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Procedia CIRP 60 (2017) 32 – 37

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27th CIRP Design 2017

Optimization of machining fixture for aeronautical thin-walled components

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Abstract

The aim of this work has been the optimization of the fixtures performance used in thin-walled workpiece machining depending on the local rigidity characteristics of the component to be machined. An extensive topology optimization activity has been performed both on fixture-workpiece systems modelled with shell elements and on fixture-workpiece systems modelled with solid elements, varying the topology design variables and/or optimization constraints for each optimization problem, in order to provide a new design of fixture. Finally, a new blended Solid-Lattice design of the fixture, starting by the design topologically optimized, has been created. In this way, it has been possible to identify void regions in the design space, where the material can be removed, regions where solid material is needed, and regions where lattice structure is required. This has allowed to generate the optimal hybrid or blended solid-lattice design based on desired functionality of the part having as natural consequence the definition of a new method for fixtures design.

Keywords: Topology Optimization, Thin-walled aeronautical structures, Fixtures.

1. Introduction

Fixtures and clamping devices are an essential part of machining systems for material removal processes. But their importance is often neglected or underestimated during the layout of manufacturing machinery and processing solutions. The relevance of fixtures regarding productivity, efficiency and quality is mostly not considered properly, e.g. with respect to the planning of production systems and related costs. Main tasks of fixtures and clamping systems are [1], [2]:

- to define the location (position and orientation) of a clamped workpiece in the workspace of the machine tool
- to maintain this defined location even under the influence of static and dynamic mechanical and thermal loads
- and to guide these loads as an integral element of the machine structure inside the force flux.

The accuracy, performance and reliability of a clamping scenario involving workpiece and fixture depends on the number, distribution and configuration of clamping devices and contact points including support pins or referencing elements. The layout of a fixture and the arrangement of clamps is a challenging task which can be accomplished by means of computer aided methods [3]-[5]. Since fixtures are part of the accuracy path of the machining system, their tolerances affect the quality of the processing result [6]-[8]. Fixture design can be supported by numerical calculation and simulation [9]-[11]. An essential aspect is the avoidance of workpiece deformations which can be caused by the clamping system itself [12]. The process-workpiece-fixture interaction has to be considered in assessing the performance of the fixture and to estimate the influence of a fixture layout on the machining process [13]-[15]. Modelling of the process-workpiece-fixture system allows the implementation of optimization strategies for attaining a suitable fixture layout.

A significant number of studies therefore aim in automated fixture configuration systems. However, fixture design is dominated by the experience and knowledge of the designing engineer [16]. In the present paper several topology

doi:10.1016/j.procir.2017.02.008

optimization problems have been performed in order to create a new fixture design such that the stiffness of the structure is maximized. The component examined has been a part of an aircraft engine: Low Pressure Turbine Casing (LPT).

Considering the results obtained with topology optimization, three preliminary case studies of blended Solid-Lattice structures have been implemented. A linear static analysis has been carried out in order to evaluate the stiffness of each proposed fixture.

2. Topology optimization

The aim of the present work has been to define a new methodology to design the machining fixture that allows to take in account of the following aspects:

- Workpiece local stiffness variation: the machined components have thin walls, non-constant sections and large diameters;
- Cutting forces: the equipment must be able to stiffen the workpiece during machining process;
- Avoid the traditional trial & error approach.

Design methodologies for fixtures can be regarded as an ongoing topic, in fact, currently, fixture design is based on the experience and knowledge of the designer**,** then, the final fixture design is the result of a trial & error process.

The workpieces are effectively “thin walled structure” because they can be described as: truncated cone shape, large diameters and thin walls. Those are a typical geometric features of low pressure turbine casings which are the part of interest in the developed activity. For confidentiality reasons, it cannot be possible to indicate further information about it. In any case, the average thickness is of few millimetres.

The vibration problems for the fixture of the thin walled components are typically solved by means the introduction of some damping systems (hydraulic actuators and rubber strips) in order to dissipate vibration energy and to damp the part during the working phase. For these reasons the aim of this paper has been to study and define, through the new defined methodology, a solution characterized of an optimal mass distribution taking into account the operative conditions (such as cutting forces) and local workpiece stiffness.

