and has been widely used. Apart from weight reduction, the structure’s sustained or improved mechanical properties are the most significant advantage of topology optimization. Despite being considered a modern technique; it is thought to be relatively impractical due to the limitations of the manufacturing process. Topology optimizations mostly implement web-based uneven and irregular material removal, making it almost impossible to manufacture using conventional methods. With the development of additive manufacturing technologies, topology optimization has gained the renewed attention of engineers and researchers. In aviation, topology optimization of the structures offers significant

challenges due to: (1) the complexity of the primary structures and their geometry and (2) strict safety regulations. This, perhaps, is the reason that few efforts were devoted to aircraft structural topologies, especially for wings. Therefore, topology optimization is very inspiring for the authors' 4R-UAV project, which, if successful, can offer material reduction, better strength properties, and eventually improved performance, hence, fulfilling 2Rs (Reduce and Redesign).

As mentioned, wing topology optimization is not a very popular topic among aviation experts. However, the topic has gained attention over the past decade, and few excellent studies have been conducted. Especially wing box optimization using curvilinear spars and ribs (SpaRibs) has gained popularity in the last decade. Locatelli [1] used SpaRibs optimization using EBF3SSWingopt with a twostep optimization methodology to optimize topology and sizing. The results showed that structures made of SpaRibs were much lighter than straight spars and ribs. In the second part of their study, Locatelli et al. [2] conducted optimization on the supersonic wing using SpaRibs. The local optimization method allowed a weight reduction of 17% and adding the mass reduction from using SpaRibs resulted in a total 28.6% reduction in mass. Shuvodeep et al. [3] used topology optimization to optimize the internal structure of wings with curvilinear spars (SpaRibs) using a mesh continuity algorithm and selective thickening. The overall weight was reduced by allowing variable thickness on the wing skin. The mentioned studies were research-based work with limited practical implementations, as only additive manufacturing would offer the full possibility of manufacturing while it would be difficult to implement it using conventional manufacturing methods.

In recent years, few good studies have been conducted on topology optimization. Zhu [4] identified the potential of topology optimization in aeronautics and astronautics engineering along with the limitations associated with it in terms of manufacturing and mass production. The paper reviewed the practical applications such as standard material layout design for airframe structures. Gao et al. [5], introduced an improved Kreisselmeier-Steinhauser (KS) function based adaptive constraint aggregation approach that enhanced the efficiency and accuracy of the optimization process by dynamically adjusting the aggregation of constraints during the optimization. The method was successful in handling large-scale multi constrained problems by reducing the number of constraints. The study by Høghøj et al. [6] investigated the simultaneous shape and topology optimization of aircraft wings, focusing on minimizing drag. The optimization was conducted on different configurations by varying the external shape and internal material distribution of the wings. The optimized wing designs showed a significant reduction in drag of up to 32% with local chord optimization with an efficient internal structure that met the specified constraints. In the study by Conlan [7], an aeroelastic optimization framework for aircraft wings was explored using a coupled 3D panel beam model for the optimization of interior and external structural properties. The framework was effective in producing optimized designs with mid fidelity models and the potential performance improvements from curved wall spars. Stanford [8] presented

a nested optimization process for the sizing and topology design of a wing box based on uncertainties in safety factors for aeroelastic constraints. A nonintrusive polynomial chaos expansion was used to propagate uncertainties to attain a balance between minimizing mean structural mass and its standard deviation to achieve robust designs. The study demonstrated that topological shifts could enhance robustness by effectively managing the variability introduced by uncertain safety factors.

This paper aims to implement topology optimization for practical application on the real wing designed (by the authors) for small-scale aircraft or UAVs. Additionally, the recommendation from this paper will essentially be implemented for small-scale 4R-UAV, as the smaller the scale, the harder it is to implement topology optimization. Therefore, our goal was to keep the process simplified yet practical, which means that material removal (mass reduction) was entirely limited to conventional manufacturing constraints. Hence, regular shaped (geometry) material removal was adopted during the topology optimization. For our work on topology optimization, Solid Isotropic Material with Penalization (SIMP) is a better choice to organize the material distribution that minimizes wing compilation, as it provides a practical approach to implement topology optimization. SIMP method has undergone several improvements since its introduction proposed by Bendsoe and Kikuchi [9] while further improved by Rozvany [10], mainly to facilitate large-scale commercial requirements. SIMP was successfully used previously for wing topology optimization; for example, in the study of James [11], the SIMP method was used to optimize the structural topology of a wing box as a part of a Multidisciplinary Design Optimization (MDO) framework and the results showed a 42% reduction in drag in the MDO design. The study demonstrated the strong capabilities of the SIMP method but was mainly focused on the mathematical approach of the SIMP, yet it is a challenge to practically implement it in real wings. In a similar manner, Felix [12] also explored SIMP to prove the independence of topology optimization on aircraft wings subjected to self-weight loads.

For the wing under consideration, due to limited manufacturing facilities at our University, the authors have designed a simple internal structure of the wing consisting of I beam spars, ribs, and skin. Additionally, only ribs were considered for the topology optimization as ribs carry most of the material while spars ensure structural stability by absorbing most of the loads. There are few studies where the topology optimization was conducted only on the ribs. For example, Krog [13] explored the multiple approaches of topology optimization for the redundant wing box ribs and found out the usage of minimum weight formulation and constraining elastic energy in each load case. Walker [14] conducted topology optimization on a three-dimensional RV-4 wing and made a 3D printed optimized airfoil model with a weight saving of 15% and 25%, focusing mainly on rib optimization. Once again, these excellent studies on topology optimization were limited to additive manufacturing only, leaving question marks for implementing conventional manufacturing.

