MECHANICAL OPTIMIZATION
WITH ARTIFICIAL IMMUNE SYSTEM

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Summary
The article shows implementation of artificial immune system in the mechanical optimization. Optimization process is mainly used during new product introduction phase and ensures that new design is well balanced and includes all critical to quality items. Artificial immune system algorithm in the mechanical optimization assumes optimal solution as a pathogen and geometric configurations as a lymphocyte which are matching with optimal design.

Keywords: topological optimization, artificial immune system, algorithm

1. INTRODUCTION

Currently in Research & Development (R&D) area we can experience more attention to the shortening new product introduction timeline maintaining durability and performance aspects on the same or even higher level with respect to legacy designs. Lead time dedicated for new products has been reduced due to business constrains and competitiveness.

Essential is to provide reliable product at the very first time and address all potential issues in advance. Any significant changes in the product definition shall be introduced in early stage design since later can heavily impact program schedule and business needs.

Design is verified typically along a development process using analytical assessments basing on company procedures, templates, design practices and using commercial as well as in-house software for 2D and 3D simulations [5][6][7].

Optimization phase is very often used to balance design and support engineering decision of down selecting the most preferable solution from certain stand point. It is very clear that requirements need to be well determined because can affect final product shape. Component which is very good from performance perspective (e.g. sophisticated sealing features) could have an issue with durability. In other words, all Critical to Quality (CTQ) items need to be addressed with the same level of resolution including reliability, performance and costs.

In the mechanical optimization process we can distinguish topologic and parametric optimization. Both are used to determine shape of the component however with different degree of freedom. Topologic optimization is
the most flexible and can be employed for preliminary definition of the component or a system. Second optimization method is parametric and can precisely tune a product through explicitly defined features of the geometry.

2. ARTIFICIAL IMMUNE SYSTEMS

Immunology [4] is a discipline researching biology and biomechanics rules of immune system on pathogens and other structures classified as enemies of the internal system. Artificial immune systems are characterized by following features: detection is not driven by the central unit, system is capable to detect anomaly’s; (identification of pathogens never met in the past). Memory is created as a network and is constantly updating “learning” basing on the information from pathogens. Detection of the pathogen based on partial conformity (Fig.1).

No necessity to define negative set of examples since remaining structures (domain subtracted with own structures) became pathogens (Fig. 2).}

Artificial immune system in the optimization process is treating optimal solution as a pathogen. System is creating lymphocytes to match as much as possible with pathogen and at the same time meet all defined criterions.

3. OPTIMIZATION ALGORITHM

Artificial immune system in the optimization process uses clonal selection algorithm [4]. During initialization phase is creating memory cells (lymphocytes). Memory size during optimization process is unchanged. Subsequently each of the cell is producing defined previously number of clones and then are subjected by mutation routine. For each of the element m which belong to the generated set, algorithm is searching similar element m*.

From elements pair (m, m*) item which corresponds better to the target is maintained while worse one is replaced by new randomly selected. In the next step algorithm is ordering all memory cells. If in some subzone of the domain there is a high density of cells, then the best element is maintained while remaining are replaced by new randomly selected. In case of not meeting requirements by the best cell algorithm is starting next iteration and clone process, mutation begins up to reaching convergence criterion.

![Fig. 1. Lymphocyte type B](image)

![Fig. 2. Capability detection of immune system](image)

Algorithm of the selection is responsible for exploitation (worse items are removed) while suppression phase for exploration (domain screening).

Before solving physical task, algorithm shall be verified using dedicated test function. The aim of the verification is to check convergence of the algorithm to the well-known test function extremum. During such verification impact of the parameter on the optimization process can be verified as well.

Test function used for validation should represent physical phenomenon and optimization nature. If physical problem basing on engineering judgment has one solution in the interested domain then similar function with one extremum shall be used. For example, Bohachevsky function [8] with just one optimum:

<table>
<thead>
<tr>
<th>Parameters set</th>
<th>n=2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>[X,Y]=(-100;100)</td>
</tr>
<tr>
<td>Global extrema</td>
<td>F(X,Y)=0 for X=[0] and Y=[0]</td>
</tr>
</tbody>
</table>
Algorithm is removing a portion of the structure which is outside load path. Each lymphocyte represents potential solution (structure shape).

Essentially topological optimization [2] is set to reduce a mass with constrain on stress results. The aim for algorithm is to find minimum of the following function:

\[ J = \int \rho d\Omega \quad (1) \]

Algorithm is removing a portion of the structure which is outside load path. Each lymphocyte represents potential solution (structure shape).

