TOPOLOGY OPTIMIZATION IN ROTORCRAFT APPLICATIONS

Jacek Dudziak, jacek.dudziak@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

Arkadiusz Gawlik, arkadiusz.gawlik@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

Paweł Guła, pawel.gula@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

Marek Tabor, marek.tabor@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

Dawid Ulma, dawid.ulma@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

Rafał Żurawski, rafal.zurawski@ilot.edu.pl, Łukasiewicz Research Network -Institute of Aviation (Poland)

ABSTRACT

To introduce a new design nowadays the engineer has to show, that it provides a significant leap in performance improvement, not only a minor step. This is the reason why new technologies are implemented as those currently used are close to the border of optimization. Among other technologies, which will certainly be widely used in future aerospace, is 3D printing. As parts are expected to be lighter and maintain the same structural strength, the best solution to produce complicated shapes is to print it out. This allows to produce complicated shapes, that can have closed, empty spaces, what provides significant mass reduction. The paper will concentrate on the manner of constructing parts ready for printing with optimization process implemented. A brief description of topology optimization helps to understand the data connections between design and manufacturing. The process of optimization is clarified with respect to construction requirements. Some strategies of optimization and different approaches to designed alike elements are shown. Conclusions present the status of the work and expected future results along with key examples enclosed. All the presented work was based on the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreements No 737955 and No 755483.

1. INTRODUCTION

Modern cities are growing dynamically, which implies the lack of free space for the new infrastructures. This is the reason why helicopters are often the only solution to transport quickly between two direct points. When the distance is not too long, the speed of aircraft do not have such a huge impact on the time of arrival. However, when it comes to travel at longer distances, a classic business jet will be quicker, although it needs airfield to land.

Figure 1. Airbus RACER – design activities by Łukasiewicz Research Network – Institute of Aviation

Airbus proposed a solution of combining vertical take-off and high cruise speed in RACER (RApid and Cost Effective Rotorcraft) demonstrator program, which is successor of X^3 demonstrator. A new construction of RACER is designed from the very beginning to meet the demanding requirements. For every flying object maximum take-off weight is a crucial parameter. In case of compound helicopter, when there are additional elements, such as side nacelles with propellers and mounts, the weight have to rise comparing to standard helicopter configuration. An answer to this challenge is to use new technologies and new materials for newly designed parts. Combining this with new, economical propulsion and careful aerodynamic design, will create a new product which will meet the requirements of maximum horizontal speed and vertical take-off with superb efficiency.

The solution to designing new components, that will be lighter maintaining the same range of structural strength and stiffness, is topology optimization. The scope of this paper is to show the use of this method and some results of its implementation to design process. Łukasiewicz Research Network – Institute of Aviation is involved in the design process as the coordinator of two tasks (fig.1). The first project has an acronym **DREAM** (**D**esign and **R**ealization of equipped **E**ngine comp**A**rtments for a fast co**M**pound rotorcraft) and the second one is **LATTE** (FuL**l** Fairing for M**A**in Ro**T**or Head or the LifeRCraf**T** d**E**monstrator).

2. TOPOLOGY OPTIMIZATION – BACKGROUND

The different optimization strategies can be implemented in order to achieve required design goals. The easiest way is to remove fragments of the designed element and verify after each step whether a part still preserves its function according to the established assumptions. This optimization strategy is called sizing optimization and can be used rather to simple constructions with well-defined regions or subparts. Of course, there are also numerous solutions, that helps to do this task.

Shape optimization is focusing on changing thickness of walls, shapes of cut-outs with the assumption, that outer borders of element are not touched. In this case some algorithms implementing this solution are necessary to obtain optimized shape, because this is much more complicated and not so directly defined, as sizing optimization. Too many possible configurations exist to do this manually for even not complicated parts.

The most universal method of optimization is topology optimization. It can be applied to any shape with given boundary conditions and loads. It is working on the basis of material distribution within limits in order to meet constraints imposed by the designer [1]. Those constraints may affect mass, stiffness, natural frequencies, shape etc. [2], [3]. This optimization method is very flexible and will be widely used in future constructions. It is much more effective in the process of designing with different, often contradictory requirements.

