COMPUTATIONAL MECHANICS 2021
36th conference with international participation
Srní
November 8 - 10, 2021

Assessment of post-processing capabilities in selected software for topology optimization

O. Ježek[a,b], J. Kopačka[b], D. Gabriel[b]

[a] *Faculty of Mechanical Engineering, Czech Technical University in Prague, Technická 4, 160 00 Prague 6, Czech Republic*
[b] *Institute of Thermomechanics, Czech Academy of Sciences, Dolejškova 1402/5, 182 00 Prague 6, Czech Republic*

Abstract

Topology optimization (TO) has come to the fore in recent years, especially with the development of 3D printing. Finite element systems often include TO functionality based on either density-based or level set methods. In the case of the first-mentioned method, the results of TO are further processed into geometry suitable for additive manufacturing. However, current programs only include basic post-processing capabilities with minimal customization options. This paper will first briefly summarize the theoretical background of TO and post-processing methods. Next, selected commercial TO programs will be compared from the perspective of shape post-processing. The final part will be devoted to applying the level set method for shape post-processing of a topologically optimized industrial robot gripper.

1. Introduction

Topology optimization (TO) has become a popular method for designing innovative components in recent years. Its goal is to find the optimal distribution of the material in a design space based on predefined requirements and constraints. The popularity of this method has grown considerably with the development of 3D printing, and today it is incorporated in many finite element programs as well as in CAD software.

The seminal paper that laid the foundations for the development of topology optimization is considered to be the work of Bendsøe et al. [1]. Since then, the development of TO has taken several directions, and nowadays, many different methods can be found in the literature. An overview of known TO methods can be found e.g. in the review article [2]. Nevertheless, only two methods, *Density-based* and *Level-set*, can be considered the most widely used.

In this paper, we will first formulate the optimization problem of compliance minimization with a constraint on the volume fraction. Then, the two mentioned methods - SIMP and level set - will be introduced. Then, selected commercial TO programs will be compared in terms of shape post-processing. The main contribution of the paper lies in the use of the level set method to postprocess the results obtained by the SIMP method. The proposed procedure is demonstrated on a popular test example of the so-called Messerschmitt-Bölkow-Blohm (MBB) beam.

2. Compliance minimization using topology optimization

A typical topology optimization problem is to find a maximally stiff structure with respect to its loads and supports. The constraint is the volume fraction, i.e., a certain ratio between the volume of the structure and the volume of the entire domain in which the optimization is performed. Such a problem can be described by minimizing an objective function c (strain energy) with a constraint on the volume fraction f, i.e.,

$$\begin{aligned} \min_{\rho} : \quad & c(\rho) = \mathbf{U}^T\mathbf{K}\mathbf{U} = \sum_{e=1}^{N} E_e(\rho_e)\mathbf{u}_e^T\mathbf{k}_0\mathbf{u}_e, \\ \text{subjected to} : \quad & V(\rho)/V_0 = f, \\ & 0 \leq \rho \leq 1, \end{aligned} \tag{1}$$

where $\mathbf{U}$ is the global displacement vector, $\mathbf{F}$ is the global stiffness matrix, $\mathbf{u}_e$ is the displacement vector of the element, k_0 is the stiffness matrix of the element with the corresponding Young's modulus, N indicates the total number of elements, $V(\rho)$ is the current volume of the material, and V_0 is the volume of the design domain.

2.1 Modified SIMP method

The SIMP method, which stands for Solid Isotropic Material with Penalization, belongs to the class of *Density-based* methods and is one of the most used in TO. It employs finite elements to describe the shape, where a fictitious density is assigned to each element. Note that this is not a real physical density but a kind of importance of the element in the system. This fictional density (referred to as the design variable in the optimization) assigns a modulus of elasticity to each element in the system.

The distribution of the material during optimization can produce a so-called checkerboard pattern, where the fictitious density changes in leaps and bounds between adjacent elements. To suppress this effect, filtering is used. This is a kind of averaging of the density values of adjacent elements using a weighting factor. The basic methods of filtering can be divided into density-based and sensitivity-based, cf. [3].