It is widely accepted that the topology optimization concept is only suitable for 3D printing or other additive manufacturing methods. Aircraft/UAV wings are already “hollow” structures and finding space for further material removal by keeping the mechanical strength properties intact is challenging. Therefore, limited efforts were devoted to aircraft/UAV wing topology optimizations. One of the studies was conducted at Airbus UK and Altair by Krog [15] which was focused on the use of the SIMP method to redesign inboard inner and outer fixed leading edge ribs and fuselage door intercostals. Interestingly, the total mass reduction was in the range of 1000 kg per aircraft. The machining trials are still going on to understand if the results can be implemented using traditional manufacturing. To summarize, in the future, the possibility of large-scale additive manufacturing will ensure the implementation of advanced levels of topology optimization; on the contrary, at the moment, it is not only costly but also limited when it comes to manufacturing large-scale structures, especially wings. Therefore, in this study, limited topology optimization was targeted to reduce the proportion of mass from the (already) designed wing for small-scale aircraft of the size of Cessna 172 aircraft [16] or similar sized UAVs. The study’s main goal is to implement topology optimization in such a way that an optimized and internally redesigned wing is possible to manufacture, not only by additive manufacturing but also using conventional manufacturing methods. In addition, the recommendations from this study could be implemented for the topology optimization of the future small-scale 4R-UAV wing (which will be mainly produced by additive manufacturing).

A stepwise workflow was adopted for this paper. In the first step, for the wing selection, the chosen aerodynamically efficient wing was, in fact, recently designed by authors in [17] for a small-scale aircraft or UAV. The wing’s improved aerodynamic characteristics were achieved due to the implementation of the aerodynamically optimized airfoil, i.e., SG6043mod. This highly efficient airfoil (SG6043mod) was generated from the parent SG6043 airfoil by developing a robust airfoil optimization methodology, details of which can be found in the authors’ related studies [18]. In the next step, the wing’s internal structure was designed. For simplicity, only the ribs, spars, and skin were considered. As mentioned earlier, it was decided to implement topology optimization only on the ribs. The SIMP method was employed using the SOLIDWORKS commercially available topology optimization algorithm. From this point on, two different materials were used for the wing structure, i.e., aluminum metal alloy 2024T3 for the small-scale aircraft wing and carbon composite T700 for the UAV wing. In the final step, computational analysis was carried out using FEM static analysis followed by modal analysis to verify the static analysis results. It was found that mass reduction by material removal is possible in both (aluminum and carbon composite) wings. Up to 20% mass reduction was achieved in ribs, while up to 10% overall wing mass was reduced after the limited topology optimization was implemented. Most importantly, the stress properties and the factor of safety were improved in the topology optimized wings.

2. Wing design

2.1. Wing design parameters

The geometry of the wing and design parameters play a vital role in determining the effectiveness of topology optimization. In other words, the topology optimization strategy highly depends on not only the wing's inner structure but also its geometric details. In this study, in order to understand an in-depth application of topology optimization on wings (which is a relatively under studied topic in past studies), the implementation was limited to small-scale light aircraft wing and UAV applications. As the focus of the authors' research project is UAV development, therefore, a medium to large-scale UAV wing (which is nearly equal to the small-scale general aviation aircraft wing) was aimed. For simplicity, the authors recently developed aerodynamically efficient wing [17] was chosen for the topology optimization analysis. Hence, this study is applicable to UAVs and small-scale aircraft only; additionally, recommendations can be further studied for small-scale 4R-UAV.

For the topology optimization analysis of the wing, the aerodynamically efficient wing was designed by implementing the SG6043mod airfoil generated from the robust optimization methodology developed by the authors in [18]. The authors' developed airfoil SG6043mod exhibited improved aerodynamic performance than that of the parent airfoil (SG6043) (and a few other commonly used airfoils). The details of the airfoil optimization methodology, wing design steps, and its aerodynamic performance analysis are described in [17] and [18], respectively. To summarize, all the steps from the airfoil development to the wing design (and its internal geometry) were performed by the authors as part of the 4R-UAV project tasks.

The geometric parameters of the wing were chosen close to the design parameters of the Cessna 172 aircraft [16] as the dimensions and operating parameters of the Cessna 172 aircraft are similar to the modern large-scale military UAVs. Fig. 1, illustrates the wing (semi-span) design (recently developed by the authors), while the wing parameters are presented in Table 1. For clarity, the initial wing designed

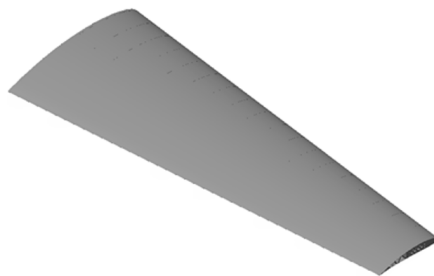


Fig. 1. 3D CAD model of the original wing

for the analysis was named as ‘original wing’ which is the wing before performing the topology optimization analysis on it.

Table 1. Wing parameters

Wingspan	11 m
Wing area	15.13 m ²
Aspect ratio	7.99
Root chord	1.95 m
Tip chord	0.8 m
MAC	1.45

2.2. Wing structure

Once the aerodynamically efficient original wing was designed, in the next step, the internal structure of the wing was devised. For the investigation and application of the topology optimization in wings, only the major structural components, such as ribs and spars along with the skin, were considered for the analysis (as these are the major load carrier components of the UAV wings). For the ribs of the original wing, a common type of rib design for small aircraft wings was adopted. The ribs’ design and their implementation were carried out in accordance with the recommendations provided by Bruhn [19]. The schematic of the wing’s ribs explained by Bruhn [19] is illustrated in Fig. 2. In this study, as per the wingspan, 19 ribs were implemented along the span with a root rib thickness of 3 cm, while the rest of the ribs’ thickness was 1 cm. Each rib additionally possessed conventional lightning holes. A 2D side view of a single rib is shown in Fig. 3, which was used in the original wing.

