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TOPOLOGY OPTIMIZATION BY A QUASI-STATIC FLUID-BASED EVOLUTIONARY METHOD

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Abstract: *The current article proposes a new algorithm for topology optimization based on a fluid dynamics analogy. The new algorithm possesses characteristics similar to the most well-known methods, as the ESO/BESO method working with discrete values and the SIMP method (using OC or MMA) working with intermediate values, as it is able to work both with discrete and intermediate densities, but always yields to a solution with discrete densities. It can be proven mathematically that the new method is actually a generalization of the BESO method, and when using appropriate parameters it will operate exactly as the BESO method. The new method is less sensitive to rounding errors than the BESO method when using iterative solvers and is able to give alternative topologies to well-known problems. The article presents the basic idea, the optimization algorithm, and compares the results of three cantilever optimizations to the results of the SIMP and BESO method.*
Keywords: *topology optimization, evolutionary method, truss structures*

1. INTRODUCTION

The classical problem of compliance minimization is used to present the idea of the new method. According to the well-known formulation:

$$\begin{aligned} \min_{\mathbf{x}} \quad & C = \frac{1}{2}\mathbf{f}^T\mathbf{u} \\ \text{s.t.} \quad & \mathbf{K}\mathbf{u} = \mathbf{f} \\ & 0 < x_{\min} \le x_i \le 1 \\ & \sum x_i V_i - V_0 \cdot f = 0 \end{aligned} \quad , \tag{1}$$

where **K** is the global stiffness matrix, V_0 is the volume of the full domain, **f** is the external force acting on the structure, **x** is the design variable (density of the elements), **u** is the displacement, f is the volume ratio to be satisfied, x_i is the density of cell i, $x_{\min}$ is the minimal density of the cells, V_i is the volume of the finite element cell i.

To calculate the elemental stiffness matrix the SIMP (Solid Isotropic Material with Penalization) method is used, where the Young's modulus is calculated according to Zhou & Rozvany [1], Bendsoe & Sigmund [2] as

$$E(x_i) = (x_i)^p E_0 , \tag{2}$$

where E_0 is the Young's modulus of the solid material, and p is the penalty factor.

The sensitivity number is calculated using the formulation of BESO (Bidirectional Evolutionary Structural Optimization) method to be consistent with the definitions [3]. We can note that there is no fundamental difference compared to the definition of the sensitivity number used by SIMP, as the equation is changed only by a constant (-1/p):

$$\alpha_i = -\frac{1}{p}\frac{\partial C}{\partial x_i} = -\frac{x_i^{p-1}}{2}\mathbf{u}_i^T\mathbf{K}_i^0\mathbf{u}_i \tag{3}$$

In this formulation (3) is proportional to the increase of the mean compliance resulting from the removal of element i. If we want to minimize the compliance (C) we have to maximize the sensitivity number of the valid elements (so we have to delete elements from the solid region, which would result in low increase of the

compliance, if deleted). From here the optimized variable will be denoted by α, as with the use of sensitivities, we are actually maximizing it instead of the minimization of the compliance.
In the followings the BESO method will be reviewed shortly to be able to present the important similarities and differences between the BESO and the new algorithm. As all topology optimization algorithms, the BESO algorithm starts with the definition (see Figure 2) of the problem, followed by the discretization of the domain and with the definition of boundary conditions. Afterwards, the iterative algorithm performs either the defined number of cycles, or until convergence criteria are reached. In each cycle we perform a Finite Element Analysis followed by the calculation of sensitivity numbers. At this point it is very important to ensure a mesh-independent solution, for which reason mesh-independence filter and historical stabilization filter are applied to the sensitivities [4]. As BESO uses a different approach compared to SIMP method, a different method has to be used for handling the volume constraint. Opposed to the SIMP method, the volume constraint is not immediately applied, but rather step by step and in each cycle elements are removed or added to ensure the volume constraint of the actual step ($\sum x_i V_i - V_0 \cdot f_j = 0$, where j is the iteration number). After this step the current cycle is finished, and a new one begins.

