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Weight reduction of an unmanned aerial vehicle pylon fitting by topology optimization and additive manufacturing with electron beam melting

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Abstract

The operating altitude of unmanned aerial vehicles can be affected by many parameters. Lightening the structural parts to achieve target altitude is one of the design efforts. Weight reduction can be achieved by converting primary and secondary structures from metallic to carbon composite material. In addition, some secondary structures, such as fittings, have to be produced metallic and usually made of aluminum alloys. In addition to the weight disadvantage, aluminum alloys have galvanic incompatibility with carbon composite materials. At this point, additive manufacturing methods offer solutions with a combination of topology optimization. Complex geometries obtained from topology optimization can be easily manufactured by additive manufacturing methods during weight reduction campaigns of unmanned aerial vehicles such as fittings. In this study, the pylon fitting of an unmanned aerial vehicle is lightened by the topology optimization method using commercial software with an engineering approach. The resulting complex geometry is produced as Ti-6Al-4V by the Electron Beam Melting additive manufacturing method. As a result of the campaign, a fitting design that is both lightweight and galvanic compatible with carbon composite primary structures has emerged. In this way, an engineering approach has been developed for weight reduction campaigns.

Keywords: Topology optimization, Electron beam melting, Ti-6Al-4V, Fitting, Unmanned aerial vehicles

1. Introduction

Mechanical designers need to know manufacturing limitations to trade-off performance vs. serial production cost. Different products have different allowances for this trade-off [1].

Topology optimization is a branch of structural optimization. This method iteratively distributes materials available in a design domain to give an optimized structure for an objective function. A typical topology optimization algorithm combines two distinct modules, one for analysis and the other for optimization [2]. Although there are several design approaches, such as shape optimization and size optimization, only the topology optimization of an additively manufactured aerospace structure is the aim of this study. Additive manufacturing allows building optimized, lightweight complex geometries which cannot be manufactured by machining.

Goh et al. [3] state according to the Breguet method; aerodynamic parameters must be maximized and weight must be minimized for longer endurance of fixed-wing unmanned aerial vehicles (UAV). However, complex inner structures cannot be manufactured by conventional methods. Additive manufacturing brings a new challenge for UAVs in the manner of shape and inner structure. The introduction of additive manufacturing has not just revolutionized the field of UAVs but has impacted the entire manufacturing arena by simplifying the design and easing the fabrication process [3]. UAVs and aerospace components routinely exploit additive techniques like fused deposition modeling (FDM), selective laser sintering (SLS), stereolithography (SLA), selective laser melting (SLM), and electron-beam melting (EBM). To date, FDM, SLA, polyjet, and SLS have been used to either fully print the UAV structures or fabricate certain parts of UAV structures.

Kim et al. [4] focused on the porous infill of a wing structure more than the overall shape and infill structure by a circle packing generation to create a hexagonal infill pattern. Altair Engineering company has been studied the topology, shape, and size optimization of a leading-edge droop nose of an A380 for AIRBUS UK [5]. The work program resulted in a set of conceptually different ribs which met the weight target and satisfied all stress and buckling criteria included in the optimization[5].

Oerlikon and RUAG Space cooperate in qualifying an optimized spacecraft bracket which will be installed on a fairing. Topology optimization with additive manufacturing reduced the cost by 25% and weight by

50%. This presents the strong capability of coupling topology optimization and additive manufacturing skills of companies.

In this study, a weight reduction campaign of a UAV pylon fitting will be performed by topology optimization using Hypermesh and Optistruct commercial software, which are included in Altair® HyperWorks® Version 2019. Then, the fitting, which is lightened by optimization, will be produced by Electron Beam Melting (EBM) additive manufacturing method.

2. Material and methods

The payload carrying UAV has a total of four payloads carrying capacity, two on each wing. The most loaded one is selected, and three different worst-case load cases are applied among all fittings and load cases. Load cases are divided into three groups such as; launch, flight, and landing. By choosing the most challenging loads in each group, it is aimed to design and manufacture a light fitting that will withstand these loads. UAV and payloads are shown schematically in Fig 1.

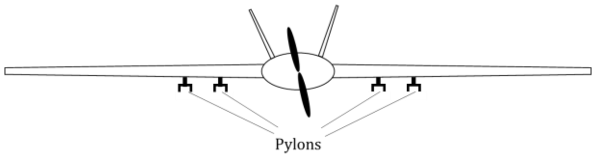

Fig 1. Schematic view of UAV and pylons which hold the payloads.

Each pylon is connected to the wing structure with two fittings; forward and rear. One of these fittings is chosen in the weight reduction campaign. The image of the fitting is shown in Fig 2.