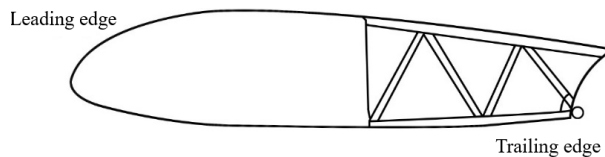


Fig. 2. Reference design of designing the ribs of wings



Fig. 3. Side view of the rib of original wing

The primary wing’s internal structure was designed carefully, keeping in mind the practical and fabrication aspects. The final version of the primary wing with the

entire internal structure (ribs and spars) is illustrated in Fig. 4. Topology optimization for the wing's internal structure involves several limitations and challenges in order not to compromise the structural integrity and feasibility of traditional fabrication. For the UAV mission (for which the wing is designed), the wing structure must withstand specific payload and structural loading where a certain structural safety (with a minimum safety factor of 1.5) is inevitable. As the UAV scale is relatively large to adopt additive manufacturing techniques, therefore, another challenge for the topology optimization was to make sure that the optimized model could be manufactured using traditional manufacturing and machining techniques. With these prerequisites, the topology optimization analysis was performed and is discussed in the next section.

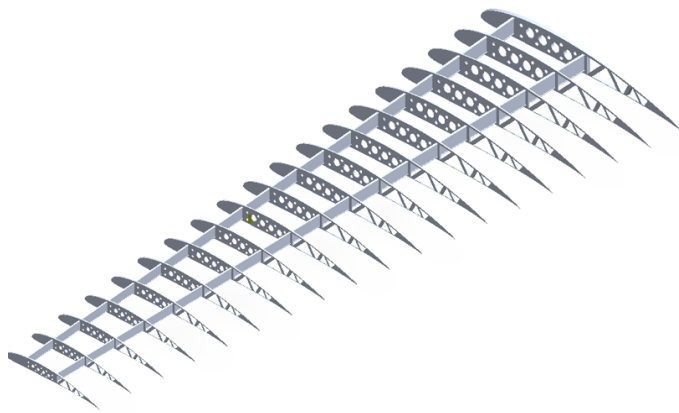


Fig. 4. Full wing internal structure: ribs and spars

3. Topology optimization

For the topology optimization of the UAV wing, SOLIDWORKS topology optimization solver was used. The solver uses Solid Isotropic Material with Penalization (SIMP) technique for topology optimization by identifying the structural characteristics. SIMP was initially proposed by Bendsoe and Kikuchi [9] and later modified by Rozvany [10]. SOLIDWORKS incorporates an in depth SIMP algorithm and offers several possibilities for topology optimization [20].

Traditionally in topology optimization, a domain is discretized into a grid of isotropic solid microstructures:

$$\rho_e = 1 \text{ where material is filled,}$$

$$\rho_e = 0 \text{ where material is removed.}$$

The introduction of a continuous density distribution function allows intermediate values to be assigned to elements, hence avoiding the on off characteristic of the problem. The relative density can vary between a minimum value of ρ_{\min}

and 1. The relation between the material relative density factor ρ_e and the material Young's modulus of the isotropic model E_0 is computed by the power law, as in Eq. (1):

$$E(\rho_e) = \rho_e^p E_0. \quad (1)$$

According to SIMP method, element stiffness is dependent on elastic modulus, and the global stiffness is modulated using Eq. (2):

$$K_{\text{simp}(\rho)} = \sum_{e=1}^N [\rho_{\min} + (1 - \rho_{\min})\rho_e^p] K_e. \quad (2)$$

Sensitivity analysis detects elements weighted with low material density factors and the material is eliminated during further iterations. The mathematical expression for the sensitivity analysis is given in Eq. (3).

$$\frac{dc}{d\rho_e} = -p(\rho_e)^{p-1} [u_e]^T [K_e] [u_e]. \quad (3)$$

Strategy for the application of SIMP-based topology:

For the study of the application of topology optimization on UAV wings, the SIMP method was utilized using SOLIDWORKS software. The study set the prerequisite condition that the topology optimization should be applied in a way that should provide the possibility of both conventional and additive manufacturing of the wings. For this, the topology optimization was performed only on the ribs of the wings. In order to ensure the structural integrity of the wing, the wing spar, which is the main load bearing structure in wings, was excluded from the topology optimization. As the application of topology optimization on aircraft/UAV wings is very complicated and limited, the SOLIDWORKS solver was further constrained to (i) prevent the topology optimization of the wing skin and (ii) keep a standard factor of safety of 1.5 for the wing (prescribed by the European Union Aviation Safety Agency). After these constraints, careful and limited topology optimization was performed only on the ribs of the wings for mass reduction. The details of the topology optimization application and constraints are described in Section 7 of this paper.