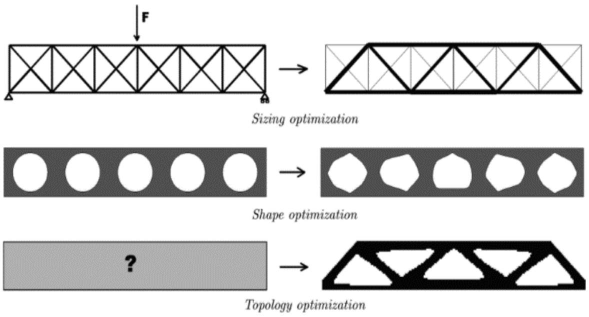


Figure 2. Comparison of different approaches to design optimization [1]

Differences between these approaches are shown on fig.2. Although solutions for sizing and topology optimization are almost the same, the main difference can be seen in the struts shape. As it is shown in this quite simple case, topology optimization algorithm optimized not only the shape of the part, but also the subparts of the structure. An algorithm calculated all the necessary cut-outs and optimized the shape of the struts. The third solution is the most sophisticated and ensures the best requirement fulfilment.

3. WORKFLOW OF OPTIMIZATION PROCESS

The start of the optimization process is very important. Initial model and boundary conditions have to be set up carefully, because every change of initial conditions results in different optimization case (fig. 3)

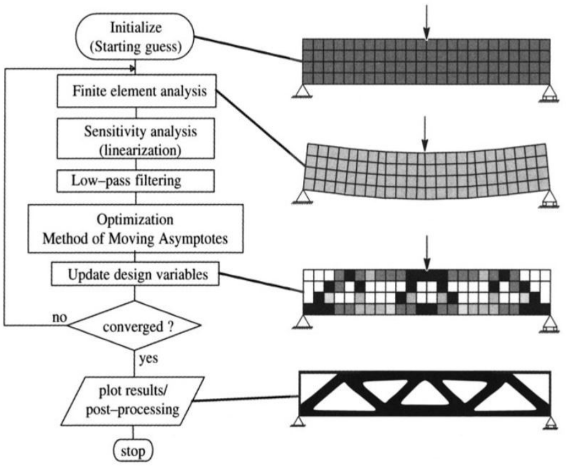


Figure 3. Flowchart of optimization process [1]

Mathematical representation of topology optimization is presented in [4] by equations:

(1) $$\min_{x}: c(x) = U^T K U = \sum_{e=1}^{N} (x_e)^p\, u_e^T k_0 u_e$$

(2) $$\frac{V(x)}{V_0} = f$$

(3) $$KU = F$$

(4) $$0 < x_{min} \leq x \leq 1$$

where **U** is global displacement vector, **F** is global force vector and **K** is global stiffness matrix. $\mathbf{u_e}$ and $\mathbf{k_e}$ are single element displacement vector and stiffness matrix, respectively and **x** is the vector of design variables, where $\mathbf{x_{min}}$ is a vector of minimum relative densities to avoid singularity. **N** is the number of elements used for representation of design space. $\mathbf{V_x}$ and $\mathbf{V_0}$ are calculated new volume and initial design space volume, respectively.

In conclusion, it is mathematically proven, that changing any of the initial values (such as the shape of the optimized body, the material, the applied forces, the number of the elements or the boundary conditions), steps the design back to its beginning and poses the need to recalculate the data. The data needs to be prepared meticulously especially in terms of the initial model, as it determines the quality of the final results. This equation also guides the whole process, as all steps of preparation have to be done in an established order to generate optimized solution.

The workflow starts with the preparation of the initial model. Volume should be adjusted to the outer boundaries and the shape of the part. It will enable to converge and produce optimal result by the algorithm.

Next, so called "protected regions" should be specified. The required minimum comprises regions of applied loads and fixing of the structure. In those regions force distribution and type of mounting have to specified (fig. 4).

