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Sizing optimization for industrial applications and best practice design process

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Abstract

Structural optimization is able to accelerate the design process and to save resources for various structural engineering disciplines. Sizing optimization is one of the most common types of structural optimization applied in industry. This is mainly due to the fact that sizing optimization problems are defined, solved and post processed with relatively small effort and only few manufacturing constraints are required for obtaining industrial feasible solutions. Academically, many sizing algorithms are well developed and discussed in the literature. However, these sizing algorithms do often not address industrial requirements and best practice design process for sizing optimization. The present work addresses some practical aspects of industrial sizing optimization using a number of selected industrial applications.
Keywords: industrial applications, sizing optimization, structural optimization software.

1 Introduction

The optimization system SIMULIA Tosca Structure [1] integrates structural optimization technologies for practical engineering environments as an add-on module easily integrated for the existing Abaqus [2] workflows. During the preprocessing of the finite element model an optimization problem can additionally be defined in Abaqus CAE environment. The user can specify the objective function to be minimized or maximized, the constraints which must be satisfied and design areas to be modified during the optimization iterations. A significant number of manufacturing constraints can be applied to ensure that the optimized designs are feasible for industrial production. Afterwards, the defined optimization problem is conducted by an iterative procedure where

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the model is automatically updated and modified using a robust non-linear constrained optimizer, see Svanberg [3], based on sensitivities derived using the semi-analytical adjoint method, see Tortorelli and Michaleris [4], Choi and Kim [5], Choi and Kim [6] and van Keulen *et al.* [7]. Both the FE equilibrium and adjoint equations are solved by the Abaqus solver. The achieved optimized thicknesses is readily available for the typical CAE post-processing.

Frequently, industrial sizing applications include multiphysics modeling and analysis. The optimization system SIMULIA Tosca Structure is able to handle such problems. To demonstrate this feature a coupled structural-acoustic problem is considered in sec. 2 where the sound pressure in the acoustic media generated by a structural excitation on a car muffler is minimized at a certain location.

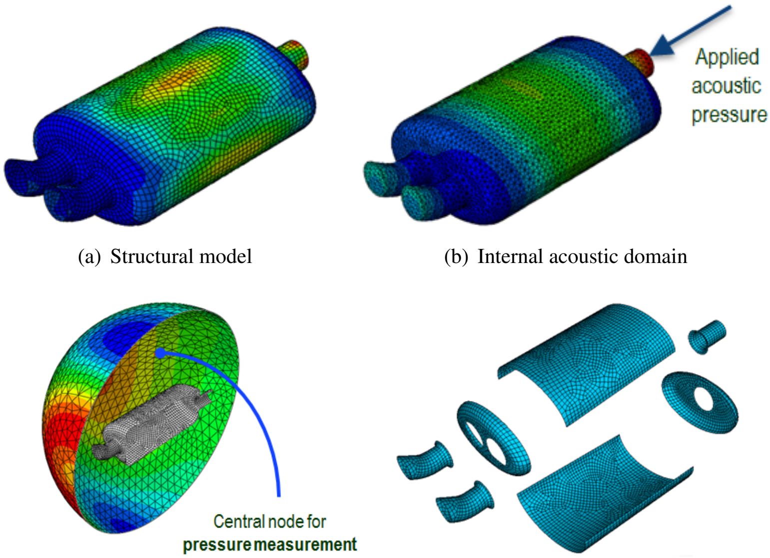
Shell elements are frequently used for thin-walled structural finite element analysis due to their efficiency and accuracy. For sizing optimization the elemental shell thicknesses are the design variables. Theoretically, the thickness design variables can have continuous and different values from shell element to shell element and can have values between predefined lower and upper bounds. Practically, thin shell and plate structures are usually manufactured using a number of prefabricated metal sheets. The thicknesses of these prefabricated sheets are frequently predefined by some standards and must be chosen from a given list of discrete thickness values. Additionally, elements in specific regions of the finite element model must have same thickness as they represent some certain metal sheets. Both aspects are taken into account optimizing the jacket structure that supports a 5MW offshore wind turbine in sec. 3.

Sizing optimization of lattice structures is an increasingly important application of sizing design in the last decade due to the constant expanding possibilities of the 3D printing technology. Models of this type lead usually to large scale optimization problems. Such solutions are implemented in the SIMULIA Tosca Structure for efficiently solving these classes of industrial problems. An example addressing this is a lattice optimization of an airplane door stop presented in sec. 4.

