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ScienceDirect

Physics Procedia 12 (2011) 459–464

Physics Procedia

LiM 2011

Systematic development of lightweight components for highly dynamic laser-remote-scanners using topology optimization

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Abstract

Lightweight design is an important issue within the product development process, especially if components are subjected to dynamical movements. This paper is a systematical approach for the development of weight optimized components for laser remote scanners using topology optimization. A topology optimization of a mirror mount is demonstrated, starting with the determination of mechanical boundary conditions of a complex laser remote scanner. Based on the optimization results, the process of designing a component suitable for production is shown. Finally, the capability of this procedure for different components for various branches is elucidated.

Keywords: Laser Remote Welding; Lighweight Design; Topology Optimization

1. Introduction

Lightweight design is a major objective of product development in several branches, in particular if dynamic movement of components is required. For example in automotive or aircraft industry lightweight components are used for saving fuel, to improve the dynamic behavior of the vehicle or to increase the load capacity. Lightweight design is also an important instrument in the development of components for laser remote scanners. A result can be an increase in scanning speed and a decrease in overall weight of a robot mounted remote scanner. Laser remote welding is an innovative welding process using dynamic mirrors for positioning a laser beam spot on the work piece across a distance up to 1000 mm.

A big challenge of component design for laser remote scanners is the balance between minimizing weight for improvement of dynamic performance and maximizing stiffness to guarantee a high positioning accuracy. In this paper a methodology utilizing topology optimization, a numeric tool to determine the optimal shape of a part, will be elucidated, to attain this balance.

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doi:10.1016/j.phpro.2011.03.157

2. State of the art

2.1. Laser remote welding

Laser remote welding is an innovative welding process often used in high volume production, if a large number of weld seams has to be produced in a short time. It is possible to realize a very quick beam positioning only by using one or more mirrors for beam guidance. Compared to conventional welding processes, where the positioning of the laser beam requires a movement of the welding head, nonproductive positioning time can be reduced significantly.

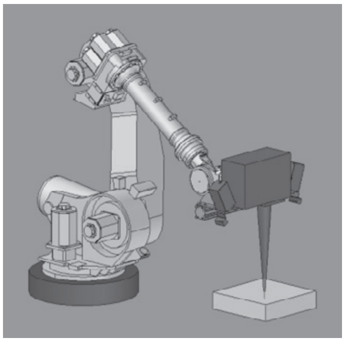

Figure 1: Principle of a laser remote scanner

2.2. Topology optimization

Topology optimization is a numerical tool supporting the engineer in the design process. The goal is to find the optimal shape of a part even for complex mechanical systems in order to realize an optimal lightweight structure. Different applications e.g. in the design of aircraft components have demonstrated the weight saving potential of this numerical tool. [1] [2]

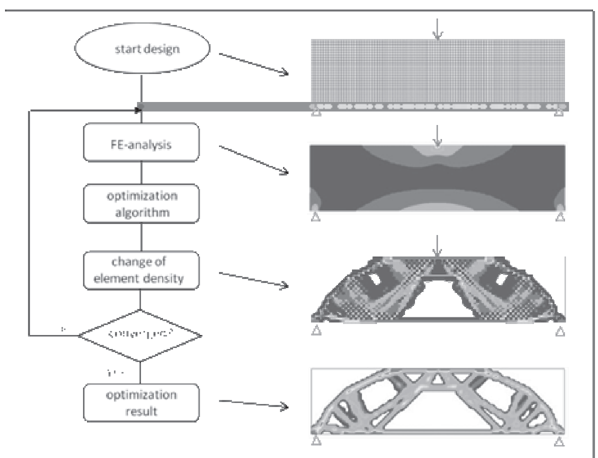

Figure 2: Principle of topology optimization [3]

Figure 2 shows the principle of the topology optimization. The process begins by defining the start design, whose size and shape cover the maximum available design space of the component. It is meshed with finite elements (FE). The start design includes mechanical forces and mountings. The iterative optimization cycle starts with a finite element analysis for determination the mechanical stress of each finite element. Using this data a numerical optimization algorithm assigns for each element the so called “element density”, which defines how much an element contributes to the overall part stiffness. Elements with low stress are defined as flexible and consequently contribute less to the components stiffness in the next iteration step. Vice versa, a high element density is assigned to elements subjected to high stresses. This cycle of FE-analysis and change of element density is carried out until the solution converges and only high stressed and unstressed elements remain. The result of this optimization is the optimal lightweight structure with respect to the applied boundary conditions. However, it is usually not possible to directly manufacture the optimized part because of its complex geometry including undercuts and fissured structures. Hence, an experienced engineer has to transform the structure into a design suitable for production.