3.1. UAV wing topology optimization limitations

As mentioned in Section 2.2, for the specific UAV mission loadings and minimum structural safety range, the wing topology optimization should be restricted to creating voids for material retention in a uniform manner. It means that a challenge was faced in implementing topology optimization as the webbing method of topology optimization (which is relatively easier and commonly seen) cannot be applied to the authors' wing. In the case of webbing-type material removal, large-scale UAV wing manufacturing using conventional fabrication techniques would no

longer be feasible. Therefore, the authors implemented limited topology strategies for creating the spaces/voids for the material removal from the wing structure. It is precise to say that the authors used limited webbing techniques for wing structure in order to cope with the limitations mentioned earlier. In addition, the topology optimization was only performed on the ribs, while no attempt was made to apply topology on spars which take the majority of the loadings, in order to ensure structural compliance. The material removal process was conducted carefully, focusing on creating straightforward shapes suitable for traditional manufacturing methods. Patterson's study [21] effectively applied topology optimization to create a truss design manufactured using anisotropic material, similar to the material used in this study. The optimization approach in [21] ensured efficient material distribution by removing excess material from non load bearing regions, resulting in lightweight components. The material removal was performed (computationally) from the leading and trailing edge of the wing ribs in a way that it would still be possible to machine or fabricate traditionally, as discussed in the following sections.

4. Material selection

From this point, in order to observe the effectiveness of topology optimization, the study was divided into two separate parts, i.e., small-scale aircraft wing (which consists of Aluminum based metallic structure) and UAV wing (which mainly consists of Carbon composites).

4.1. Small-scale aircraft wing

As mentioned in [17] and in Section 2.1, the wing was designed with parameters similar to Cessna 172 [16] wings. The material selected for the small-scale aircraft wing (ribs, spars and skin) was 2024-T3 Aluminum alloy, which is predominantly used in the aviation field for its superior strength to weight ratio and acceptable level of fatigue resistance [22]. The properties of 2024-T3 Aluminum alloy are mentioned in Table 2.

Table 2. Aluminum 2024 T-3 properties

Property	Value	Unit
Elastic modulus	72400	MPa
Poisson's ratio	0.33	N/A
Shear modulus	28000	MPa
Mass density	2780	kg/m ³
Tensile strength	485	MPa
Yield strength	345	MPa

4.2. UAV wing

For the UAV wing, carbon composite materials are mainly used for the wing structure. Therefore, the geometric and design parameters of the wing were unchanged, however, carbon composite T700S was chosen for the computational analysis and topology optimization. T700S was selected as the main material for UAV wing due to its high tensile strength and wide range use in industries such as aviation, aerospace, recreational pressure vessels, etc. In addition, Patterson [21] also used T700S as the main material in his excellent study for manufacturing of UAV wings. The properties of carbon composite T700S [23, 24] are mentioned in Table 3.

Table 3. Carbon composite T700S properties

Property	Value	Unit
Elastic modulus	135 000	MPa
Poisson's ratio (transverse)	0.28	N/A
Shear modulus	24000	MPa
Mass density	1800	kg/m ³
Tensile strength	2550	MPa

The layer orientation for the carbon composite structure (T700) was set as [0/90/+45/-45/90/0]. The thickness of the wing skin (upper and lower) and rib was set to 1 mm, and the spar ply thickness was set to 2 mm, as it is the main load-carrying structure. The ply pattern and thickness of the T700S composite layers are summarized in Table 4.

Table 4. Summary of the T700S composite properties

Wing component	Ply pattern	Layer thickness (mm)
Upper skin	[0/90/+45/-45/90/0]	1
Lower skin	[0/90/+45/-45/90/0]	1
Spar	[0/90/+45/-45/90/0]	2
Rib	[0/90/+45/-45/90/0]	1

5. Computational scheme: Grid generation

Computational analysis was performed in SOLIDWORKS. The mesh of the entire wing structure was generated using blended curvature mesh. The rib was the main structure of focus for the topology optimization; hence, finer mesh was applied to internal structures compared to the skin to improve the accuracy of the topology optimization results. The high quality mesh was used for the entire wing

with a minimum element size of 1.8 mm. The mesh consisted of 3147991 nodes and 1827064 elements. Fig. 5, shows the mesh scheme of the semi-span wing used for the analysis.

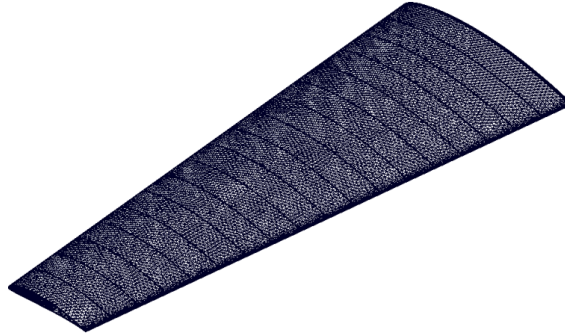


Fig. 5. Computational grid scheme of the wing

6. Computational scheme: Application of forces and loads

The aircraft wing, in fact, is a cantilever structure as one end of the wing is rooted to the fuselage while the free end of the cantilever is the wing's tip. There are several types of loading and forces that affect the wing's aerodynamic and structural performance. As the wings are lift generating devices, it is evident that they should be able to withstand the aerodynamic and structural loadings to create sufficient lift force. These loadings vary with the atmospheric conditions (such as pressure and temperature). In addition, engines and propulsion forces also contribute to the structural loadings on the wing. It is difficult to imitate all the flight conditions and the variety of loadings a wing may encounter during flight; hence, a common practice is to observe the wing's fatigue limit by implementing a uniformly distributed maximum loading within the airworthiness regulations (safety factor of 1.5) [25]. Similar practices are followed for the standard fatigue testing of actual wings. Therefore, for the simulations on SOLIDWORKS, the root of the wing was set as a fixture to imitate the cantilever effect as well as the actual wing fatigue testing techniques. The authors' wing can withstand a maximum uniformly distributed loading of 22 kN to ensure the minimum allowed safety factor for airworthiness standards. Fig. 6, illustrates the maximum loading (22 kN) applied to the pressure surface of the wing, as per industrial practices. As suggested by Felix [12], the weight of the wing itself does not affect the topology optimization; therefore, the weight of the wing was excluded while applying the (maximum) loading force on the wing.