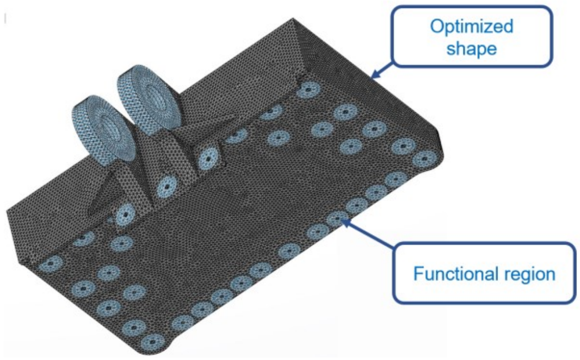


Figure 4. Initial setup for topology optimization

The mesh of the optimized part should be accurate. This means, that big mesh will not allow to perform good optimization. However, if too small mesh will be applied (N is high), necessary calculations will take too much time and obtaining results will not be cost effective. The optimal mesh size, according to experience gained from the past projects, is two to four mesh elements at the smallest part dimension. Such mesh values provide good results in acceptable time of work. When the concept shape closely complies with the requirements, number of grid elements can be increased for final tuning.

Additionally, some other constraints, such as maximum allowed stress level, natural frequencies, shape symmetry etc. can be applied and software can do the optimization job. The result of the optimization should also be validated and carefully checked. The algorithm allows to adjust the volume of the optimized part, so there is no need to calculate result for each volume value. A good presentation of this topic can be found in [5].

4. OPTIMIZATION CHALLENGES

The process of topology optimization consists of several iterations in order to obtain result. Typically, for not complicated cases, the number of iterations is between 60 to 80 and each iteration time depends on the number of nodes and additional conditions. This is the reason not to overload one case with many restrictions, as the algorithm will have to perform much more iterations and result still might not be acceptable. We present some of the problems below.

First challenge is to apply proper mesh size. It can be especially hard to get good balance between number of mesh elements and time of calculation, when in one optimized design there are subregions, that have very different dimensions. In such case it is better to split such element into smaller pieces, and then perform optimization process. Otherwise, the result can be as shown on fig.5. Very small mesh applied to the optimized shape may cause artifacts. It is possible to remove them manually, but in case that there are not to many of them. It is much more effective to start from large mesh and change its quality to see, how the design shape is optimized. Long calculations may not bring satisfactory results and this is essential in terms of the topology optimization method.

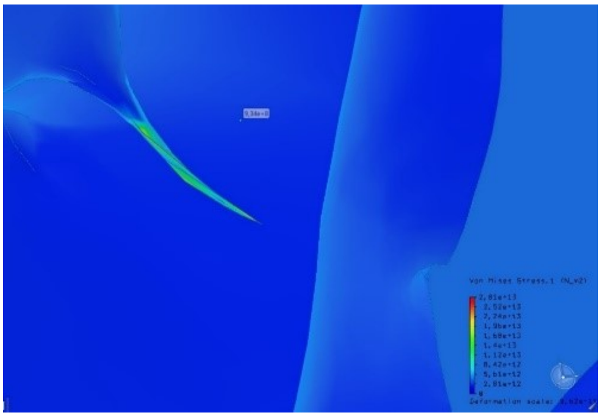
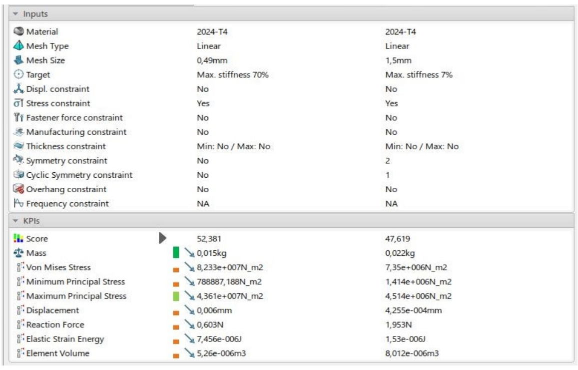


Figure 5. Artifacts produced by too small mesh size application

Furthermore, it is crucial to use additional restrictions carefully. Too many of them applied in the same case always lead to significant rise of time of each iteration. Additionally the number of iterations also grows, as the standard value of 80 do not secure coincidence of optimization case. Solution to this problem is to apply each restriction for starting model, selection of most promising solution and another optimization case for new part. This approach reduces the calculation time and makes the case less complicated (searching the cause of the problem in complex cases may be hard). Also, the whole path of optimization is secured and it is always possible to reanalyse it to find another way to solve the problem.