2 Coupled structural-acoustic sizing optimization

The current application demonstrates the structural optimization of a car muffler coupled with an air cavity in order to minimize the pressure measured at a nodal location inside the acoustic domain when the structural component is subjected to a harmonic loading as illustrated in fig. 1. A mass constraint is applied to keep structural weight below or at the same initial value. The corresponding theoretical background is presented in Søndergaard and Pedersen [8]. The structural model consists of 7 metal sheets which thicknesses are to be optimized. The optimization system SIMULIA Tosca Structure performs 45 iterations to obtain a converged solution. The corresponding iteration history is shown in fig. 2.

As we can recognize, the acoustic pressure is dramatically reduced still having the same structural mass. The initial and the optimized thickness configurations for the muffler are illustrated in fig. 3.



(a) Structural model (b) Internal acoustic domain

(c) External acoustic domain (d) Structural sheet components

Figure 1: Structural-acoustic modeling of a muffler.

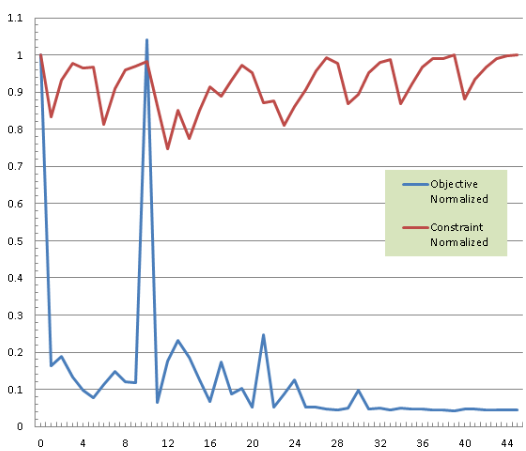
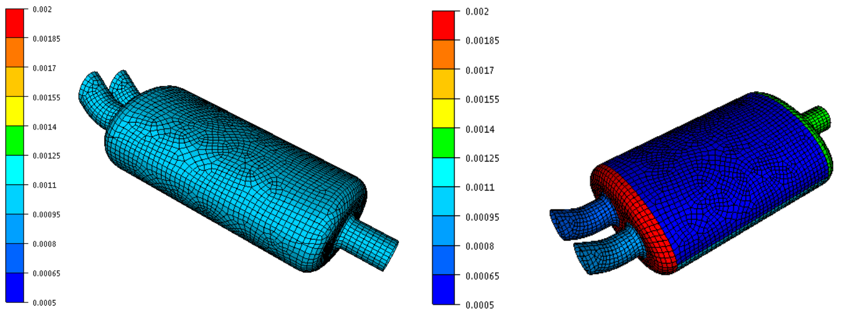


Figure 2: Iteration history: normalized values of objective and constraint.



(a) Initial thicknesses (b) Optimized thicknesses

Figure 3: Initial and optimized muffler design.

3 Sizing optimization with discrete thickness values

Often parts are manufactured by cutting, forming and joining metal sheets. Most automated processes are calibrated for standard sheet thicknesses. Thus, it is cheaper to manufacture optimized parts if no custom specific thicknesses have to be used for manufacturing. This means that in the context of sizing optimization the optimized values of design variables must correspond to values from a given list of possible values. Theoretically, this is a contradiction to the usage of gradient based optimization techniques in which the variables should be continuous. SIMULIA Tosca Structure offers a solution to this problem using a heuristic approach. The system performs some prescribed number of initial iterations within gradient based optimization tacking all design variables into account. Then some percentage of design variables values is rounded to the nearest list values and is fixed for the rest of optimization iterations. The optimization process is continued and the last step is repeated after some iterations until all of the design variables corresponds to the list values. The user can prescribe when to start with the process, in which interval and how many variables should be fixed. The decision for which variables should be fixed is done automatically based on the design variables history. Variables with the lowest changes in some last iterations are initially fixed.

To demonstrate this feature we consider the 5MW offshore wind turbine jacket structure which was introduced in Matos *et al.* [9]. Its modal dynamic behaviour was optimized maximizing its lowest eigenfrequencies. For the truss jacket structure continuous metal sheet thicknesses where considered as design variables. A volume constraint was applied. The structure was subdivided into 9 independent cluster groups, see fig. 5a. Within this contribution the same optimization problem is solved but now tacking available discrete thickness values defined in tab. 1. We perform 9 initial iterations and after that fix 20% of all variables each 4th iteration. The corresponding optimization iteration history is presented in fig. 4. The blue and the red curves represent the normalized objective function and constraint values. As one can recognize the objective function increase in the lowest modal

Table 1: Available discrete metal sheet thicknesses.