From this point on, the work was directed in two directions, i.e., topology optimization of a small-scale aircraft wing (Aluminum metal structure) and the UAV wing (Carbon composite structure).

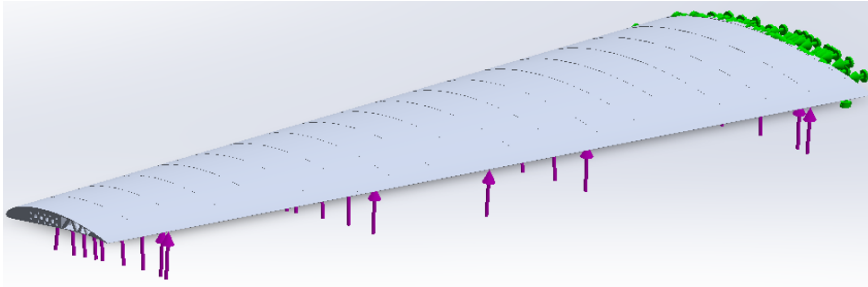


Fig. 6. Application of load and fixture over the wing surface

7. Topology optimization strategy and results

For an in depth understanding of the application of topology optimization on wings (aircraft and UAV), static and modal analysis was performed for the verification of the results. Usually, static analysis is considered sufficient but modal analysis was specifically performed in order to understand the dynamic loading characteristics of the carbon fiber UAV wings. The modal analysis could suggest accurate natural frequencies and mode shapes of a structure or system. As the end goal of the study is to eventually implement the technique on a small-scale 4R-UAV, modal analysis is preferred.

7.1. Topology optimization and mass reduction

As the topology optimization was performed only on the ribs with the limitations discussed in Section 3.1, the wing rib structure was optimized by (constrained) material removal. Leading and trailing edges were the areas where the topology was applied for the material removal. These were the only regions on the rib that offered the possibility of material removal without affecting the structural integrity. In addition, at the leading and trailing edges, the excess material zones were located with relatively less complicated geometry. The SOLIDWORKS solver was given three constraints before applying topology:

- The skin thickness (of the wing) was preserved and was unchangeable, which means that the solver was restricted from removing material from the skin.
- Spars were restricted from applying topology as they bear the main loads of the wings.
- The factor of safety was constrained to 1.5, as recommended by the airworthiness standards of EASA [25].

Fig. 7 illustrates the comparison between the original rib and the topology optimized rib. The rib in Fig. 7b is the topology optimized rib with the material removed from the leading and trailing edge zones. The constraint of conventional machinability is fulfilled as instead of a web based topology a regular shaped

topology was enforced. A similar topology scheme was adopted for both aircraft and UAV wings, so, there was no geometrical difference between the two ribs except for the material (aluminum or carbon composite).

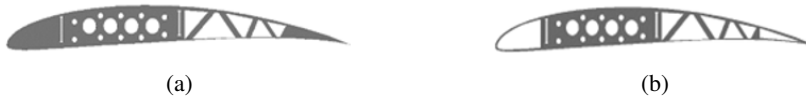


Fig. 7. Comparison of the wing rib design: (a) original (b) topology optimized

The total mass of 19 ribs of the Aluminum bodied semi-span wing was 65.92 kg and after the topology optimization (performed only at the leading and trailing edge of the ribs) the mass was reduced to 52.62 kg. For the full-span wing structure (with 38 ribs), the total reduction of weight is more than 26 kg which is about 20% weight reduction of the ribs only. In addition, the total mass of the Aluminum-bodied semi-span original wing (ribs, spars, and skin) was approximately 129 kg and after the 26 kg mass reduction by topology optimization of ribs, nearly 10% total mass reduction of the full-span wing structure was achieved. It is important to notice that it is the weight reduction from the original wing's structure without flaps, slats, ailerons, etc., which may offer further possibility of weight reduction in their respective structures.

For the UAV wing, the total mass of 19 ribs of the carbon composite bodied semi-span wing was about 43 kg and after the topology optimization (performed only at the leading and trailing edge of the ribs) the mass was reduced to about 34 kg. For the full-span wing structure (with 38 ribs), the total reduction of weight was approximately 16 kg which is about 20% weight reduction of the ribs only. Additionally, the total mass of the carbon composite bodied semi-span original wing (ribs, spars, and skin) was approximately 83 kg and after the 16 kg mass reduction by topology optimization of ribs, nearly 9% total mass reduction of the full-span UAV wing structure was achieved. It is important to notice that UAV structure is also possible to manufacture with additive manufacturing methods; hence, if additive manufacturing is implemented, the possibility of weight reduction would be much higher than the one achieved in this study (due to the conventional machining limitations). Table 5 presents the summary of the topology optimization achieved results of aircraft and UAV wings.

Table 5. Mass reduction comparison of small-scale aircraft wing and UAV wing

Wing	Material	Number of ribs	Mass of the ribs (kg)	Mass of the full wing (kg)	Mass reduction of ribs (kg)	Mass reduction of rib (%)	Mass reduction full wing (%)
Small-scale aircraft	Aluminum	38	65.92	129	52.62	20	10
UAV	Carbon composite	38	43	83	32	20	9

7.2. Structural analysis

The concept of topology optimization is not only the mass reduction by material removal; moreover, the real challenge lies in sustaining the structure mechanical properties. In other words, topology optimization is only feasible if no compromise is made on the structure strength and sustainability. Therefore, FEM analysis for stress distribution and fatigue properties is inevitable. As mentioned at the start of this section, along with the static analysis, a modal analysis was also performed for the higher accuracy of the results. Static structural analysis simulations were carried out in SOLIDWORKS, as it has been practiced for studying the stress distribution, deformations, loadings, and safety factor evaluation.