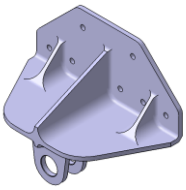

Fig 2. Isometric view of rear pylon fitting to be optimized.

This study, it is aimed to reduce the weight of the pylon fitting carrying the payload in an unmanned aerial vehicle (UAV). The weight reduction campaign is shown in Fig 3 as a flowchart. Qualification studies are not included in this paper; only the steps from analysis to production are explained.

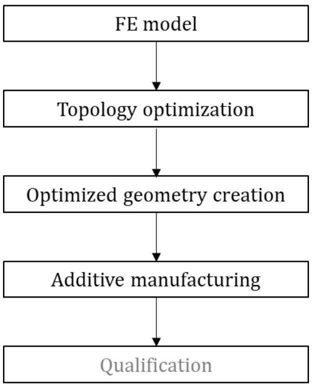

Fig 3. Generic process flow of weight reduction campaign.

2.1. Finite element modeling of the fitting

The first step of the fitting weight reduction campaign is the creation of an accurate FE (Finite Element) model. This model is established according to the flowchart given in Fig 4. In this campaign, a solid model will be used for meshing, assigning properties, and generating boundary conditions. The worst cases of three load cases are applied to the model, and the model is run for quasi-static analysis.

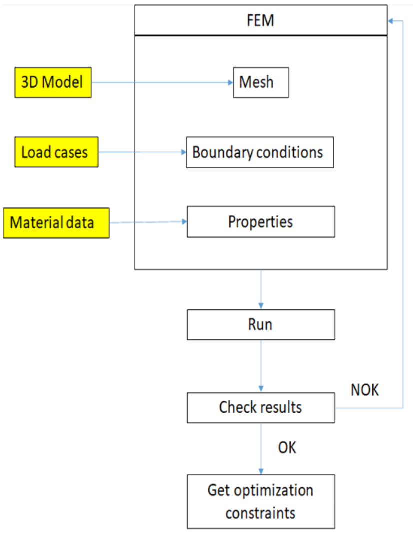

Fig 4. Process flowchart FE model creation.

The fitting material is an aluminum alloy. The material specifications are taken from the Metallic Material Properties Development and Standardization (MMPDS) Handbook. Rice et al. [6]state that the MMPDS Handbook is recognized internationally as a reliable source of aircraft materials data for aerospace materials selection and analysis.

The fitting installation model is presented schematically in Fig 5. The opposite part of the fitting is taken as symmetrical. This is due to the application of loads to the center of gravity.

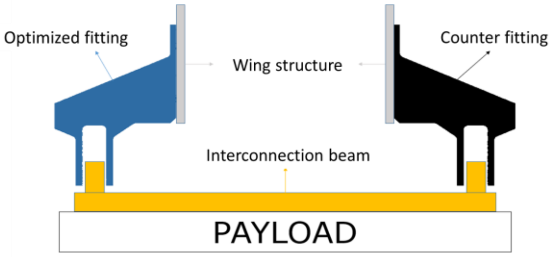

Fig 5. Generic presentation of the simulation.

Loads are evaluated from the global FE model as they are exposing to the center of gravity (CoG) of the interconnection beam and payload. The generic view of the model is shown in Fig 6. Applied forces and moments to the CoGs in 6 DoF are also visualized in the figure.

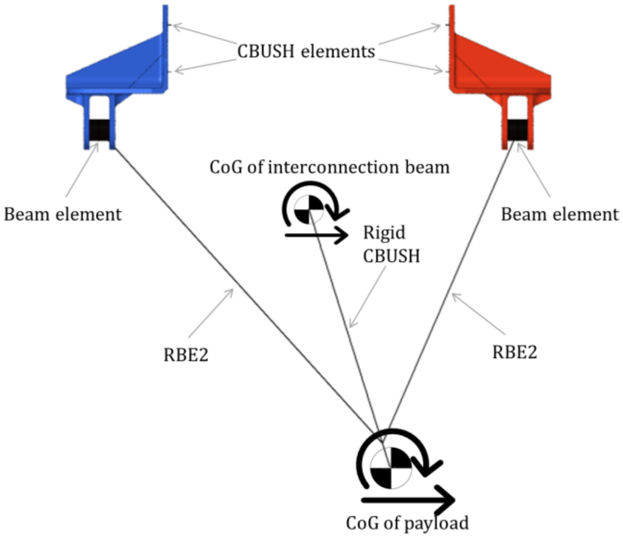

Fig 6 FE model of the fitting.

