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Topological optimization design for additive manufacturing, taking into account flexion and vibrations during machining post processing operations.

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Abstract

This article focuses on including into the topological optimization method, all the mechanical stresses applied during the part lifetime and especially during machining phase. Thus, in addition to the part technical specifications, we consider static and vibratory forces during machining, and also forces during mounting and unmounting in the machine tool and then in the aircraft. Results show that taking into account handling and machining forces, static and vibratory, strongly impact topological optimization, thus shapes and weight, and should be considered during the early stage of the design in order to optimize the additive manufactured parts costs.

1. Introduction

For more than 20 years additive manufacturing has been used for prototyping in research and development. Nowadays the aeronautic industry is able to 3D print functional parts at production scale especially using SLM (Selective Laser Melting) technology, but mostly exclusively for high cost parts. [1] Additive manufacturing allows engineers to create very innovative designs but machining post processing operations are quite always necessary, and these parts are often very difficult to machine with conventional turning and milling processes, increasing final cost. Using Design for Additive Manufacturing (DFAM) methods, such as topological optimization, engineers should be able to design the best possible part in order to comply technical specifications and to minimize production and post-production complexity due to low rigidity parts. The cost of additive manufactured parts is very strongly related to the size and the material used, but it is quite independent of the shape complexity. Machining may represent up to 50 % of part final cost, and sometimes simply reveals to be impossible without part redesign. This article focuses on including into the topological optimization method, all the mechanical stresses applied during the part lifetime and especially during machining phase. We consider here static and vibratory forces during machining, and also forces during mounting and unmounting in the machine tool and then in the aircraft itself. To have a better view of this design approach, we will illustrate it through a given aeronautical part.

2. Literature review

The main goal of this article is not to create a new DFAM method but to incorporate new parameters. The current DFAM method considered is described by an algorithm, proposed by Louvigny, Meunier, Nzisabira, Duysinx [2], [3].

In 2001, Sigmund [4], has written a very famous article named “a 99 lines topology optimization code written in Matlab”. This article is well known to very clearly describe a topology optimization algorithm. Different approaches are possible to solve such an optimization problem, the first one is the homogenization based approach presented by Bendsøe and Kikuchi [5]. In the article provided by Sigmund, the topology optimization approach is called “power-law approach” or SIMP (Solid Isotropic Material with Penalization, Bendsøe & Sigmund [6]). In this approach material properties are linear, isotropic and constants but the relative material densities are variable along the structure.

The most important part of this previous article was the explanation of a quite simple algorithm (99 lines of Matlab, including comments), able to process a 2D multi load topological optimization. The objective function to be minimized is $e(x)$, with \mathbf{U} the global displacement and \mathbf{K} the global stiffness matrix, from FEM method:

$$\text{Multi load topology optimization objective function: } e(x) = \sum_{i=1}^n U_i^T K U_i \quad [1]$$

The last part of this literature review is about different theories about cutting forces in milling and turning [7]. For turning, the well-known Oxley theory [8] incorporates several physical phenomena which allows numerical models to be pretty accurate. It takes into account the dynamic strain hardening, primary, secondary, and tertiary shear zone. This theory allows to estimate deformations speed and temperature from cutting conditions and tool engagement. It can predict the cutting forces but many parameters have to be measured, and most of the time these parameters are not available, and not easy to measure. For milling, Merchant theory [9], [14] is more used because it is much simple to use. For better precision and because of the complexity milling tools geometry, Budak theory [10], Engin [11] and Milfener theory [12] are useful but need some experimental cutting forces tests in order to obtain integrated cutting force coefficient.

3. Method and calculations

As said previously, we will use the classic DFAM method background. In machining subcontractor context, it is usually difficult to really know the space available for redesigning the part. The considered part is a 2 ways connecting Ti6Al4V bloc for aeronautical applications as shown in figure 1. The initial shape, which can be obviously optimized, will be considered as the available space for redesigning the part.