Configuration management is a very useful tool to handle a variety of configurations. It shows all the necessary parameters, to which some weights can be added in order to easily compare different cases. In this manner, it is much easier to choose the optimal solution and this is done automatically. Fig. 6 illustrates the concept.



Inputs			
Material		2024-T4	2024-T4
Mesh Type		Linear	Linear
Mesh Size		0,49mm	1,5mm
Target		Max. stiffness 70%	Max. stiffness 7%
Displ. constraint		No	No
Stress constraint		Yes	Yes
Fastener force constraint		No	No
Manufacturing constraint		No	No
Thickness constraint		Min: No / Max: No	Min: No / Max: No
Symmetry constraint		No	2
Cyclic Symmetry constraint		No	1
Overhang constraint		No	No
Frequency constraint		NA	NA
KPIs			
Score	▶	52,381	47,619
Mass	🟩 ↘	0,015kg	0,022kg
Von Mises Stress	🟧 ↘	8,233e+007N_m2	7,35e+006N_m2
Minimum Principal Stress	🟧 ↘	788887,188N_m2	1,414e+006N_m2
Maximum Principal Stress	🟩 ↘	4,361e+007N_m2	4,514e+006N_m2
Displacement	🟧 ↘	0,006mm	4,255e-004mm
Reaction Force	🟧 ↘	0,603N	1,953N
Elastic Strain Energy	🟧 ↘	7,456e-006J	1,53e-006J
Element Volume	🟧 ↘	5,26e-006m3	8,012e-006m3

Figure 6. Configuration management tool

5. OPTIMIZATION RESULTS DISCUSSION

For optimization process two types of joints and hinges were selected. All settings of optimization process were selected according to previous chapters guidelines. As main criteria of activity, maximise stiffness solution was chosen with maximum mass reduction.

- first case – rotor fairings support

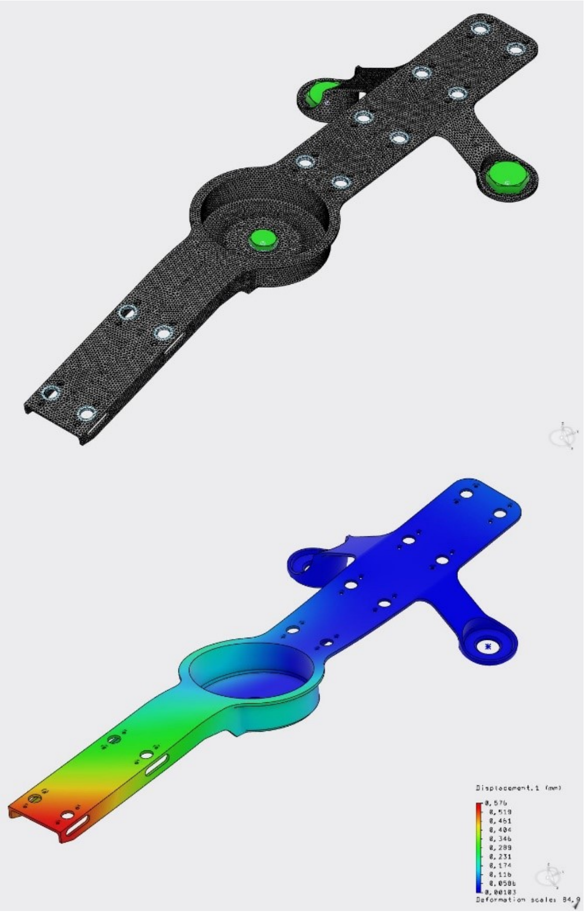
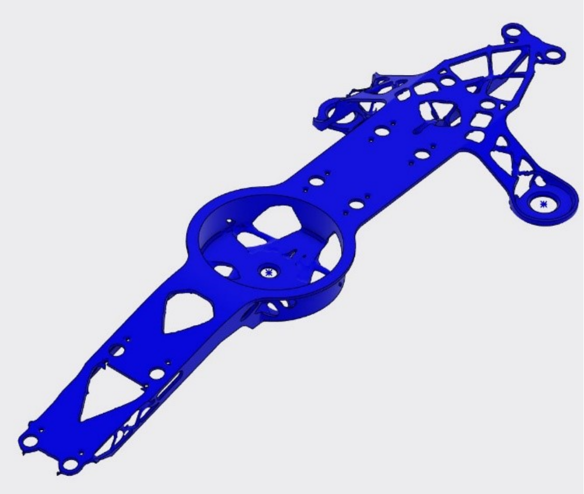