2. QUASI-STATIC QUASI-FLUID APPROACH

Our new approach is based on a resemblance taken from the nature (as e.g. simulated annealing algorithm). Fluids usually tend to move away from high-pressure regions to lower pressure regions, or from higher values of a potential field to lower levels (e.g. waterfall) to create an equilibrium. This behaviour can be used for an optimization process. If we want to minimize a scalar-field, we simply need to define the pressure of the fluid to be higher in regions with higher scalar values, so it will move away from it. In the case of maximization however, the rule is the inverse.
After solving the equation **Ku=f** for an intermediate solution of the topology optimization process, a quasi-static quasi-fluid simulation step will be performed (further on called as QSQF). The following concepts need to be defined:

Density of the fluid continuum (the design variable itself): At the beginning of the QSQF step $\rho_f = x$, therefore $\rho_f \in [0,1]$ must be satisfied. However, following the QSQF step $x \neq \rho_f$, instead we will introduce a ***h**istorical **d**ensity-damping* scheme.

$$\rho_f^{new} = x = H_D \rho_f^{old} + (1 - H_D)\rho_f^{calc}, \tag{4}$$

where H_D is a ***h**istorical **d**ensity- damping* coefficient for stabilizing the solution (which must be within the range of [0,1]).
The idea behind this formulation is that the fluid continuum can move extremely quickly in the presence of huge pressure differences. However due to the $\rho_f = x$ definition the optimized solid structure should be updated in a coupled manner with the fluid continuum. As this would require vast computational resources, we apply instead a quasi-static approach, where the optimized solid structure and fluid continuum is updated in a segregated way. To do this however we need to make sure, that no sudden change can happen inside the continuum. This is actually similar to the averaging scheme applied to sensitivities by BESO method.

Potential field: $U(\alpha)$. The potential field acting on the fluid continuum is a function of the sensitivities. This function defines whether we are maximizing or minimizing. However without the loss of generality from here on we will only consider minimization.

Equation of state for the fluid continuum: $p_f(\rho_f)$. This function defines the connection between the pressure and density of the fluid (compressible fluid). To prevent fully void regions, the density must be between the defined values (x_{min} and 1). Additionally, the pressure must be positive.
Equilibrium equation for the fluid:

$$p_f(\rho_f) + U(\alpha) = const. \tag{5}$$

This equation means that the sum of the energy stored by the potential field and the energy resulting from the pressure of the fluid is constant in every point (see **Figure 1**). The term quasi-fluid comes from the fact that this is not an equation for a real fluid, but rather for a continuum behaving *similarly* to fluids. It is worth noting that the hydrostatic equation is very similar to the previous form:

$$p_f(\rho_f) + U_{gravity} = p_f + \rho g z = const. \tag{6}$$

In the followings we will denote *const*. in Eqn. 5 by *EquilibriumLevel*, as it represents an important parameter of the method.

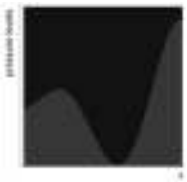

Figure 1: Quasi-static equilibrium state, Grey=Potential energy, Black=Pressure of the fluid continuum

3. WORKFLOW OF ALGORITHM AND APPLIED FILTERS

Although the main idea is easy to understand now, presenting the workflow of the optimization process is still necessary. The comparison of the BESO and QSQF method's workflow is summarized on Figure 2.