The part is used to connect hydraulic hoses which carry some oils to operate some airplane components, as flaps. So, as shown in figure 2, the component includes 4 hydraulic couplings (2x G4 coupling and 2x G5 coupling corresponding at their diameter) and two ducts. With the 3 lugs, all these regions represent functional surface which defines volumes that are not available for topological optimization.

We used the Abaqus software, according to the following parameters: Young modulus: 110 000 MPa, Poisson's coefficient: 0.31, load pressure on the interior ducts walls: 31 MPa, clamp on the 3 fixtures zones, on threads diameters.

Before performing topological optimization, we have to design the ducts shape, which cannot be designed by the optimization software used, and we choose also to pre-design also the thickness of the ducts. We used FEM calculation with Abaqus to validate the thickness. The chosen design is a simple cylindrical shape, with the same diameter as the initial design and with the maximum radius possible in order to reduce pressure drop. The pressure drop comparison between the initial and the new design can be analytically computed as shown below:

$$\text{Regular pressure drop equation: } \delta p_{reg} = \lambda * \frac{L}{D} * \rho \frac{V^2}{2} \quad [2]$$

$$\text{Singular pressure drop equation: } \delta p_{sing} = \xi * \rho \frac{V^2}{2} \quad [3]$$

With λ the friction coefficient (according to Moody diagram), L the pipe length, " D " the pipe diameter, " ρ " the fluid density, " V " the flow velocity and ξ a pressure drop coefficient (using Abaqus shells elements according to elbow geometry). Using these calculations, the proposed new geometry allows to reduce about 75% of the pressure drop.

The next step of the DFAM method is to define the optimizable volumes. We excluded the volumes associated to the functional surfaces, following the rules proposed by R. Ponche, et al, in 2013 [13].

$$\text{Thickness equation for minimum machining thickness: } E \geq t + \frac{a}{2} + e_{min} \quad [4]$$

$$\text{Thickness equation for maximum machining thickness: } E \leq t + \frac{a}{2} + e_{max} \quad [5]$$

Where p is the tolerance linked to the functional area, a the spatial precision of the additive manufacturing process, E the thickness, t the minimal thickness corresponding at the local mechanical tolerances, e_{min} and e_{max} are respectively the minimal and maximal allowances which are linked to the post additive manufacturing process and the functional area geometry

As the initial part will be machined, in order to reduce the cost, we have considered that a short-term solution is to use the machining program already created for the initial forged part. We would adapt, then simply delete all the non-useful machining paths. The different machining steps are here: Outside blank contouring of couplings, outside finish contouring of couplings, outside edge chamfering, outside threading plus a vacuum pass, inside shapes implanting using shaped drills, outside surface finishing.

Considering only the needed machining phase for the new design, we are able to estimate all cutting forces applied on the part. We have considered experimental static cutting forces available in our laboratory, for Ti6Al4V forged part machining, leading in our case to maximum radial forces roughly evaluated to 2000N during threading. However, the cutting forces are not the only major forces applied on the part during its life time. Indeed, we took into account, what we called, manipulation forces (see Table 1).

| Load | Type | Value | Surfaces |
|-----------------------------|--------------|---------------|------------------------------|
| Pressure | Universal | 31 MPa | On internal ducts walls |
| End caps fixation | Universal | U1, U2, U3 =0 | At end caps |
| Over torque on coupling | Manipulation | 100 N.m | Axe of coupling (UR2 or UR3) |
| Pull-out forces on end taps | Manipulation | 200 N | Axe of coupling (U2 or U3) |
| Compression forces | Manipulation | 500 N | Y axe of the ducts elbow |