Shape of the structure is described by set of control points [3]. Each control point has own value of pseudo-density \((0 - 1)\). Pseudo-density value determines if portion of the structure remains in the geometry variant or not.

Red range of pseudo-density means that element will be removed while green range maintained. Below figure demonstrates a control point concept:

This approach reduces number of parameters of each memory cell since resultant shape is defined by density function approximated through control points. For 2D structure density function became \(R3; d=f(x,y)\) while for 3D structure density function will be represented by \(R4; d=f(x,y,z)\).

As an application example of topological optimization by using artificial immune system in the article has been presented 2D structure (200mm x 100mm x 4mm). Following figure shows optimization domain with supports and mechanical load as well as control points definition:

On the contrary if engineer is expecting multiple local results. The aim for algorithm is to reduce a mass with constrain on stress results. The aim for algorithm is to find minimum of the following function:

\[ J = \int \rho d\Omega \quad (1) \]

Algorithm is removing a portion of the structure which is outside load path. Each lymphocyte represents potential solution (structure shape).

Quantity of the memory cells and clones need to be set accordingly to the optimization task. More memory cells are improving accuracy of the solution however computational time is increasing as well for each iteration.

4. TOPOLOGICAL OPTIMIZATION

Fig. 4. Test function Bohachevsky

Fig. 5. Test function Rastrigin

Fig. 6. Density distribution during optimization

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As an application example of topological optimization by using artificial immune system in the article has been presented 2D structure (200mm x 100mm x 4mm). Following figure shows optimization domain with supports and mechanical load as well as control points definition:

Fig. 7. Control points concept

Fig. 8. Optimization of the 2D plane model subjected to mechanical load

Fig. 9. Distribution of control points; system symmetry
Structure defined after 68 iterations. Parameters of the algorithm included in the table 2.

Tab. 2. Algorithm parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Clones quantity</td>
<td>8</td>
</tr>
<tr>
<td>Memory cells quantity</td>
<td>4</td>
</tr>
<tr>
<td>Parameter of mutation</td>
<td>0.18</td>
</tr>
<tr>
<td>Congestion coefficient</td>
<td>0.21</td>
</tr>
<tr>
<td>Allowable von Mises stress</td>
<td>80 MPa</td>
</tr>
</tbody>
</table>

Fig. 10. Optimized shape

Initially mass of the optimized structure was equal to 0.63kg while in the optimized shape is equal to 0.19kg (achieved percentage reduction 69%). Maximum von Mises stress is 70.5MPa and is below allowable stress set in the algorithm (von Mises stress below 80MPa).

Another example tested in the topological optimization is following 2D structure constrained on left side and subjected to the vertical load on right side (Fig. 11).

Fig. 11. Optimization of the 2D plane model subjected to mechanical load

Structure defined after 31 iterations. Parameters of the algorithm included in the table 3.

Tab. 3. Algorithm parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Clones quantity</td>
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<tr>
<td>Memory cells quantity</td>
<td>4</td>
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<tr>
<td>Parameter of mutation</td>
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<tr>
<td>Congestion coefficient</td>
<td>0.50</td>
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<tr>
<td>Allowable von Mises stress</td>
<td>200 MPa</td>
</tr>
</tbody>
</table>

Fig. 12. Optimized shape

Initially mass of the optimized structure was equal to 0.63kg while in the optimized shape is equal to 0.17kg (achieved percentage reduction 72%). Maximum von Mises stress is 144MPa and is below allowable stress set in the algorithm (von Mises stress below 200MPa).

For both analyzed structures evaluated shape not necessarily will be global extremum but for sure shall meet design target in terms of requirements set by engineer.

Parametric optimization can be implemented sub sequentially aimed to adjust thicknesses/radiiuses of the 2D structure and prepares detailed description for product definition engineer.

5. CONCLUSIONS

Artificial immune systems are used in the optimization process and support down selecting of the most balanced design concept. Both optimization types (topologic and parametric) can provide suitable design which meet defined requirements.

In mechanical perimeter typically optimization is used to determine structure with minimum material and capable to sustain defined level of the stress [1]. Nevertheless, optimization could be used as well to determine structure with desired natural frequency values; (eigenvalues to avoid any resonances in the operating ranges or to increase margin to resonant point) and this aspect is part of further research. Currently research is focused on the optimization of natural frequency of the aircraft engine low pressure turbine stator component subjected to low frequency excitation coming from rotor imbalance.
Bibliography

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