Different topology optimization problems have been performed both on fixture-workpiece systems modelled with shell elements (2D) and, on fixture-workpiece systems modelled with solid elements (3D), varying the topology design variables and/or optimization constraints for each optimization problem. The purpose has been to redistribute a given amount of material in a design domain, such that the stiffness of the structure is maximized. A simplified assumption has been to consider only a quarter of fixture-workpiece system modelling with solid elements for computing reasons. For the numerical simulations have been used OptiStruct® of HyperWorks suite. For all topology optimizations a manufacturing constrain, minimum member size, has been used. It controls the smallest dimension to be retained in topology design, as well as minimizing the checker board effect caused by the mesh and giving a more discrete design.

The solver calculates an equivalent density for each element, where 1 is equivalent to 100% material, while 0 is equivalent to no material in element (voids).

The solver then seeks to assign elements that have a low stress value a lower equivalent density before analyzing the effect on the remaining structure. In this way extraneous elements tend towards a density of 0, with the optimum design tending towards 1.

2.1. Case studies of 2D topology optimization

As mentioned above, topology optimization has been performed on fixture-workpiece system modelled with shell elements (thickness 1 mm). The structural model with applied loads, constrains and optimization constrains, for three case studies are shown in Fig. 1.

The objective has been to minimize the weighted compliance. 2D topology optimization has been performed to find preliminary the optimal material placement and reduce the mass of fixture.

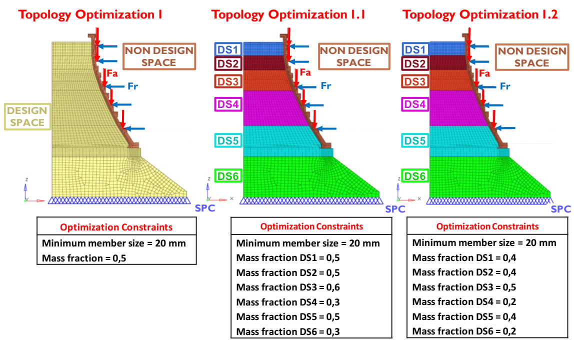

Fig. 1. 2D FE Model and optimization constraints

Fig. 2 shows element density contour plot of final iteration of 2D topology optimization and for assigned element densities for the three studied cases. Element densities equal to 1 refer to structurally important elements and density value close to 0 indicate voids.

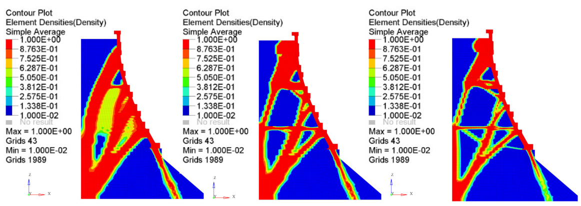

Fig. 2. Element density of 2D topology optimization

These results allow to understand what preliminary could be the “effect” of a topology optimization applied to fixture-workpiece system modelled with solid elements.

2.2. Case studies of 3D topology optimization

As mentioned above, a topology optimization has been performed on fixture-workpiece system modelled with solid elements. In order to reduce the time calculation and the memory required, only a quarter model has been considered.

The mass of only a quarter fixture model is equal to 5294 kg. The objective has been to minimize the weighted compliance. Topology optimization has been performed to find the optimal material distribution and to maximize the stiffness. Five different model with different topology optimization set up have been studied. The two first structural model with loads and applied constrains are shown in Fig. 3.

In this case, the loads (vertical and radial forces) have been applied on 15 nodes of the working component and the bolt holes are constrained (all degree of freedom are fixed).