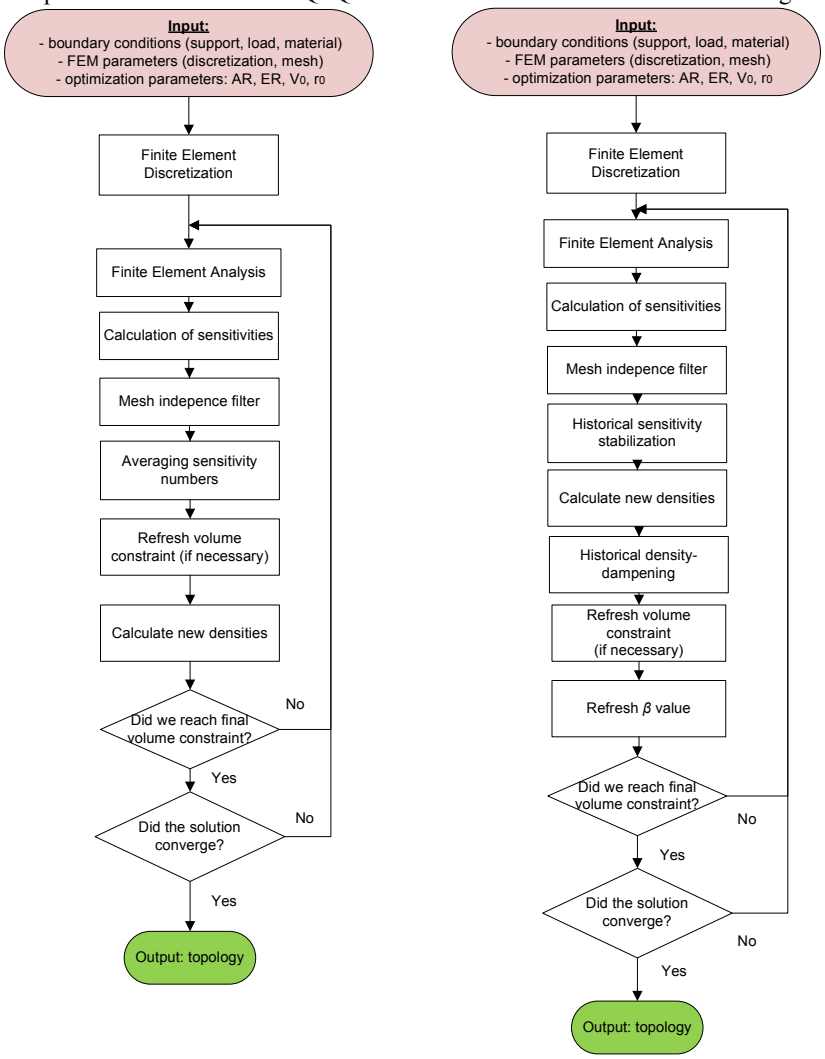

Figure 2: Proposed workflow of QSQF (quasi-static quasi-fluid) optimization (right side) compared to BESO method (left side)

One can see that although we used a completely different approach and analogy from nature, the two algorithms have very similar workflow, with the only difference being that the new algorithm is capable of working with intermediate densities. However at $\beta=\infty$ it yields to the BESO algorithm, thus it is a generalization of BESO method.

4. TEST EXAMPLE

In the followings the results of the new method are presented and compared to the results of the previous methods, SIMP&OC and BESO, using some classical problems. The FEA was solved using preconditioned conjugate gradient method with the final residual error always in the range of 10^{-6}-10^{-10} N (3D problems) and 10^{-8}-10^{-10} N (2D problems), depending on the problem. The FEA code was successfully validated against an example of a bent cantilever using ADINA R&D Inc. ADINA®.
Although the chosen problem is well-known and well-researched basic example of the optimization and thus we cannot expect to achieve huge improvement, we found it important to validate the algorithm against these tests. For the presented cases the new method has achieved the well-known solutions without error and for two cases it could even provide, although only slightly, but better solutions with different topologies compared to the literature. We consider this a major achievement, as these problems have been examined for decades.
All tests were run for 200 steps to ensure that no sudden change happens in the later iterations and C_{200} is presented along with $j_{1\%}$ and/or $j_{2\%}$, where C_j is the compliance in step j and

$$j_{k\%} = j, \text{for which } \left|\frac{C_j - C_{200}}{C_{200}}\right| \le {}^{k}\!/_{100} \tag{7}$$

Convergence criterion is reached when the compliance is within ±1 or ±2% of the compliance at step 200. This criterion was proposed in order to ensure that the final solution was really reached and not only slow convergence occurred. Except for the benchmarking of the software normal convergence criterion should be used (e.g. $\left|\frac{C_j - C_{j+1}}{C_{j+1}}\right| \le {}^{k}\!/_{100}$).

4.1 A bent cantilever

As on the field of linear elasticity, where the example was tested, the resulting structure does not depend on the magnitude of the load or Young's modulus, publications and books use many times small but easily comparable load and Young's modulus values. Here in *Example 1* we will use E=1 MPa, v=0.3, 160 x 400 mm domain with 160x40 discretization. The load is F= −1 N, the volume constraint V_f =0.5, while x_{min}=0.001, r_{min}=3.0 mm (Figure 3). The calculated values corresponded to the values given by Huang & Xie [5]
for both SIMP&OC and BESO method with the current in house code (Figures 4-7). The C_{200}, $j_{1\%}$ are given for all cases, and $j_{2\%}$ values for the examples with convergence history.