3. Optimization process

Using the example of a mirror mount for a laser remote scanner, shown in figure 3, the process of a systematical lightweight design of scanner components will be described. As the FE-Analysis results of the original non-optimized design do not comply with the mirror mounts stiffness requirements an optimization is needed.

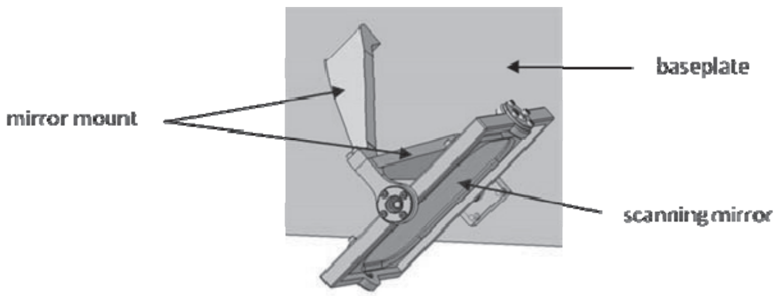

Figure 3: Original design of the mirror mount to be optimized using topology optimization

3.1. Determination of the boundary conditions for the topology optimization

Aim of the optimization of scanner components is the maximum weight saving in consideration of system boundary conditions. Unlike typical optimization problems, where the yield strength of the material is a limiting factor, in this system the deformation of the bearing seat is critical in order to achieve a high accuracy. The maximum tolerable displacement can be determined by analysis of the geometrical system and required specifications of the accuracy of the laser beam spot on the work piece. Additionally, the maximum load on the mirror mount has to be taken into account. The determination of these values will be explained below.

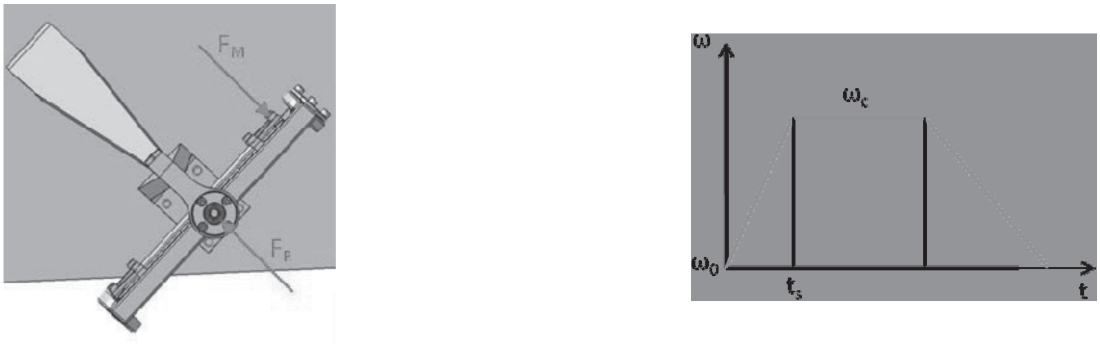

Figure 4: (a) Mirror positioning forces; (b) mirror movement: angular speed vs. time

In order to determine the forces acting on the mirror mount, the forces during mirror positioning have to be identified. According to figure 4 (a) and the equilibrium of forces, the resulting force $F_{R(t)}$ is equal to the motor force $F_{M(t)}$.

$$\Sigma F_{(t)} = 0 = F_{M(t)} - F_{R(t)} \,. \quad (1)$$

This equation shows that there is a dependency between the forces and the time respectively the movement of the dynamic mirror. For the dimensioning of the mount a static worst case scenario has to be analyzed in order to determine the maximum force. This case can be derived from figure 4 (b). The maximum motor force appears during the maximal acceleration of the mirror. In this case the angular acceleration α_s can be derived from the maximum angular speed ω_c of the mirror and t_s, the maximum allowed time to achieve this speed.

$$\alpha_s = \omega_c / t_s \,. \quad (2)$$

The maximum angular speed ω_c can be calculated from the specification of the focus speed on work piece by using simple geometrical relations.

Based on the design of the mirror device, the inertia of masses J can be determined and the required toque can be calculated to

$$M = J \cdot \alpha. \quad (3)$$

Consequently the force of the motor has to be

$$F_M = M \cdot r. \quad (4)$$

This is the force based on the mirror movement, which acts on the mirror mount.

If the laser remote scanner is mounted on a robot there are additional force components due to the acceleration of the robot arm which can be calculated from the acceleration and the mass of the scanner components using

$$F = m \cdot a. \quad (5)$$

3.2. Topology optimization

Based on these results, the optimization model can be implemented. Starting with a rough estimate of the overall design, shown in Figure 5 (a), the available design space can be defined and meshed with finite elements. The forces as well as the supports can be implemented in order to start the optimization with the aim of volume respectively weight reduction. To consider different load situations of the systems, e.g. the robot acceleration in the different directions, four different load cases have been defined and taken into account during the optimization.