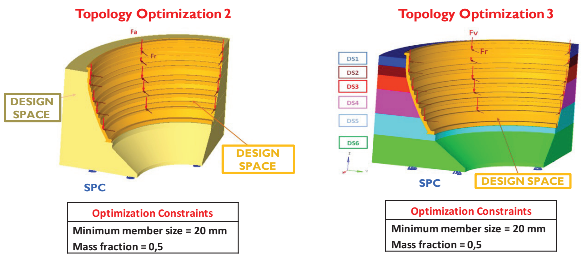

Fig. 3. 3D FE Model and optimization constraints for TO2 and TO3 models

As shown in Fig. 3, for the first model (TO2) a single design space has been defined, while, for the second model (TO3) six design spaces have been considered. For this last case, the aim has been to understand what happens when:

- DS1 is the only design space;
- The remaining five sectors DS2 - DS6 are not design spaces.

The optimizer generates a new design for DS1. Subsequently:

- The new optimized structure is meshed;
- DS2 is the only design spaces;
- The remaining five sectors are not design spaces.

The optimizer will generate a new design for DS2. The same procedure has been repeated to obtain a new design for each individual space (Fig. 4).

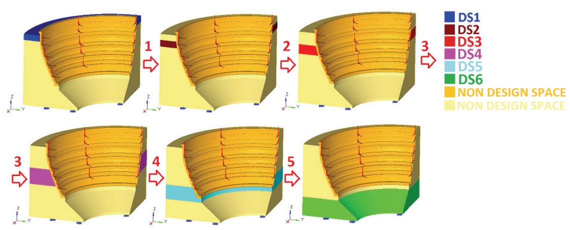

Fig. 4. Definition of Design Space for TO2 model

Fig. 5 shows element density distribution of the two models TO2 and TO3.

Among the various solution proposed TO3 is the least feasible because this exploratory procedure give a design which cannot be manufactured.

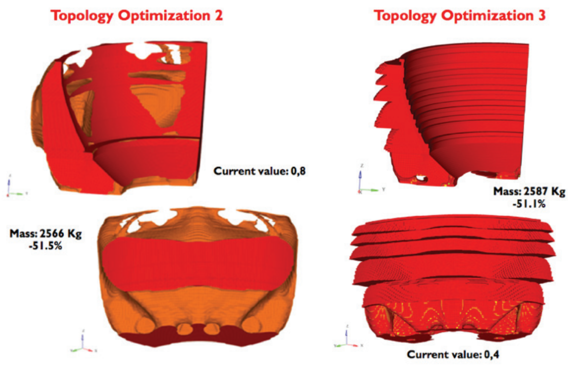

Fig. 5. Element density distribution of 3D topology optimization for TO2 and TO3 models

Among the various solution proposed TO3 is the least feasible because this exploratory procedure give a design which cannot be manufactured.

Fig. 6 shows the structural model of Topology Optimization 4 (TO4) with loads and applied constrains. In this topology optimization problem, the loads are distributed on 5 rows of nodes along z-axis. This case study provides two step (Fig. 6):

- Step 1: Topology optimization of the only DS1 space;
- Step 2: Topology optimization of the only DS2 space.

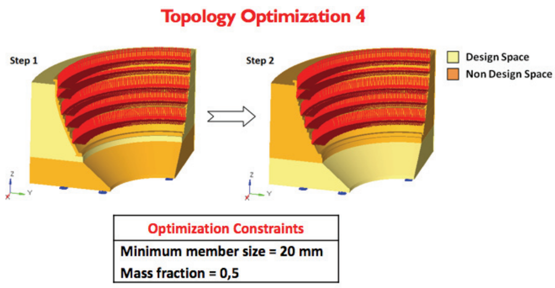

Fig. 6. 3D FE Model with Design Space definition and optimization constraints for TO4 model

Fig. 7 shows the element density distribution of TO4 final design characterized of a mass reduction equal to 51.5%.