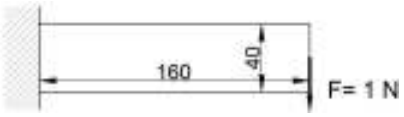

Figure 3: Problem 1

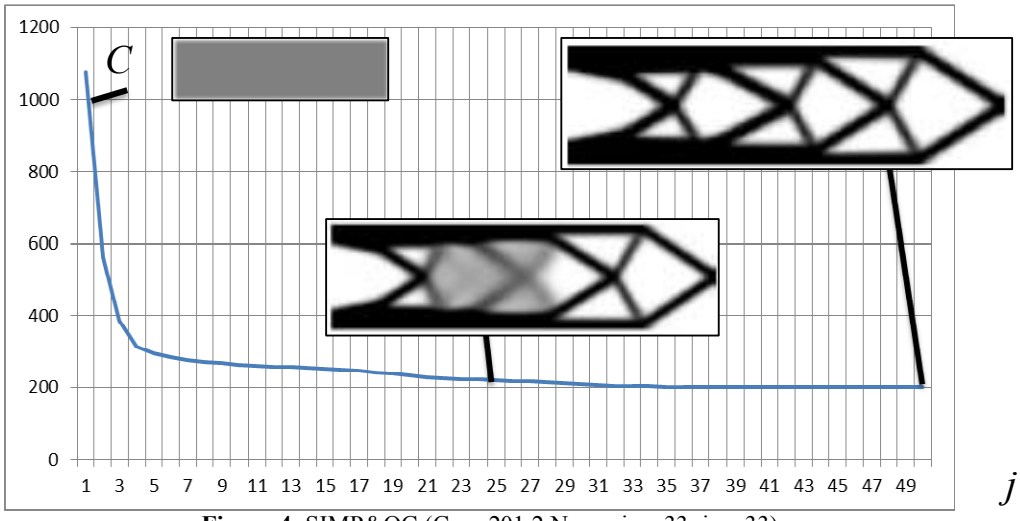

Figure 4: SIMP&OC (C_{200}=201.2 Nmm; $j_{1\%}$=33; $j_{2\%}$=33)

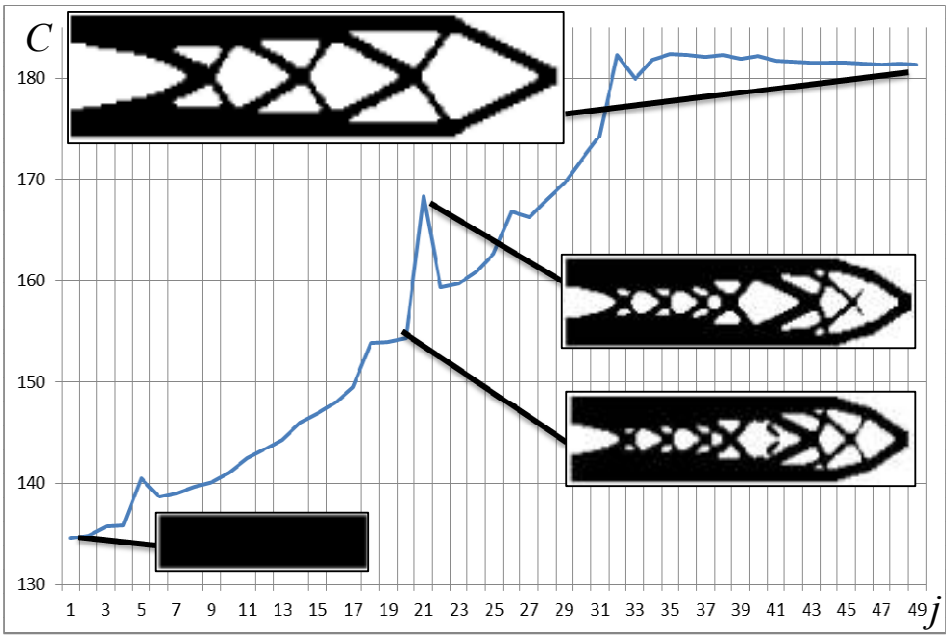

Figure 5: BESO (C_{200}=181.4 Nmm; $j_{1\%}$=32; $j_{2\%}$=32) ER=2.0%; AR_{max}=50.0%

It is important to point out that all algorithms reach the $j_{1\%}$ state at almost the same speed, but they need significantly more time to reach the C_{200} value: the SIMP method reaches the presented value only at j=188, the BESO at j=46, and the QSQF at j=93. However it is important to note, that the result given by QSQF is 0.22% lower than the result of BESO method, but with a different topology! The convergence history is given for Figures 4-6**,** while Figure 7 only presents that using a different β value the QSQF method is also able to give the previously known topology. Depending on the supports and loadings, there can be asymmetric solutions as well Cheng & Liu (2011).

Note: At SIMP the values are higher due to the presence of intermediate densities.