According to Figure 5 (b), the result of the optimization shows only elements which have significant influence on the load transmission. Elements with low or no stresses have been removed during this optimization process.

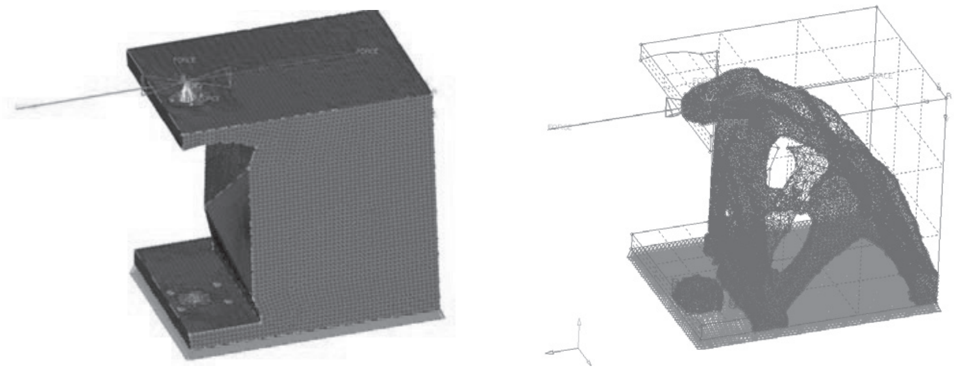

Figure 5: (a) Optimization model including finite elements, loads and boundary conditions; (b) design space vs. optimization results

3.3. Interpretation of the topology optimization results for manufacturing

A direct manufacturing of the topology optimization result is not possible because of its complex design as described above. To acquire a CAD model suitable for production, an engineer has to interpret the result in accordance to general design rules for machining.

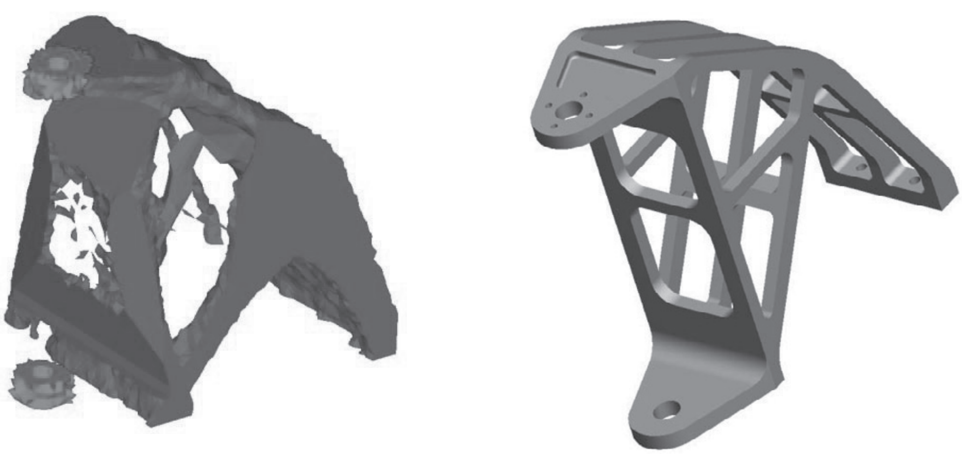

Figure 6: (a) Optimization result; (b) Adapted CAD model suitable for production

Figure 6 demonstrates how the relevant load paths have been adapted into a lightweight design suitable for milling. The surface has been smoothed and undercuts have been avoided to ensure the accessibility for the milling head.

3.4. Validation

To validate the design a final FE-analysis is carried out. The maximum displacement of 17 µm verifies the correct dimensioning of the mirror mount. Thus, all specifications are fulfilled and a lightweight design has been developed. This improves the dynamic behavior of the system.

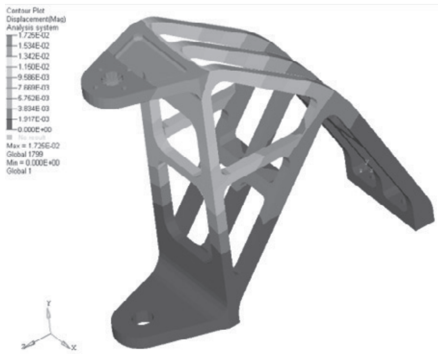

Figure 7: FE-Analysis of the optimized design: maximum displacement of the mirror mount

4. Conclusion

The demonstrated approach for the systematic development of lightweight components using topology optimization enables the engineer to design light constructions even for complex mechanical structures. Especially for dynamically moved systems, such as a mirror mount of a laser remote scanner, significant weight reduction can be realized in comparison to conventional design that is based on the experience and intuition of the engineer.

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