7.3. Stress distribution

7.3.1. Small-scale aircraft wing

The stress distribution over the aluminum bodied wing structure in terms of max von Mises stress is illustrated in Fig. 8. The max von Mises stress in the (topology) optimized lighter weight wing decreased to 240.3 MPa compared to the original wing with 273.2 MPa. Up to 12% of overall stress reduction was manifested in the topology optimized wing. There are no significant over stressed zones on both the (original and optimized) wings, while the reduction of stress in the optimized model is due to better stress distribution compared to the original model, as shown in Fig. 8, with the max von Mises values. In fact, by removing the excess mass from the original wing structure, new stress paths were created, causing improved stress distribution while ultimately reducing the maximum von Mises stress.

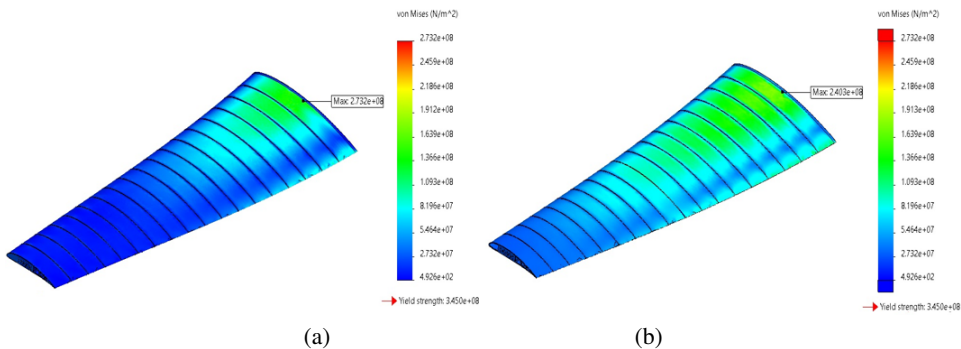


Fig. 8. Stress distribution of aircraft wing (aluminum body): (a) original (b) topology optimized

7.3.2. UAV wing

The stress distribution over the carbon composite bodied UAV wing structure in terms of max von Mises stress is manifested in Fig. 9. The max von Mises

stress in the (topology) optimized lighter weight wing decreased up to 262 MPa compared to the original UAV wing with 295 MPa. Up to an 11% decrease in overall stress was achieved in the topology optimized wing.

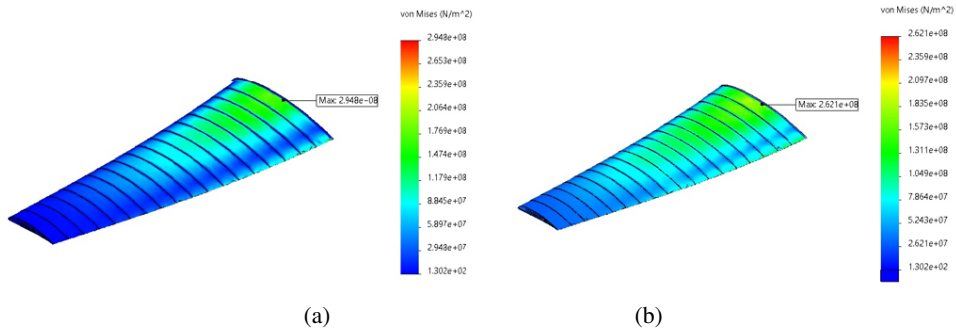


Fig. 9. Stress distribution of UAV wing (carbon composite body): (a) original (b) topology optimized

7.4. Deformation

7.4.1. Small-scale aircraft wing

Deformation, which is the bending of the structure (specifically in wings), was observed during the static analysis and is presented in Fig. 10. The ‘bendability’ of the (topology) optimized lighter weight aluminum bodied small-scale aircraft wing increased up to 126 mm as compared to the original (heavier) wing with a deformation value of up to 119 mm. This is an expected result as removing material improves the structure’s deforming characteristics by weakening the stiffness within it. Up to 6% more deformation was observed in the optimized wing; most importantly, this deformation criterion is within the safety range.

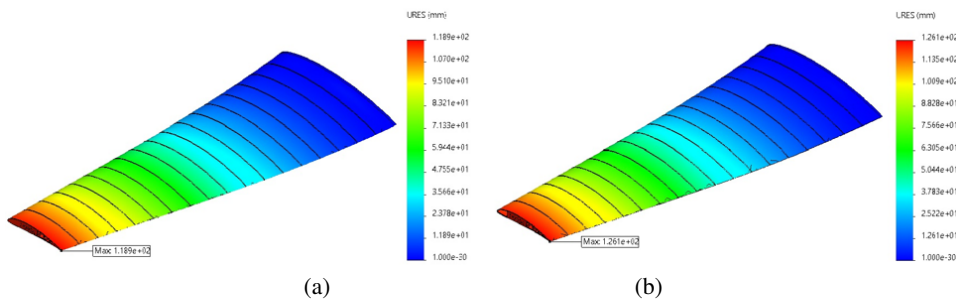


Fig. 10. Deformation of aluminum wing: (a) original (b) topology optimized

7.4.2. UAV wing

For the (topology) optimized lighter weight carbon composite bodied UAV wing, the deformation increased to 93 mm as compared to the original (heavier)

wing with a deformation value of nearly 92 mm. The overall deformation increment was nearly 1%, which was well within the safety range. The deformation of carbon composite UAV wing is compared in Fig. 11.