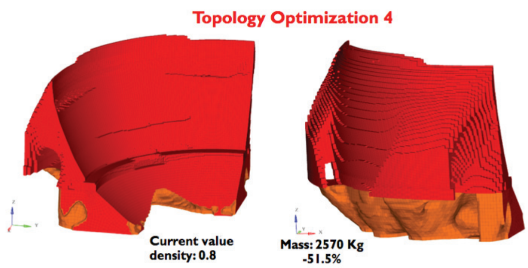

Fig. 7. Element density distribution of 3D topology optimization for TO4 final design

Fig. 8 shows the boundary conditions, loads and constrains of topology optimization problem 4.1 (TO4.1), that are the same as previous case but, change the design space and relative constraints in term of mass fraction response. Six design space have been defined, optimized simultaneously but, for each design spaces different constraint value, in term of mass fraction responses, have been defined.

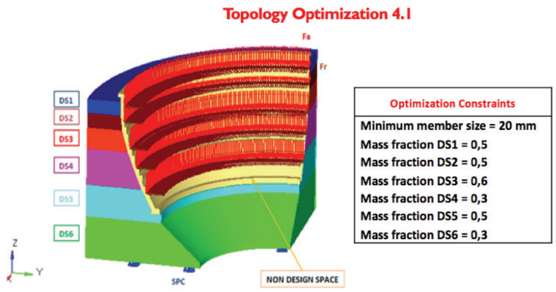

Fig. 8. 3D FE Model with Design Space definition and optimization constraints for TO4.1 model

Fig. 9 shows the element density distribution of TO4.1 final design characterized of a mass reduction equal to 63.7% and with element density value greater than 0.7.

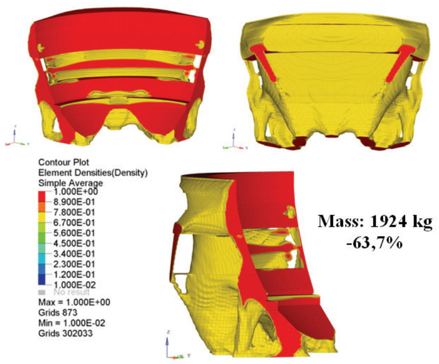

Fig. 9. Element density distribution of 3D topology optimization for TO4.1 final design with element density value greater than 0.7

Finally, Fig. 10 shows the boundary conditions, loads and constrains of topology optimization problem 4.2 (TO4.2), that are the same as previous case but, change optimization constraints in term of mass fraction response. Six design space have been defined, optimized simultaneously but, for each design spaces different constraint value, in term of mass fraction responses, have been defined.

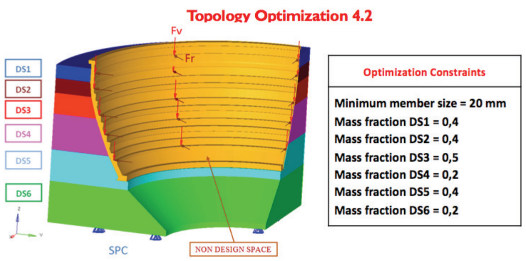

Fig. 10. 3D FE Model with Design Space definition and optimization constraints for TO4.2 model

Fig. 11 shows the element density distribution of TO4.2 final design characterized of a mass reduction equal to 71.5% and with element density value greater than 0.8.

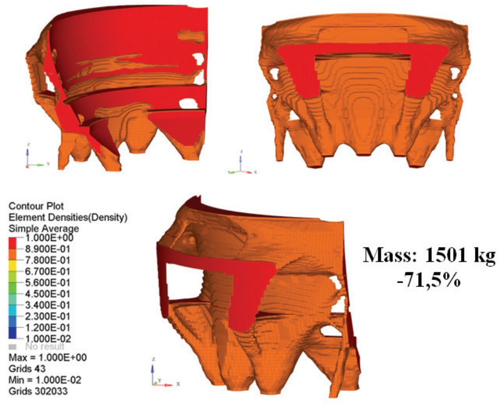

Fig. 11. Element density distribution of 3D topology optimization for TO4.2 final design with element density value greater than 0.8

2.3. Comparison results

For each solution proposed, Table 1 shows the percent change in mass and the embodiment feasibility.