0.01	0.015	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055
0.06	0.065	0.07	0.075	0.08	0.085	0.09	0.095	0.1	0.105
0.11	0.115	0.12	0.125	0.13	0.135	0.14	0.145	0.15	0.152

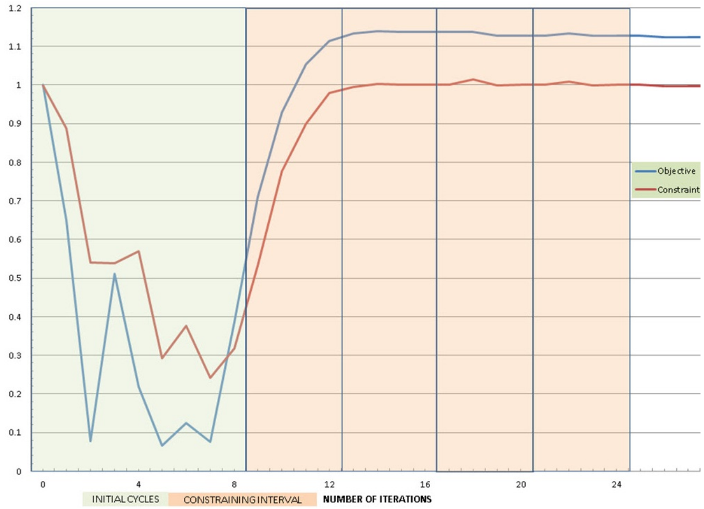
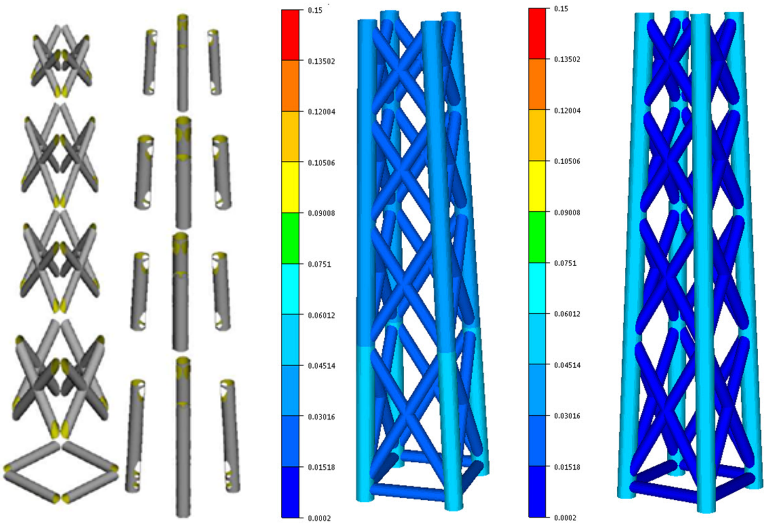


Figure 4: Iteration history: normalized values of objective and constraint.

Table 2: Optimized thicknesses for the jacket structure.

cont.	0.055	0.000	0.006	0.009	0.009	0.006	0.063	0.057	0.057
discr.	0.05	0.01	0.01	0.01	0.01	0.01	0.055	0.055	0.055

eigenfrequency is about 12% and the volume constraint is satisfied. As noted in Matos *et al*. [9] the increase of the objective function using continuous design thicknesses was about 15%. To compare both results the corresponding optimized thicknesses are summarized in tab. 2. As the smallest available thickness in tab. 1 is 0.01 this value is assigned to thicknesses of groups 2–6. But due to the active constant volume constraint the choice of thicknesses of groups 1 and 7–9 is not just a rounding of values. The corresponding optimized structures are presented in fig. 5.



(a) Cluster groups (b) Continuous (c) Discrete

Figure 5: Optimized thickness configuration of the shell model jacket.

The possibility of SIMULIA Tosca Structure to induce cluster thickness groups and consider discrete thickness values from a predefined list during the sizing optimization process is a valuable feature being able to solve industrial applications.