The result of the SIMP method is a scalar field of fictitious densities ρ, where each element is assigned constant fictitious density ρ_e. To obtain the shape, elements from a certain density threshold can be labeled as solid ($\rho = 1$), and elements with lower density can be labeled as void ($\rho = 0$). The density threshold is set to ensure that the volume fraction f is preserved. This removal of material produces sharp edges. If the component were made identical in shape to the element model, a large number of stress concentrator zones would be created. This should be avoided, and the model should be suitably modified so that these zones are smoothed, and the resulting stress concentrators are removed. To perform the actual smoothing, so-called shape post-processing is used. In the case of 2D objects, shape post-processing can be performed by simple sketching in CAD software. For more complex solids, it is necessary to use automated techniques.

2.2 Level set method

In the SIMP method, the design variables are element-dependent. The level set (LS) method [5], on the other hand, uses a level set function (LSF) to describe the shape. In the 2D case, the intersection of this function with the cutting plane produces the contour of the shape, i.e., the boundary between the solid and the void space. The height of the cut plane (level set) usually passes through zero ($\phi_{\text{plane}} = 0$). However, in special cases, its height can be changed, thus affecting the volume fraction f.

In order to use this method in topology optimization, it is necessary that the LSF evolves over ”time” and that the shape of the optimized object changes gradually. The Hamilton-Jacobi equation is often used for this purpose.

Level set methods do not need post-processing. The LSF defines a clear boundary between solid and void material. An advantage is that this boundary is independent of the edges of the elements. The resulting geometry of the optimized object is therefore smooth.

3. Post-processing capabilities in selected software for TO

TO has become an integral part of many finite element systems. These systems usually use Density-based methods to obtain the optimal material distribution. The main advantage of these methods is their robustness. However, the results are not smooth enough, and also no clear transition between full material and empty space is given, Fig. 1. For this reason, shape post-processing of the results is required to obtain sharp and smooth geometry. For this purpose, commercial software uses very basic shape post-processing based on the density isocontour method with linear segment approximation. The results from this method are not of very high quality, and elements of the original finite element mesh are evident on the obtained geometry. Some software uses B-spline curve segments to smooth the geometry, but here the results are of much higher quality. Unfortunately, all available software offers little or no user customization in terms of shape post-processing.

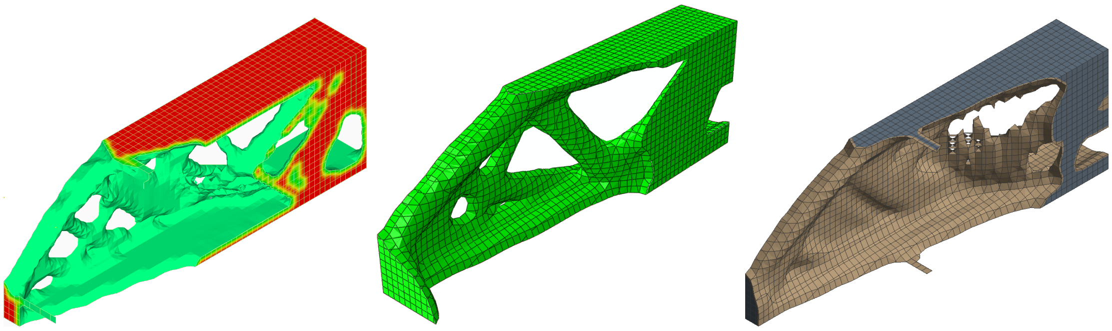

Fig. 1. Comparison of TO 3D MBB beam results performed in selected programs: results from FEMAP are on the left, Abaqus in the middle and Ansys on the right

4. Post-processing by the level set method

We propose to combine the two methods by constructing a level-set function for post-processing of the SIMP method results. First, the nodal values of the fictitious densities are calculated as the averages of the values of the adjacent elements. Next, by implementing radial basis functions (one radial basis function with height corresponding to the fictitious density is placed at each node of the mesh and then summing these functions), the LSF shape can be obtained. The intersection of this function with the cutting plane produces the contour of the object. The height of the cutting plane h can be used to modify the volume fraction f and also the shape of the object. A more detailed procedure is given in the work of [4]. The TO result using the SIMP method is shown in Fig. 2 (left). Subsequent shape post-processing using the LS method produced the result seen in Fig. 2 (right).