Table 1. Percentage change in mass and embodiment, for each solution optimized

Topology Optimization	Mass [kg]	Percentage difference [%]	Embodiment feasibility		
			Low	Medium	High
2	2566	-51,5	V		
3	2587	-51,1	V		
4	2570	-51,5		V	
4.1	1924	-63,7			V
4.2	1501	-71,5			V

As shown in Table 1 the topology optimization problems, TO2 and TO3, are characterized by a low embodiment feasibility. Best solutions are the topology optimization 4.1 and topology optimization 4.2. These optimized solutions have a high embodiment feasibility and the percentage change in mass is more than 60%.

3. Fixture: From Concept Design to blended Solid- Lattice Design

The new Additive Manufacturing processes offers much greater flexibility in terms of manufacturability, compared to the traditional methods. Indeed, by means these technologies it is possible to obtain innovative geometries that allow to reduce the weight respecting the design constraints.

In particular, in the past the topology optimization has been constrained to the feasibility that the traditional processes offer. The Additive Manufacturing has exceeded these constraints and this allows to the designers to develop new innovative geometries such as the lattice structures. Topology optimization and Additive Manufacturing have many similarities in their philosophies:

- Additive Manufacturing allows freedom of form complex designs can be easily manufactured, and designs are customized. It facilitates accelerated production since there is no need to develop for tooling;
- Topology optimization takes full advantage of the package space provided. It finds freeform and efficient material layouts where unique designs can be created, and the overall design process is shortened because design iterations are minimized.

These similarities provide the wonderful synergy that these two technologies share. Taking advantages of Additive Manufacturing, several finite element software has been implemented the functionality to generate lattice structures and use topology optimization to drive the material layout including the lattice regions to reduce weight. In this way, it is able to identify void regions in the design space, where the material can be removed, regions where solid material is needed, and regions where lattice structure is required. This allows to generate the optimal hybrid or blended solid-lattice design based on desired functionality of the part.

The hypothesis to insert lattice sectors in appropriate zones has been considered in order to improve the fixture global stiffness limiting and, at the same time, the mass. However, this is a preliminary study and a further activity will be performed in order to define an hybrid structure that will consider the following aspects:

- Optimal lattice location in order to improve the fixture structural performance;
- Optimal topology lattice cell in terms of: stiffness, weight and geometry in order to avoid the fatigue problems.

The operative fixture conditions must be in elastic field, therefore, the hybrid approach will take into account of the admissible threshold in terms of stress and displacements in order to avoid local plasticity. Moreover, the magnitude of the loads applied on the fixture can be considered of an order for which, possible buckling conditions are not in any case part of the practical scenario given by the working conditions. To achieve this goal some design constraints will be opportunely defined and verified in the optimization methodology.

Finally, the 3D printing technologies choice depends of several aspects such as: material, maximum sector dimensions, geometry complexity, surface quality, etc. Therefore, after this first early design phase, next steps will be done to complete the development of the promoted entire methodology. The authors will consider the best 3D printing process taking into account the technological and design constraints. For example, for components with large dimensions the suggested technology is Laser Metal Deposition.

3.1. Case studies with lattice structures

The objective of this section has been to create a new blended Solid-Lattice structures which will be engineered to create the detailed final design of the component studied in this paper. The considered concept optimized design has been “Topology Optimization 4.2”. A linear static analysis has carried out in order to evaluate the stiffness of each fixture proposed. The lattice elements have been generated with opportune software and three different solid-lattice structures are proposed (Fig. 12).

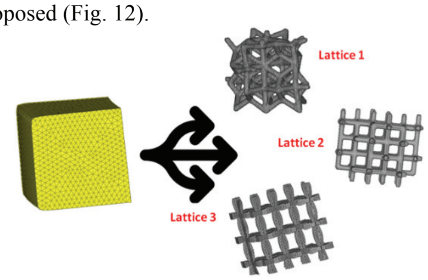

Fig. 12. Lattice structures generated by software

The lattice elements are not the results of a Lattice Structure Optimization, but, preliminarily, the designer have been chosen the regions where lattice structure could be useful. In this way it is possible to evaluate the “effect” of this lattice elements in terms of local stiffness and to validate the results of topology optimization (if the stiffness of the structure remains the same, the elements that have low density, effectively can be considered voids). Specifically, these lattice elements have been placed in the blue regions shown in transparency, in the Fig. 13.