Figure 7. Initial model and displacement analysis



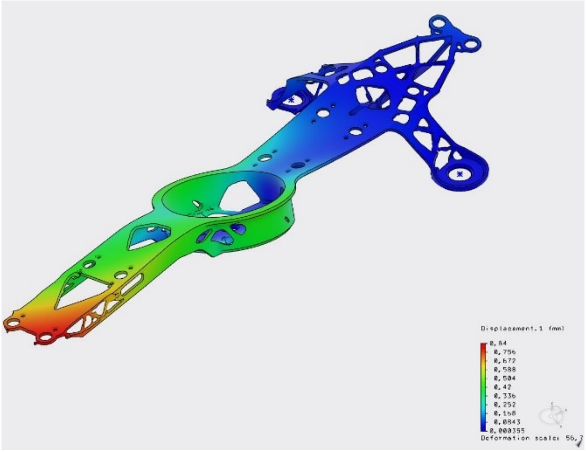


Figure 8. Optimized model and displacement analysis

In fig. 7 and 8 it is shown, that optimized solutions' deformation is greater of 31% - from 0,576 [mm] to 0,84 [mm]. Respectively, the mass of the element decreased also by about 30% from 0,270 [kg] to 0,188 [kg].

- second case – rotor fairing main support

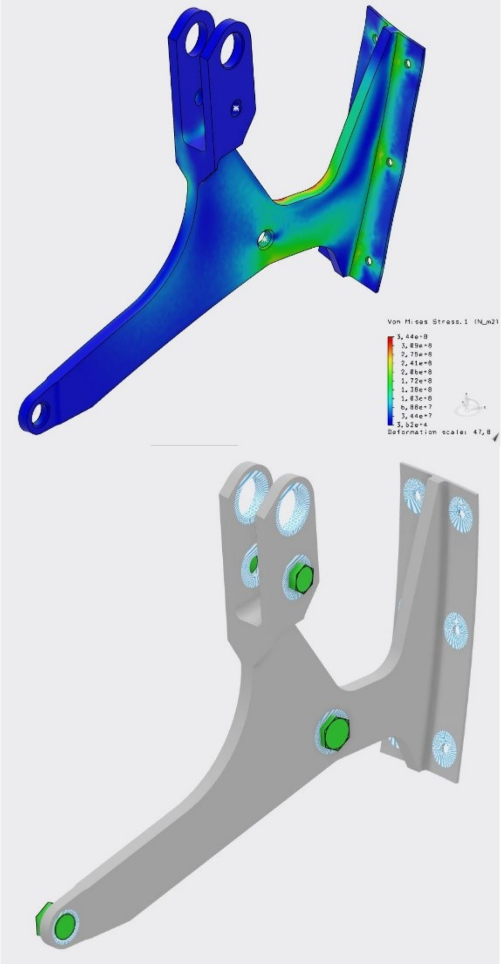