5. Conclusions

In the first section of this paper, a brief insight into topology optimization was given. Two main TO methods, SIMP and level set, were presented. The SIMP method belongs to the family of *Density-based* methods using finite element shape and fictitious densities to describe the shape. The Level-set method works on a different principle, using the LS function in combination with

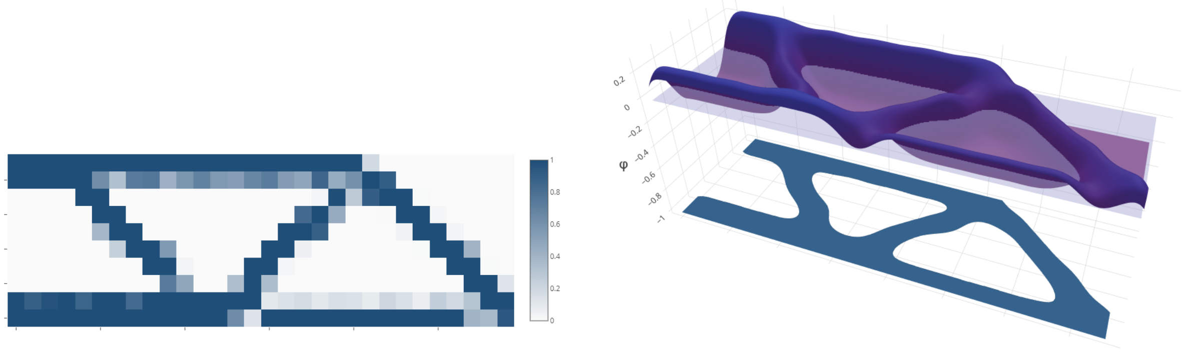

Fig. 2. The principle of the level set method on a 2D MBB beam problem

the cutting plane to describe the shape. In practice, the *Density-based* methods are preferred because of their robustness and the possibility to introduce new holes during optimization. On the other hand, the level-set method does not require shape post-processing. In the second part, the possibilities of shape post-processing within commercial programs were briefly discussed. Furthermore, a comparison of the selected programs was made on the 3D MBB beam. In the last part, the procedure of shape post-processing using the LS method was proposed. The construction of the LSF itself was performed using Radial Basis Functions combined with a fictitious density of node points of the finite-element mesh. By intersecting the cutting plane with the LS functions, a sharp transition between the solid and void material was achieved. It can be seen from Fig. 2 that a very good result was achieved.

Acknowledgements

The work was supported by the Technology Agency of the Czech Republic under grant No TN01000024/08 (National Competence Center-Cybernetics and Artificial Intelligence) - subproject “Automation and production system optimization” and the European Regional Development Fund under Grant No. CZ.02.1.01/0.0/0.0/ 15_003/0000493 (Centre of Excellence for Nonlinear Dynamic Behaviour of Advanced Materials in Engineering) within institutional support RVO:61388998.

References

[1] Bendsøe, M. P., Kikuchi, N., Generating optimal topologies in structural design using a homogenization method, Computer Methods in Applied Mechanics and Engineering 71 (2) (1988) 197-224.

[2] Sigmund, O., Maute, K., Topology optimization approaches: A comparative review, Structural and Multidisciplinary Optimization 48 (2013) 1031-1055.

[3] Sigmund, O., Morphology-based black and white filters for topology optimization. Structural and Multidisciplinary Optimization 33 (4–5) (2007) 401-424.

[4] Swierstra, M. K., Post-Processing of topology optimized results: A method for retrieving smooth and crisp geometries, Master Thesis, Delft University of Technology, 2017.

[5] van Dijk, N. P., Maute, K., Langelaar, M., Van Keulen, F., Level-set methods for structural topology optimization: A review, Structural and Multidisciplinary Optimization 48 (2013) 437-472.