Interconnection beam each endpoint attachment to the clevis is modeled by a cylindrical steel beam element that fits the lug shown in Fig 6. This beam element is attached to the inner surface of the lug by rigid RBE2 elements.

The fitting is connected to the wing structural walls using bolts. It is necessary to give flexibility to the fasteners for a realistic model. This flexibility can be achieved with CBUSH elements. CBUSH elements model connectors. The connection of the CBUSH elements in Fig 6 to the inner hole surfaces is made by RBE2 rigid elements. CBUSH defines a generalized spring-damper structural element for 6 degrees of freedom (DOF). 6 stiffness values for CBUSH elements must be specified. The shear stiffness is determined by the Huth method; the axial stiffness is calculated by a bar element in axial loading. Other stiffness values are specified based on experience. Stiffness values for aluminum fitting and Ti-6Al-4V fitting mounted on aluminum wing structures are listed in Table 1.

Table 1. CBUSH element stiffness values

Stiffness components	**Aluminum-Aluminum [N/mm]**	**Ti6Al4V-Aluminum [N/mm]**
Axial stiffness, K_1	407 377	931 205
Shear stiffness, $K_{2,3}$	30 583	43 673
Rotational stiffness, $K_{4,5}$	1×10^9	1×10^9
Rotational stiffness, K_6	100	100

2.2. Topology optimization of FEM model

Topology optimization aims to devise the optimum material layout of a structure within a borderline[7]. The topology optimization model is created using the FE model. In the original fitting model, the material is aluminum alloy, but since EBM will manufacture the final fitting, the material properties have been changed to Ti-6Al-4V alloy. On the other hand, some non-design regions must be assigned. In this problem, non-design regions are shown in yellow in Fig 7. Besides, when defining the topology variables at the first step, properties such as symmetry plane, additive manufacturing build direction and overhang angle value can be specified. This value is entered because the overhang angle of the EBM device is 60 degrees. The symmetry plane and build direction are the parameters also entered as topology variables as seen in Fig. 7.

The optimization model is run, and after a few loops, the most suitable design is selected. This selected optimum design does not have a smooth geometry, so it is smoothed and exported as an STL (Standard Triangle Language) file. This STL file is not a surface or solid; it is a mesh of triangles. This mesh data needs to be converted to a solid model for further steps.

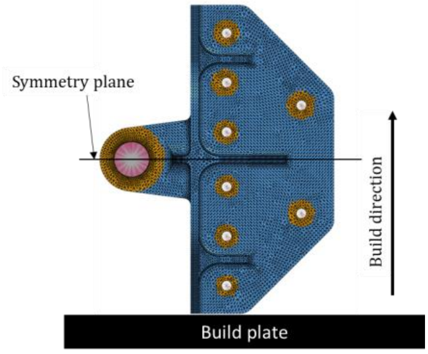

Fig 7. Optimization model including build direction.

2.3. Optimized solid geometry creation

After exporting the STL file of the optimum design obtained after a few optimization loops, this data should be converted to a surface or a solid geometry. The converted geometry will then be used for reanalysis and, if deemed appropriate, will be produced by additive manufacturing. These conversion and analysis steps are summarized in the flowchart in Fig 8.

This flowchart is developed during this weight reduction campaign.

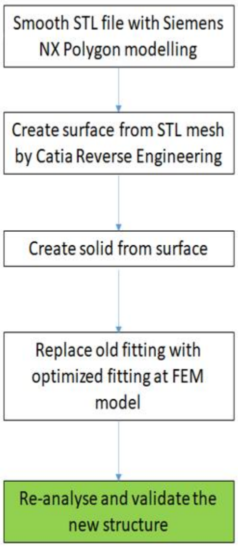

Fig 8. Process flowchart optimized geometry creation.

Next, STL mesh data, which has a dispersed structure, is smoothed using Siemens NX polygon modeling. Then the smoothed mesh data is transferred to the Catia V5 Reverse Engineering module as an STL file again. Then, the mesh data is first converted to a surface, then filled into a solid. Finally, this solid model is replaced with the fitting in the first FE model, and verification re-analysis is performed. Obtained and verified final geometry will be lighter; however, it will have a complex shape. This geometry must be manufactured appropriately.

3. Results and discussion

Constraint values are obtained by running the FE analysis of the original aluminum fitting. The clevis lug endpoint has the maximum displacement on the fitting and is displaced by 0.64 mm.

Values of Von Mises, maximum principal, and minimum principal stresses are retrieved after FE analysis. These values will then be used to determine the constraint values in the optimization step. Maximum Von Mises stress, maximum principal stress, and minimum principal stress were determined as 278 MPa, 298 MPa, and -311 MPa, respectively.