Figure 9. Initial model and stress analysis

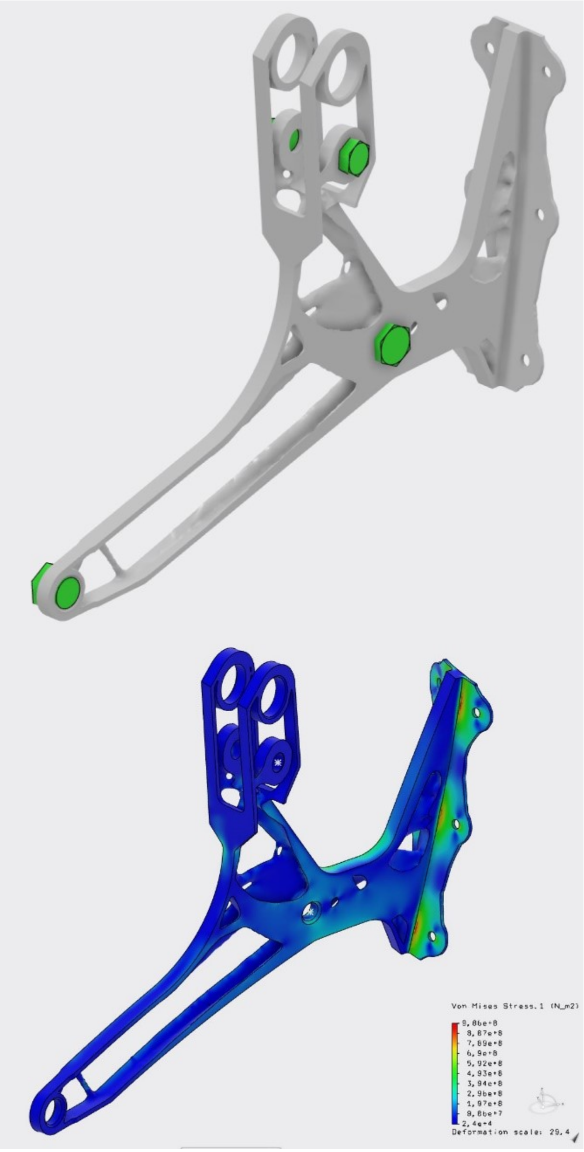
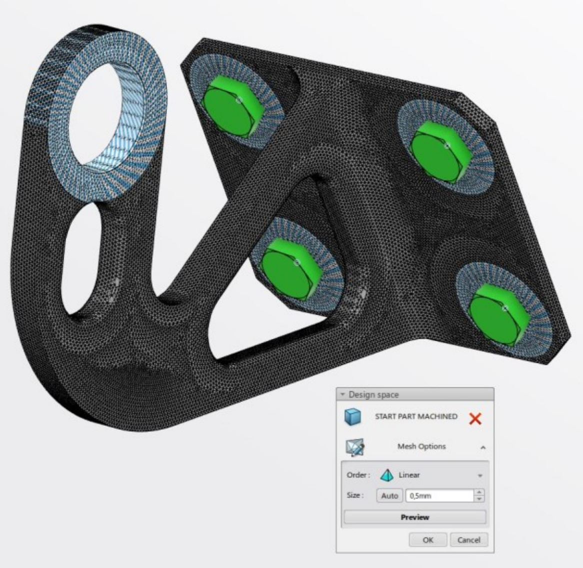


Figure 10. Optimized model and stress analysis

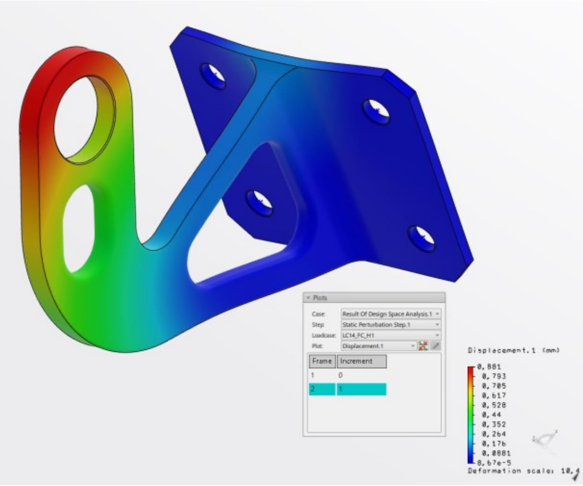
Fig. 9 and 10 show, that optimized solutions' maximum stress increases by factor 2,87 - from 344 [MPa] to 986 [MPa]. Respectively, the mass of the element drops down by approximately 50% - from 0,776 [kg] to 0,386 [kg].

