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MULTIOBJECTIVE AND MULTIDISCIPLINARY STRUCTURAL OPTIMIZATION OF A CONCEPT PART

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Abstract: *In most of the cases, the concept design of how a particular part will look and how it will fulfill the functional requests defined by the standards and norms of a specific application is largely based on the experience that the design engineer accumulated from previous similar situations, and often restricted to that experience. The current paper presents a finite element method (FEM) based topology optimization approach for a simple concept part with various functional and technological requests, and a critical discussion over the variety of alternative multiobjective and multidisciplinary optimization scenarios that can be considered for the design of this concept part.*
Keywords: *concept, design, FEM, structural optimization*

1. INTRODUCTION

By definition, optimization at large is a mathematical technique for finding maximum or minimum of functions, by the means of mathematical tools comprising the definition of a set of controllable variables subjected to a set of constraints.
Structural optimization applies the general principles of optimization to structures, considering the structures as systems defined by means of parameters that can be altered (design variables) governing functioning principles (load cases, analysis type), and system responses (measurable output). Responses, individual or combined, may constitute the objective of the structural optimization. Both design variables and responses can be subjected to known constraints, which main objective is to narrow down the field of possible solutions for the given system to the ones that are feasible within the given problem definition. Structural optimization responses are obtained by the means of the finite element method (FEM). Computer assisted structural optimization is a very recent development in the computer aided engineering (CAE) software world, which matured practically only in the last decade. There are two main categories of applications: those which function as independent applications with an integrated finite element analysis (FEA) solver (such as Altair® OptiStruct®, MSC/NASTRAN® SOL200, Simulia Abaqus® ATOM®, which are currently the most important products used for simulation in the automotive and aerospace industries), and those which are solver neutral (that organize optimization scenarios based on parameters and responses, but trigger external solvers for the responses, such as Altair® HyperStudy® or LMS Optimus®). There are significant differences between the two categories, but their treatment is not within the purpose of the current paper. However, probably the most important difference that is related to the subject is the fact that latter category is not designed to solve concept overall optimization, but fine tuning and local improvements for structures in the detail design phase. In exchange, the latter can trigger any kind of complex analysis and consider any nonlinearity that a real investigation case may request, while the former is often restricted to linearized and simplified problems, as an approximate analysis model is created and optimized at each iteration (design variable variation), and thus even a simple linear setup becomes very resource-consuming.
Structural optimization in concept phase is a very important asset for all the industries, as it enables the design engineer to expand the frame of the possible solutions to a given problem. In most of the cases, the concept design of how a particular part, component or assembly will look and how it will fulfill the functional requests defined by the standards and norms of a specific application is largely based on the experience that the design engineer accumulated from previous similar situations, and often restricted to that experience. Also, it is a known issue that a complex product is designed and engineered for manufacturing by different engineering departments, and often the inter-departments communication fails or is incomplete, and certain parts may be designed without

considering all the necessary functional and technological requests. Another known constraint is time. Often, the production process global efficiency demands that the design phase in the product life cycle may be as short as possible. All these factors may cause a design engineer to haste and propose for the new design solutions that might fail to meet all the requirements, and thus to propagate insufficiently studied solutions down flow in the design process. Such things are seldom noticed or repaired in the detailing phase, unless thorough analyses are done, and are very difficult to readdress once the tooling for the finite product was prepared.
To illustrate the benefit of using optimization as early as possible in a product's development cycle, the current paper describes an optimization approach for a simple concept part with various functional and technological requests, and proves that based on the definition of the optimization analysis scenario, finite element method based multiobjective and multidisciplinary optimization can provide a variety of alternatives for the design of the considered concept part. For illustrating the above, a very simple cantilever arm part was considered, from the set of tutorial public models that belong to the documentation accompanying Altair® OptiStruct®. **Topology optimization** was used as a method for preliminary design, as this method provides in the earliest design stage a good insight over the load path and the basic shape of the future detailed part will be. This method is also suitable for integrating the future manufacturing process constraints (in the current case casting or forging) into the design. The topology optimization finds the optimum material placement within the design space, according to the given objective and constraints. Altair® OptiStruct® uses for this the SIMP method (Solid Isotropic Material with Penalty), also known as the density method. A pseudo material density is the design variable inside the design space. This material pseudo-density varies continuously between 0 and 1, with 0 representing void state (absence of material) and 1 solid state (presence of material).

2. CONCEPT PART OPTIMIZATION

2.1. Baseline Model Setup

The finite element representation of the model proposed for optimization is illustrated in **Figure 1**. This part is a concept part, and this means that its detailed shape is not yet known, so the whole space that might be occupied by it was defined as a bulk space claim, made of cast iron, isotropic and homogeneous. This space claim was divided into the following regions, essential for the topology optimization: the three hinges (in yellow color, these the connection that the part should have with the assembly where it belongs, which are known already or should be assumed in the concept phase), representing **the non-design space**, namely the region that will not be modified during optimization, and the body (in light blue color), representing the **design space**, the region which shape will be altered during the optimization process.