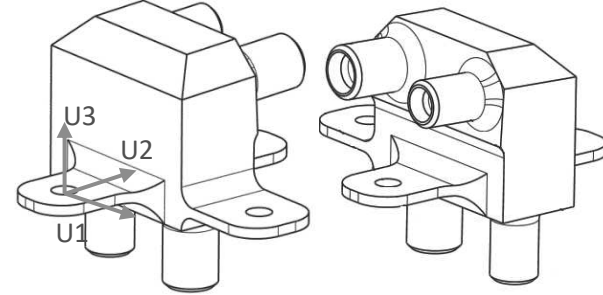
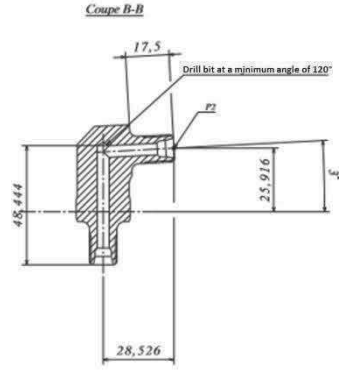


Figure 1: Original part scheme

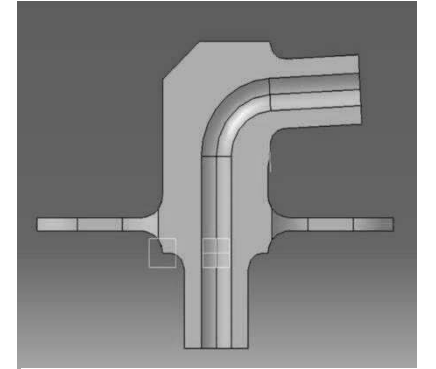


Figure 2: New ducts geometry in the redesign part

| | | | |
|-----------------------------|--------------|--------|--|
| Pull-out forces on the part | Manipulation | 300 N | F_x (U1); $F(\cos 45, 0, \sin 45)$; F_z (U3); $F(\sin 45, 0, \cos 45)$ on the ducts elbow |
| Accelerations / Shocks | Manipulation | 50 G | At the gravity centre in the direction U1, U2, U3 |
| Machining forces | Machining | 2000 N | End of the ducts end caps on (+/-) U1, U2 and U3 |

Table 1: Table summarizing forces on the numerical model

We have initially considered 32 load case scenarios. In order to simplify the calculation and to detect which scenario are really important for the optimal shape, we have reduced the number of load cases, keeping the most influent.

Because of the specifications and the aeronautical background, we used mass minimization to obtain the lightest possible component. Another part of the specifications had to be taken into account, the part shall not vibrate too much during machining and during its life time in a plane. Inspire® software is able to consider vibrations but only for maximizing frequency natural modes, with various options. We decided only to impose that to the first mode because all vibratory tests on a plane are below 2500 Hz

4. Results

The optimized geometry obtained after topological optimization is illustrated figure 10. The optimisation goal is to minimize the mass with a limit yield stress value of 1100 MPa, considering the 17 non-insignificant load cases. The result obtained is 65 % mass reduction, i.e. the original part mass is 210 grams. and the optimised one is 74.5 grams.

The displacements and stress obtained are given on table 2.

| | Value | Unity |
|-------------------------|----------|-------|
| Maximum displacement | 7.02E-04 | m |
| Re max | 81,5 | % |
| Maximum traction stress | 8.17E+08 | Pa |
| Maximum traction stress | 8.97E+08 | Pa |
| Maximum shear stress | 5.17E+08 | Pa |
| Von Mises stress | 8.97E+08 | Pa |

Table 2: Table of static calculation results

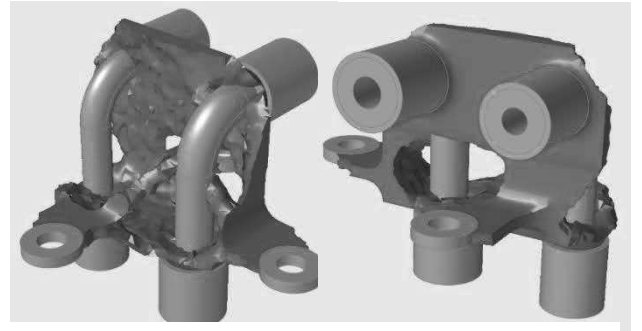


Figure 3: Topology optimization calculation result

In order to have a good surface quality of the functional surfaces, according to the definition drawing, flexion and vibrations during machining must be limited. Maximum displacement during machining static force is significant: 0.7 mm max, normally to the machined surface. Reducing this flexion would involve more materials to build the part, but this material would be needed only during machining. To avoid this, it is possible to build a specific workpiece-holder in order to stiffen the piece during machining, or to remove this additional material at the end of machining. Such solutions will be presented in a next paper. A comparison is presented in table 3, to compare the effect of such loads on the mains 3 load cases, the final design.