- third case – cowlings hinge



Order : Linear
Size : Auto 0,5mm

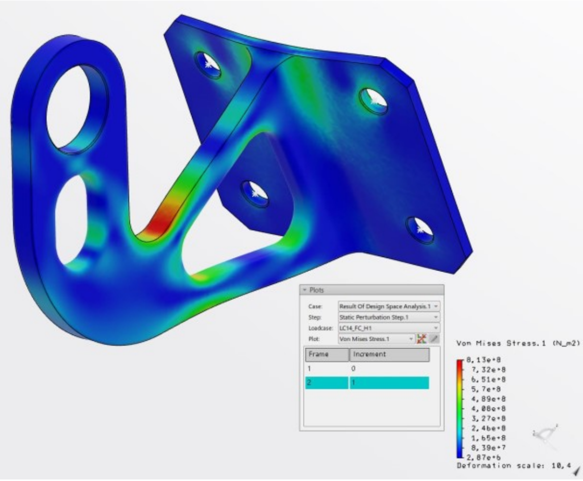
Figure 11. Hinge model - grid



Case: Result Of Design Space Analysis.1
Step: Static Perturbation Step.1
Loadcase: LC14_FC_H1
Plot: Displacement.1

Frame	Increment
1	0
2	1

Figure 12. Hinge model – displacement



Case: Result Of Design Space Analysis.1
Step: Static Perturbation Step.1
Loadcase: LC14_FC_H1
Plot: Von Mises Stress.1

Frame	Increment
1	0
2	1

Figure 13. Hinge model - stress

Third case shows cowlings hinge, that was initially filled. Analysis showed, that it can be produced in a conventional way.

6. CONCLUSIONS

Mass reduction for every new design aircraft is crucial in order to achieve gain of performance. There are many solutions to fulfil this task, but only significant reduction by using new materials and techniques guaranties success. In this paper it is shown, that topology optimization can give useful results, that can be applied directly to flying constructions. Parts designed in this technology will by widely used in the near future. To do this, hard work is needed in the area of statical and dynamical performance of such parts, as to go to the next level, 3D printing technology needs to be widespread. Material properties for calculations can be found in [6] [7] or [8].

We proposed standard solution of manufacture optimized parts, because conservative approach is safer, especially for demonstrator design. There are regulations concerning additive manufacturing [9], but this is beyond the scope of this paper, as such solution will currently be not accepted by aviation authorities.

ACKNOWLEDGEMENTS

This work was based on DREAM and LATTE projects.

This projects received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 737955 and No 755483.

Copyright Statement

REFERENCES

[1] Bendsoe MP, Sigmund O. Topology Optimization: Theory, Methods, and Applications. Springer Science & Business Media; 2003.

[2] Rindi A, Meli E, Boccini E, Iurisci G, Corbò S, Falomi S. Static and Modal Topology Optimization of Turbomachinery Components. J Eng Gas Turbines Power 2016;138:112602-112602–9. doi:10.1115/1.4033512.

[3] Picelli R, Townsend S, Brampton C, Norato J, Kim HA. Stress-based shape and topology optimization with the level set method. Computer Methods in Applied Mechanics and Engineering 2018;329:1–23. doi:10.1016/j.cma.2017.09.001.

[4] Sigmund O. A 99 line topology optimization code written in Matlab. Structural and Multidisciplinary Optimization 2001;21:120–7. doi:10.1007/s001580050176.

[5] Larsson R. Methodology for Topology and Shape Optimization: Application to a Rear Lower Control Arm. Master's thesis in Applied Mechanics. CHALMERS UNIVERSITY OF TECHNOLOGY, 2016.

[6] Michaels S, Sachs EM, Cima MJ. Metal parts generation by three dimensional printing. 1992 International Solid Freeform Fabrication Symposium, 1992.

[7] Alcisto J, Enriquez A, Garcia H, Hinkson S, Steelman T, Silverman E, et al. Tensile Properties and Microstructures of Laser-Formed Ti-6Al-4V. J of Materi Eng and Perform 2011;20:203–12. doi:10.1007/s11665-010-9670-9.

[8] Lewandowski JJ, Seifi M. Metal Additive Manufacturing: A Review of Mechanical Properties. Annual Review of Materials Research 2016;46:151–86. doi:10.1146/annurev-matsci-070115-032024.

[9] F42 Committee. Guidelines for Design for Additive Manufacturing. ASTM International; n.d. doi:10.1520/F3154-18.