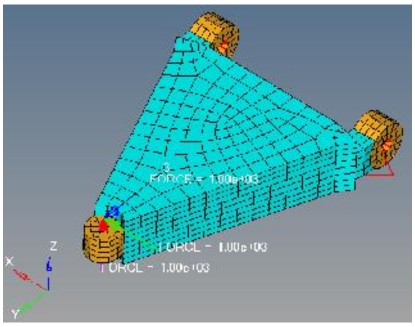

Figure 1: baseline cantilever arm model

The two base hinges are constrained (the center of the rigid connectors that represent the hinges have all the degrees of freedom blocked), and the loading at the top hinge is divided in three static load cases, consisting each of a force of 1000N applied in the direction of one global coordinates system axis (X, Y and Z respectively). An additional case of normal modes calculation was also considered.

2.2. Topology Optimization Setup and Results

For topology optimization in concept phase, it is important that the model is simple and linear, and the loading is also linear, and reduced to a small set of relevant load cases. Nonlinearities of all kinds (material, contacts, gaskets, load dependent behavior) should be avoided. The setup used for optimization should be a **linearized equivalent approach** that covers the most critical and extreme aspects from the real loading.
The topology optimization **initial scenario** was defined, as follows:

1) The **design variable**: this refers the design space, where the pseudo-density of the material will vary;
2) The optimization **responses** that are calculated with FEM:
   a) The model compliance, weighted over the static load steps;
   b) The volume fraction defined over the design space;
   c) The displacements of the top hinge force application point in the directions of the forces;
   d) The first five normal modes.
3) The optimization **objective**: to minimize the weighted compliance, over all the linear static cases.
4) The **constraints**, applied to the responses:
   a) Lower limitation of the volume fraction: no less than 30% volume of remaining material;
   b) Imposed maximum values for the three displacements of the top hinge forces application point;
   c) Imposed minimum value for the first eigenfrequency, over 65Hz.

The results produced by the defined initial approach are presented in **Figure 2**. The figure displays the element pseudo-densities for the last iteration feasible design proposed by the algorithm (in the left side), and one of the possible shapes (keeping all elements that have pseudo-densities over 0.5, in the right side).

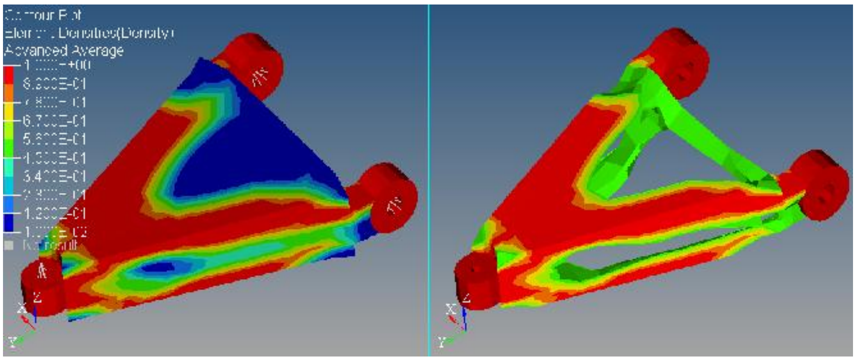

Figure 2: baseline cantilever arm initial scenario result

The result in shows **Figure 2** that the lack of (sufficient or realistic) manufacturing constraints definition produced a shape which is not acceptable from technological point of view. In order to have a fully feasible design, an **updated scenario** was proposed, with manufacturing constraints (technology specific), as follows:

5) **Manufacturing constraints**:
   a) Draw direction: the direction of global axis Z;
   b) The minimum acceptable wall thickness;
   c) The presence/absence of holes in the draw direction.

This update provided results that are acceptable also from the technological point of view (**Figure 3**). The elements with pseudo-densities over 0.3 were kept.