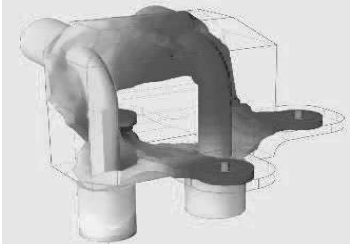
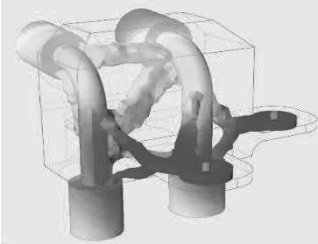
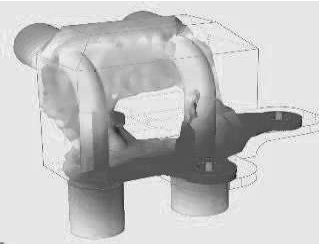
| | Only functional loads and manipulation loads | Only functional loads and machining loads | All loads taken into accounts |
|--------------------|---|--|---|
| Mass gain | 67.08% | 71.37% | 64.31% |
| Displacements (mm) | 0.698 | 0.897 | 0.795 |
| Illustrations |  |  |  |

Table 3: Table summarizing mass gain in term of load cases types

In this case, both cutting forces and manipulation forces generate significant mass increase and significant displacements and. Machining forces are significant, but what fears most the machinist for such workpieces is chatter, i.e. machining vibrations. Topological software such as Inspire®, allow calculation and optimization of natural frequencies. We have considered that to avoid resonance, the natural frequency should be above a given value, linked to the machining process used. The first natural frequency of the optimized geometry is 2514 Hz. Various frequency excitation is applied on the workpiece during his life time, especially

during machining and during flight. To calculate the frequencies caused by machining phases we used equation [6], which takes into account, the nominal rotation speed of the machining spindle “S” and the number of teeth on the tool “Z”.

$$f_m = \frac{S}{60} * Z \quad [6]$$

127,33Hz*3≈0,4 kHz is the maximal frequency excitation during machining, and considering more harmonics of the cutting frequency would not be a problem. For turbo engines, the aeronautical standard DO-160 stipulates that the highest frequency to be considered is 2500 Hz. As the first natural frequency of the optimized geometry is already 2514 Hz, so we didn't have in this case to optimize the design for the frequency criteria of machining chatter.

5. Conclusion and perspectives

An industrial titanium hydraulic coupling has been considered for topological optimization. Various load cases have been considered, such as oil pressure, mounting/unmounting forces and cutting forces, as static forces and as frequency excitations. The main results of this study can be resumed as:

- It is possible and necessary to include in DFAM (Design for Additive Manufacturing) many load cases applied during the life time of the workpiece, as forces and as frequencies.
- In this case, only 2 load cases among 32, have strong impact on the design (i.e. mounting/unmounting torques applied on the exterior edge of the hydraulic end caps on hooses, and cutting forces), but it is difficult to know that by advance and it is necessary to integrate at first many load cases.

Another paper will follow this one and the research perspectives for it are:

- Compare the topological optimisation algorithm between Abaqus Tosca® and Inspire®, in order to find which one is the more suitable to process the best design regarding to the specs.
- In this paper, the machining strategy is based on the program for the subtractive manufacturing part, the goal of the next one will be to adapt the machining program to prevent too much loads and stresses during the post processing operations and so to increase mass gain.
- The last perspectives will be the integration of lattices structures in the DFAM.

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