While determining the displacement constraint in the topology optimization, a value close to the displacement value in the original fitting is selected. Excessive displacement of the fitting may damage the counter fitting and/or the aircraft airframe structural part. The optimization model is run several times for different options. Among these options are the build direction and symmetry plane options exist. Finally, after deciding on the appropriate optimal result, the geometry is smoothed and exported as an STL file. Fig 9 shows the exported STL mesh geometry.

Unfortunately, after the optimum result is smoothed and exported, it does not have the desired smoothness. Besides, this STL data is neither a surface nor a solid geometry. This design needs to be converted to solid geometry by further smoothing for subsequent use.

Fig 9. Smoothed and exported STL mesh data.

With the help of Siemens NX polygon modeling and Catia V5 Reverse Engineering, the final optimum design in Fig 10 is obtained. Holes and lugs are replaced from the original geometry for isoparametric design purposes. Although this design is made of the denser Ti-6Al-4V alloy, it is lighter than the original fitting with less density. The weight of the new design is 376 g and a 31% weight reduction has been achieved. The original aluminum fitting is 544 g.

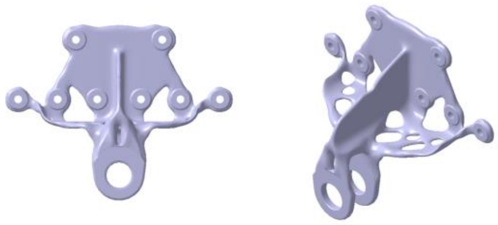

Fig 10. Optimized final solid geometry, front and isometric view.

After the desired solid model is obtained, the analysis is repeated by replacing the original fitting with the optimized fitting to repeat the FEM analysis. As a result of the analysis, the displacement magnitude at the clevis lug endpoint is 0.60 mm and does not exceed the constraint determined as 0.65 mm.

In addition to the displacement, the stress values are also taken from the point where the maximum stress values are retrieved in the original fitting are read. Then these values are checked whether they exceed the constraint values. The original fitting and optimized fitting FEM analysis results are compared in Table 2. Reserve factor (RF) values which are calculated by yield strength/actual stress, are also included in this table. According to these results, the optimized fitting is both lighter and more reliable in terms of quasi-static loads due to higher reserve factors.

After verification with FEM, the optimized fitting is produced with the EBM machine. Fitting is built by melting Ti-6Al-4V powder, which has spherical geometry with 45-106 µm diameter. During manufacturing, the holes are left as 2.5mm pilot holes and will then be enlarged to the final diameter. Offsets are left on some functional surfaces to be machined later. The produced fitting is shown in Fig 11.

In addition, material characterization tests are also carried out for EBM machine manufactured Ti-6Al-4V alloy. These tests are ASTM E8 tensile, ASTM E466 fatigue, and ASTM E238-17a pin-bearing tests. As a result of the tests, tensile properties are better than conventional alloy, while pin-bearing properties are observed to be the same as conventional material. Furthermore, fatigue properties are consistent with the conventional alloy. This test campaign shows that this EBM machine and manufactured Ti-6Al-4V material can be used for manufacturing of the optimized fitting.

Table 2. Comparison of FEM analysis maximum values.

	Original fitting (7050 Aluminum)	RF (yield) Yield/Actual	Optimized fitting (Ti-6Al-4V Titanium)	RF (yield) Yield/Actual
Modulus of elasticity [GPa]	71.01	NA	110.3	NA
Max displacement [mm]	0.64	NA	0.60	NA
Von Mises Stress	278 MPa	**1.58**	334 MPa	**2.60**
Max Principal Stress	298 MPa	**1.48**	345 MPa	**2.51**
Min Principal Stress	-311 MPa	**1.46**	-372 MPa	**2.47**
Weight [g]	544	NA	376	NA

Fig 11. Optimized fitting manufactured by EBM.

4. Conclusions

To increase the operating altitude of a UAV, it is desirable to reduce weight in structural parts. Weight reduction efforts are somehow achieved by converting metallic primary structures into composites. However, it is not possible to convert secondary structures such as fittings into composites. They are generally produced from aluminum alloy and are not galvanically compatible with carbon composite materials. At this point, additive manufacturing and topology optimization provide solutions for the weight reduction of secondary structures. In addition, additive manufacturing of Ti-6Al-4V alloys is galvanically compatible with carbon composites. This study achieved to reduce the weight of a conventional aluminum fitting by 31% using topology optimization of additively manufactured Ti-6Al-4V alloy.

Acknowledgments

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Author’s statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and is performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

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