4 Lattice structural optimization

The current application of lattice optimization considers a door stop model of an airplane, see fig. 6. The bottom surface of the model is clamped. The red marked surface represents the loading side on which 8 loadcases are applied. The structure is modeled considering 171000 circular beam elements based upon the Timoshenko formulation with approximately 2 million of degrees of freedom in total.

The objective is to minimize structural compliance under a constant mass constraint for obtaining a stiff structure for a given mass. Additionally, a displacement constraint for the loaded surface was applied to avoid twisting of the structure. The radii of the circular beams are considered as design variables. Their initial values, the upper and the lower bounds are defined in tab. 3.

SIMULIA Tosca Structure performs 25 optimization iterations to solve the present optimization problem. The corresponding optimization iteration history is shown in fig. 7. The optimized structure has 392% higher stiffness for the same mass and the displacement constraint is also fulfilled. The optimized lattice structure for the door stop is illustrated in fig. 8. It is evident that it would be not

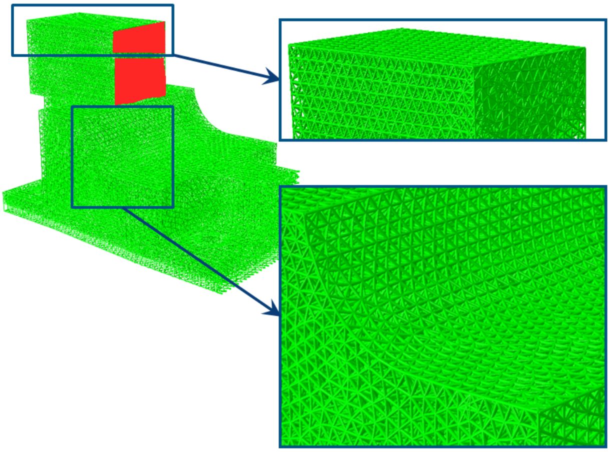
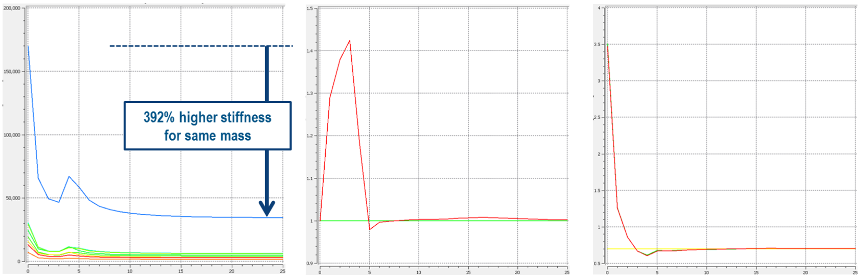


Figure 6: Initial lattice door stop.

Table 3: Radii of circular beams of the door stop model.

Initial	Lower bound	Upper bound
0.18	0.00001	0.70
	≈ void	289%



(a) Compliance objective (b) Mass constraint (c) Displacement constraint

Figure 7: Optimization iteration history for the door stop example.

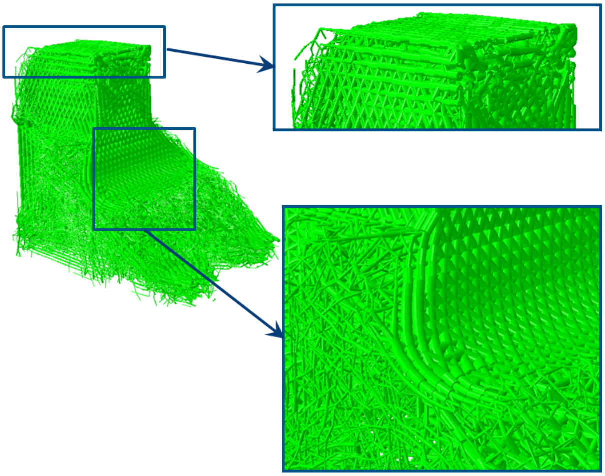


Figure 8: Optimized lattice door stop.

possible to create such a design proposal just based on the engineer's intuition. For such large models it is advantageous to use efficient equation solvers available in Abaqus. Also the utilized semi-analytical adjoint sensitivity analysis method is beneficial with respect to the computational time and to the required memory.

5 Conclusion

Structural optimization has shown to be a powerful automatic tool to fulfill the growing industry requirement for efficient resource usage. The optimization system SIMULIA Tosca Structure offers tools which can be easily integrated in the existing users' workflows and takes into account industrial processes. Hence, the product development times and effort can be dramatically reduced using the present technology.

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