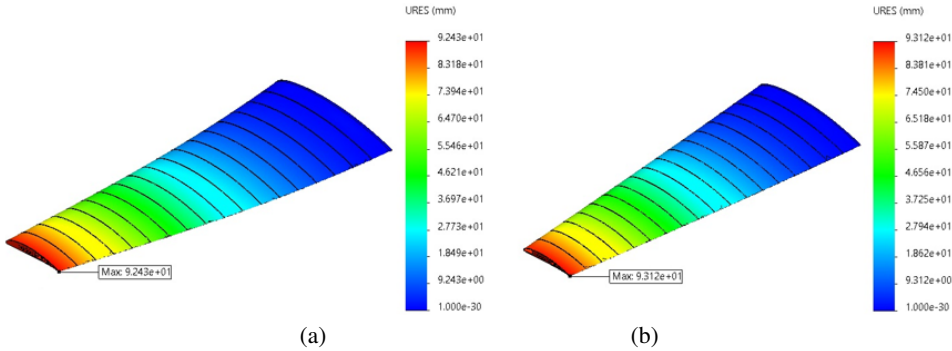


Fig. 11. Deformation of UAV wing: (a) original (b) topology optimized

Table 6 summarizes the results of static analysis that also includes the information on safety factors. The topology optimized models are within the safety range prescribed by EASA [25].

Table 6. Static structural analysis summary

Wing	Material	Original			Optimized		
		Von Mises stress (MPa)	Deformation (mm)	Factor of safety	Von Mises stress (MPa)	Deformation (mm)	Factor of safety
Small scale	Aluminum	273.2	126.1	1.5	240.3	118.9	1.7
UAV	Carbon composite	294.8	92.43	8.6	261.2	93.12	9

7.5. Modal analysis

Modal analysis is, in fact, the verification of static analysis by determining the natural frequencies and mode shapes of a structure or system. In order to understand the dynamic characteristics of the optimized model, a modal analysis which ensures that a structure can withstand the dynamic load it may experience during operation was conducted. Agarwal [26] did a modal analysis to observe the vibrational frequencies of aluminum, glass fiber, and carbon composite-based cantilever beam structures. Unlike solid beams, in our study, a ‘hollow’ topology optimized wing structure is studied for the modal analysis; therefore, it is important to confirm that under the different mode frequencies, the wing structure remains stable. Modal analysis for both the wings (original and optimized) was performed in SOLIDWORKS, and the natural frequency modes were calculated and are given in Table 7.

Table 7. Resonance frequencies of the optimized wing models

Mode number	Original wing (AI-2024-T3)	Optimized wing (AI-2024-T3)	Original wing (T700S)	Optimized wing (T700S)
1	30.803	35.467	36.816	58.579
2	64.944	70.442	98.543	120.37
3	144.43	206.37	174.18	330.51
4	214.28	238.76	334.13	410.35
5	257.91	263.58	414.88	444.26

The results of the five order free modes of the optimized aircraft aluminum wing and UAV carbon composite wing are depicted in Figs. 12, 13. It is evident from the figures that both optimized wings have similar mass participation in all the modes with different natural frequencies. The higher frequencies seen in the optimized carbon composite wing are due to the mechanical properties of the carbon fiber T700S, which caused more deformation for the same load acting on the UAV wing surface, as discussed in Section 5. The first mode shows the upward movement in mainly the Y direction, making a flapping movement and causing maximum deformation at the tip. The second mode is a mix of movements in X and Z directions, causing the structure to turn inward at the tip, resulting in maximum deformation at the tip zone. The 3rd mode is similar to the 2nd mode, with a ‘stronger’ movement in the X direction, initiating a wave movement and possessing maximum deformation at the wing tip. The 4th mode is similar to mode 2 and with mass participation in X and Z components, causing the wing to bend

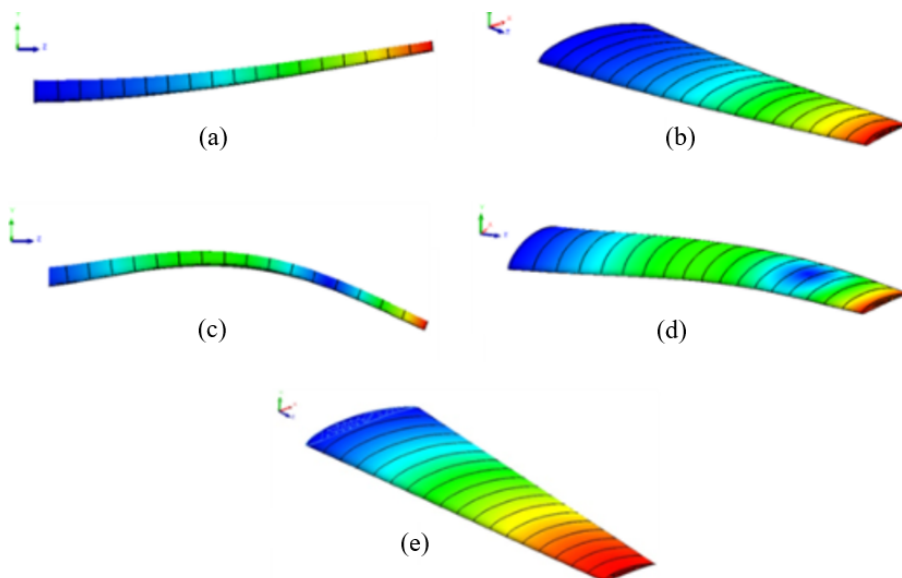


Fig. 12. First five natural frequency modes of topology optimized aircraft wing (aluminum)

inward as well as twist. The 5th mode is the breathing mode which causes the upper and lower skin to move along the Z direction.