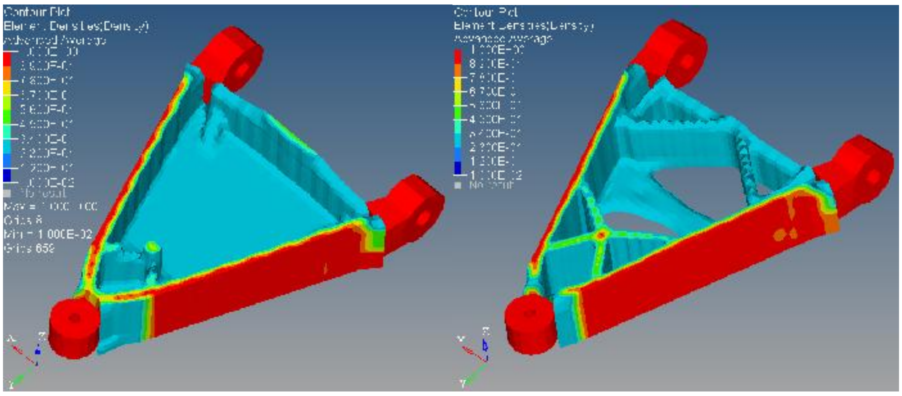

Figure 3: results for the updated scenario

It is to be noted here that the more constraints are added in the model, the longer the optimization process takes, and the more iterations the algorithm needs to establish a feasible design. In the initial setup case, the solution was ready after 26 iterations. In the case of the manufacturing constraints, the no holes scenario completed in 31 iterations, and the one with holes in 47 iterations, and almost double of the initial time.

This concept result needs to be re-engineered according to the detailed design requests (even the wall thicknesses, add rounds and draft angles) and validated by a full simulation (in real conditions) and/or testing.

2.2. Multiobjective and Multidisciplinary Scenarios Discussion

It is to be noted that the definition of more that one objective in this type of approach is impossible, in a direct manner. However, the **multiobjective** approach is very much possible by the **combination of the objective and constraints**/responses that are used. If the algorithm converges, i.e. finds the feasible design (the set of requests and constraints is realistic), this design will satisfy anyway the objective and all the constraints. Therefore, one can consider **commuting between objective and constraints** in any way one sees fit.

In the initial scenario defined above, the main idea was to obtain a model that withstands deformation in a sustainable way, and thus the objective was to minimize the compliance, while another important request, as the model overall mass, was imposed indirectly via a constraint: not to decrease the volume of material below a certain value. This means the algorithm will provide a model of minimum compliance and minimum occupied volume (hence mass) within the given requests, keeping also the displacements within limits. An approach that was tested on the updated setup (with holes allowed) was to minimize the model mass as an objective, and introduce a stress and volume fraction constraint, the resulting shape being similar with the one in **Figure 3**, right side.

Another way to introduce the multiobjective approach is to **define as objectives the functions that combine responses** that are already defined. One example would be to minimize the sum of responses of the same kind, as the top hinge displacements, while defining the maximum stress in the model as a constraint. This approach was not used for the current case, as it does not guarantee that each of the displacements will stay under a certain value, while the sum would still comply with the request. Constructing a function that combines the eigenfrequencies and then maximizing it alone also does not qualify, as this results in no material elimination.

Another way of introducing multiple objectives is the **design object reference** functionality, for special cases when multiple stress targets are considered. One case would be the minimization of a principal stress. This functionality would decrease its positive values and increase its negative values in the same time. This applies also for the case of parts and assemblies that are made of multiple materials, for which the objective stress targets are very different. This functionality was not applied in the studied case.

A **multidisciplinary** approach was applied to the updated setup (with holes allowed), with considering the combination of the weighted compliance in static cases and the weighted sum of the reciprocal eigenvalues, with a normalization factor to ensure that the two terms are comparable, in a function defined as in the formula (1) below (this type of combined response is implemented in the application).

$$S = \Sigma w_i \mathrm{C_i} + \mathrm{NORM}\frac{\Sigma w_i \,|\, \lambda_\mathrm{i}}{\Sigma w_i} \qquad (1)$$

The objective was to minimize this function over all the load cases. The solution was ready after 51 iterations, taking more than two hundred times the duration of the initial case. The shape was not qualitatively different from the one in **Figure 3**, right side, suggesting that a pseudo-density of 0.4 to 0.5 for the updated setup (simple and computationally effective) would be suitable to meet the multidisciplinary objective.

3. CONCLUSION

Topology optimization in concept phase is a very resourceful tool in the concept design process. There are many parameters and scenarios combinations that can provide a lot of variation through the design process. The optimization tool is an automate process, which functions under a defined set of rules, no matter how simple or complex the part/assembly may be, and therefore a critical eye must be kept over the results of this process: the degree in which they are useful depends almost exclusively on the quality, relevance and completeness of the scenario that was considered. Also, the negotiation of the relevant responses, objective, constraints and method should be considered in a critical manner, as it is possible to get similar results using various methods, with various degrees of complexity and durations, and the selection of the optimum from this point of view belongs exclusively to the user. The result of the concept design optimization process is a concept proposal, or a set of proposals, that must be re-engineered according to the detailed design requests and validated through simulation in real conditions and/or physical testing.

REFERENCES

[1] *** Altair® OptiStruct® Users Manual, Altair Inc., http://www.altair.com