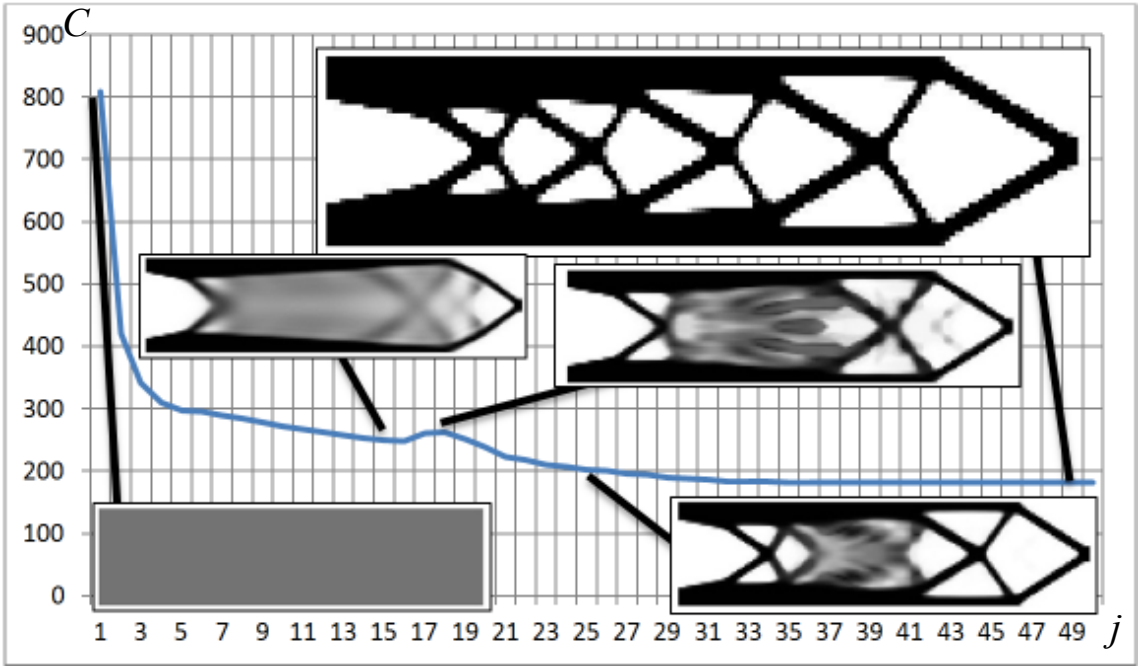

Figure 6: QSQF (C_{200}=181.0 Nmm; $j_{1\%}$=35; $j_{2\%}$=32, pcw.) V_0=0.55; ER=1.5%;H_s=0.5; H_d=0,5 (it.<30); β=4,6,8…

Figure 7: QSQF (C_{200}=184 Nmm; $j_{1\%}$=52, inv.pow) V_0=0.7; ER=1.5%;H_s=0.5; H_d=0,4 (it.<40); β=4,5,6…

5. RESULTS AND CONCLUSIONS

In this article we have proven, that the BESO method can be derived using an analogy from nature. Moreover we proposed a new algorithm, which is generalization or extension of the BESO method, as it is able to work both with intermediate densities, but in special cases ($\beta=\infty$, H_D=0) it behaves like the BESO method. Moreover due to the introduced new parameters it provides flexibility and more options than BESO or SIMP. Although at first is seems that the introduction of new parameters makes the decision maker's task more difficult, but we want to emphasize, that most parameters are only present to help advanced users in their research. Usually, H_D=0.5; H_s=0.5; β_0=4 and *piecewise linear fuzzyfication functions* are the recommended, so we only have to choose ER_{max}, AR_{max}, V_f and β_{inc}.

The main advantage of QSQF is not that it is much faster compared to SIMP or BESO method, but the different path to the solution. As the algorithm converges through designs containing intermediate densities, it is less sensitive to rounding errors (i.e. with the use of iterative solvers for the FE model) and instead of immediately deleting bars, it slowly makes them disappear, which also removes the local peaks in the convergence history (see Figure 5-6). Moreover, as topology optimization at the moment only serves as a starting tool for the design, in real world applications engineers usually use them as an intuition, and therefore they may need more alternatives for the same problem. Just note, that the QSQF method was able to find a slightly better but different topology on Problem 1 (see Figure 6 compared to Figure 4).

We would like to point out again that the main advantages of the algorithm are the generalization of the BESO method, and the possibility to provide many different, but equally good solution to the same problem, thus giving alternatives to the engineers, or the possibility to choose more aesthetic solutions, which is a more and more urging need in the field of civil engineering and mechanical engineering, where the attractivity of a product is defined more and more by its design and aesthetics, rather than structural simplicity and simple functionality.

Although extensive testing is still needed, the method can already be applied to many cases successfully. In our future work we would like to extend the analysis of the QSQF method to not only compliance minimization problems, and perform an extensive comparison to BESO and SIMP method. We would like to find other analogies as well taken from nature (e.g. the use of gravitational fields). An ambitious plan would be to find a generalization, which includes ESO, BESO SIMP and QSQF algorithm too, but the existence of such an algorithm is an open question.

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