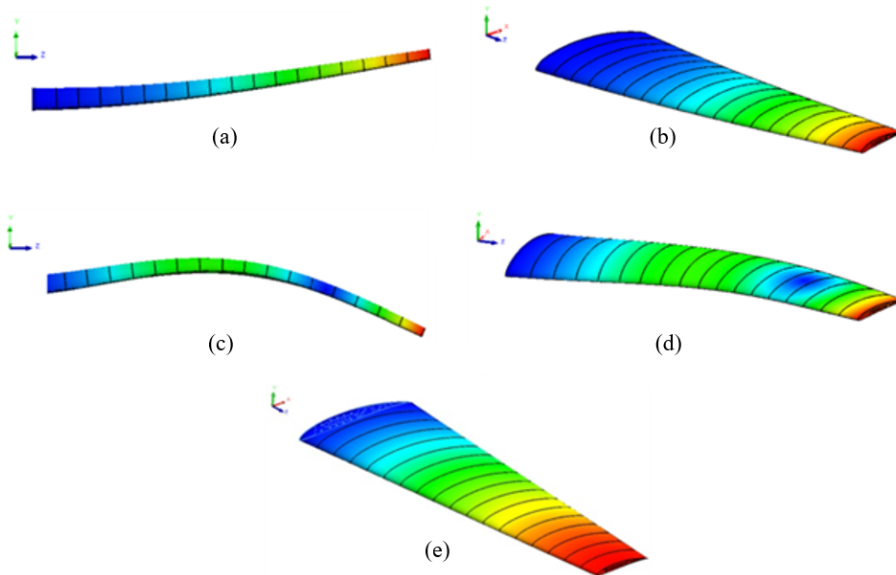


Fig. 13. First five natural frequency modes of topology optimized aircraft wing (composite)

The modal analysis provided the dynamic characteristics of the optimized wings and confirmed that the structure (under maximum loading) was stable and does not contribute to any mechanical damage.

8. Discussion

4R-UAV project is an attempt to implement the 4R (Reduce, Recycle, Reuse, Redesign) circular aviation concept by developing an aerodynamically efficient and environmentally friendly UAV. The current study was specifically focused on two Rs (Reduce and Redesign) of the project implementation plan. Topology optimization was implemented to reduce the mass (material) of the UAV/aircraft wings by redesigning the internal structure while sustaining the mechanical properties. This preliminary study was mainly conducted to investigate the possibility of topology optimization on wings (which was a somewhat neglected idea in the past) before it was finally implemented in small-scale 4R-UAV wings. With the current developments in additive manufacturing, topology optimization is more realistic, and 4R-UAV will be a recyclable, zero waste, zero emission UAV with minimum material consumption. On the other hand, for topology optimized large-scale wings, conventional manufacturing is still the greatest constraint; therefore, in this study, wings nearly the size of general aviation small-scale aircraft and UAVs (which can

be manufactured by additive and conventional manufacturing) were investigated for material removal/mass reduction.

In this study, nearly 10% overall mass reduction was achieved in both the aluminum and carbon composite wing structure. Even with the limited topology, surprisingly, improved structural properties and factors of safety were achieved in the (topology) optimized wings. These positive results (especially for carbon composites) are an inspiration to implement the topology optimization in the future small-scale 4R-UAV, which will constitute polymers, carbon fiber, and Kevlar as the main structural material. Therefore, the authors strongly believe that in the future study of small-scale 4R-UAV, an overall mass reduction (by material removal) of up to 20% can be achieved, due to the possibility of additive manufacturing. This study will serve as the base for future work. The results of this study are summarized in Table 8.

Table 8. Optimized model computational result comparison of small-scale aircraft and UAV wing

Wing	Material	Original			
		Ribs mass reduction (%)	Full wing mass reduction (%)	Stress reduction (%)	Deformation (%)
Small scale (aluminum)	Al-2024 T3	20	10	12	6
UAV (Carbon composite)	T700S	20	9	11	1

9. Conclusions

The following conclusions can be drawn from the study:

- Mass reduction by topology optimization was successfully achieved on the ribs of the wing for both the considered cases, i.e., aluminum based aircraft wing and carbon composite based UAV wing.
- With strict design and structural constraints, topology optimization was still managed to achieve at least 20% overall mass reduction of the wings.
- Simplicity in terms of design and manufacturability was the main advantage of the limited implementation of topology optimization (targeted only to the selected sections of the wing structure), which demonstrated performance nearly similar to the modern/complex methods of topology optimization.
- The study demonstrated that topology optimized wings (with reduced mass) of the aircraft/UAV can be manufactured either by conventional or additive manufacturing means.
- With the constrained topology optimization, the overall mass reduction of aluminum and carbon composite wings was 10% and 9%, respectively.
- The stress distribution of the (topology) optimized wings (aluminum and carbon composite) was improved with a higher factor of safety (within the range prescribed by EASA).

- With reduced mass, the 2 Rs (Reduce and Redesign) of the 4R-UAV circular economy principle were achieved. In future, the study will be implemented for the actual designing and manufacturing of the 4R-UAV variants.

Acknowledgements

This work has been supported by the Latvian Council of Science, Fundamental and Applied Research Project, Project Nr. lzp-2021/1-0558. Project title: “Design and development of an aerodynamically efficient UAV (Unmanned Aerial Vehicle) by implementing the eco-friendly 4R circular economy concept in aviation: (4R-UAV)”.

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