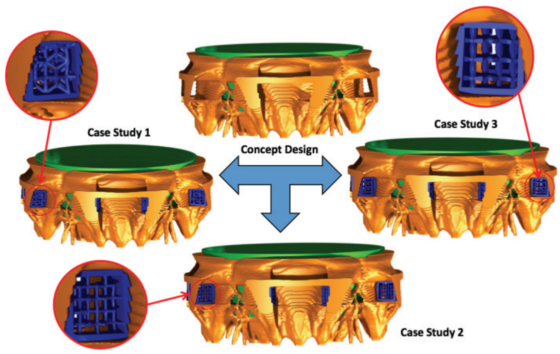

Fig. 13. Region where lattice structure has been considered for TO4.2

The boundary conditions and load cases are shown in Fig. 14. All nodes that lie on the XY plane have been constrained (all dof are fixed). Furthermore, the plane symmetry constrains (XZ and YZ) are considered.

The loads (vertical and radial forces) have been distributed on 5 rows of nodes along z-axis and they are organized in 5 different load collector.

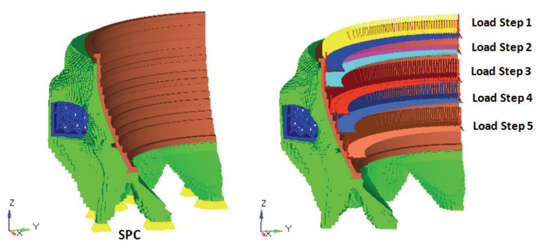

Fig. 14. Boundary conditions and Load Cases

The results, in terms of displacements, have been compared with those relating to fixture without lattice elements obtained by topology optimization discussed in Section 2. It is worth to mention that, the final results it is not only a save of mass thanks to the applied optimization but, also, a more efficient fixture, taking into account the working conditions and worked component geometry, in terms of an appropriate stiffness distribution in accordance with component geometrical characteristics.

3.2. Analysis results

Table 2 shows the maximum displacement values for the initial design and the three blended Solid-Lattice structures proposed.

Table 2. Maximum Displacement values for initial design and blended Solid-Lattice structures

	Initial Design	Case Study 1	Case Study 2	Case Study 3
Load Step	Max Displacement Magnitude	Max Displacement Magnitude	Max Displacement Magnitude	Max Displacement Magnitude
	[mm]	[mm]	[mm]	[mm]
1	0,021	0,020	0,020	0,020
2	0,017	0,017	0,017	0,017
3	0,015	0,015	0,015	0,015
4	0,013	0,013	0,013	0,013
5	0,009	0,009	0,009	0,009

As shown in Table 2 the maximum displacement values are the same in all case studies analyzed, for each load step.

This means that the addition of lattice structures in initial design have not brought the expected results. Also, this confirm the results obtained with topology optimization.

However, the lattice structure allows to lower the displacement values on ribs of the fixture. On the basis of the obtained results, a new fixture design could be achieved replacing topology elements with a range of intermediate densities (for example between 0,3 and 0,7) with lattice elements.

4. Conclusions

Several topology optimization problems have been analyzed in order to obtain a new concept design of the initial fixture, which will be engineered successively. Topology optimization has provided a preliminary fixture design that has been used as input for a new idea of design. This idea includes the presence of lattice structures in opportune void zones of the optimized fixture, to create blended Solid-Lattice structures. Linear analysis, conducted on these blended Solid-Lattice structures, has shown a quite insignificant influence of the lattice elements, at least in terms of maximum displacements, if compared with those of the fixture optimized. Therefore, further studies are necessary to improve the robustness of the methodology.

The engineering phase is actually in progress and the expected results will be a new concept of fixture that will be compared with the As-Is equipment by means numerical-experimental campaign.

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