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Mechanical Project of an Automotive Part Using Numerical Analysis-Based Reverse Engineering

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Abstract. In the diverse areas of mechanical industry, sometimes it is difficult to find specific reposition parts. In such cases, it is necessary to manufacture a single part, which must have its mechanical properties similar to the original one. In this work, we develop a technique to design a replacement part based on finite element simulations and optimization techniques, seeking to produce a new part with optimal similarity to old one regarding mechanical properties, even if material, geometry and manufacturing process are not the same as in the original context. This is done by considering that there is no previous knowledge about the design loads, being known just the material and geometry. The mechanical analysis is based on triangular isoparametric finite element with cubic approximation for plane stresses elasticity. In order to perform shape optimization, we employ an evolutionary algorithm. The developed technique is applied to a lower control arm of a vehicle that is no longer under production as a replacement strategy.

Keywords: Structural Optimization, Finite Element, Genetic Algorithm.

1 Introduction

This work is inserted in the context of replacing an old part in the condition of not much previous knowledge about the original structure. This approach requires computational simulations, since the new part must behave in a similar way as the original one. In addition to the mechanical simulation a shape optimization is carried along in order to achieve a more efficient geometry.

The finite element method (FEM) applied to solid mechanics has reached an advanced level of maturity and is the most employed tool for structural analysis. Another field that has been directly linked to finite analysis, is the structural optimization, which can be viewed as an approach to reduce material waste while keeping the strength of the structure to a given load set.

Among the optimization methods applied to structural problems, two common approaches are: the evolutionary structural optimization (ESO) [1], which consists in removing (or adding) elements with respect to a sensitivity parameter; and the solid isotropic material with penalization (SIMP) [2], that does not remove elements altogether, but instead decreases or increases the density of elements according to the loading conditions.

Another possible approach, when dealing with optimization problems, especially when a cost function is difficult to derive explicitly, is to use a non-deterministic approach. Among such approaches, are the genetic algorithm based methods [3], that basically consists of random features generation and selection of the best fitted one. In this work, we use FEM combined to ESO ant to genetic algorithm to develop a reversal engineering technique to design replacement parts for old machinery.

2 Mechanical problem

Considering loads in the plane of the structure, with no loading or constraints in the thickness (much smaller) direction, a plane stress state can be assumed to simulate the structural problem. We assume such conditions to develop our reversal engineering technique for simplicity and also to save computing costs.

2.1 Isoparametric finite element model

In order to allow initially curved boundaries, and so increase the discretization precision, we use the isoparametric approach, approximating the initial geometry by the same shape function that approximates the displacements. In this case, it is essential to use a numerical integration method, as the Hammer method applied here [4].

The adopted finite element consists of 10 nodes triangles (cubic shape functions) as shown in figure 1. Such choice is made in order to give stresses representation at a good resolution level and at same time to represent accurately the curved boundaries.

Isoparametric finite element formulation for linear elasticity plane stress problems is a very well known approach and can be found in any of the FEM standard text books such as [4, 5].

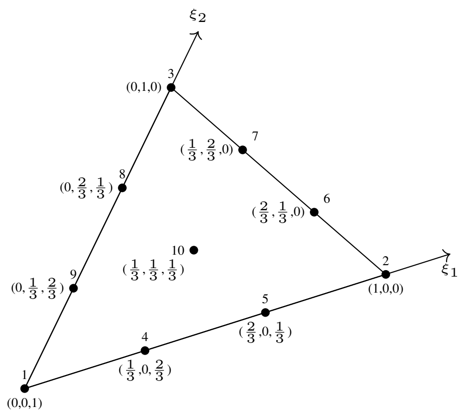

Figure 1. 10 nodes triangular finite element

3 Applied shape optimization algorithm

3.1 ESO shape optimization

The ESO method consists removing finite elements based on some criteria of sensibility. An usual sensibility criteria is the use of some equivalent stress state measure, like the Von-Mises (VM) equivalent stress. The full algorithm can be represented by the diagram depicted in Figure 2.

The mean stress in the element is given by the integral defined in Equation 3.1, and RM (rate of removal) is an increment in the minimum stress in order to remove the elements with VM stress average lower than the prescribed level.

$$\sigma_{avg} = \frac{\int_{\mathbf{\Omega}} \sigma d\Omega}{A_{\Omega}} \tag{1}$$

A significant flaw in this algorithm is the arising of the chessboard pattern, but it can be significantly reduced by the use of an artificial delay [6] in removing internal elements, the ones that will generate cavities inside the structure when removed. This adjustment consists of employing a parameter that allows for the interior elements to have a lower VM stress averages than the cutting stress value (σ_{cut}) by a factor that ranges between 0.8 and 0.9. This simple strategy in delaying the generation of cavities significantly reduced the checkerboard pattern effect.

The algorithm is initially tested in a common optimization problem, a cantilever beam restrained on one of its ends and with a concentrated load applied on the other end. The results are shown in the Figure 3, where the optimized shapes on the right present a better aspect.

3.2 Genetic algorithm for specific geometry parameters optimization

Another tool used in this technique is the genetic algorithm [3]. This step is used to find the ideal set of parameters that optimize the structure minimizing the differences of the mechanical properties between the new and the old parts. The genetic algorithm used in this work goes through the following steps:

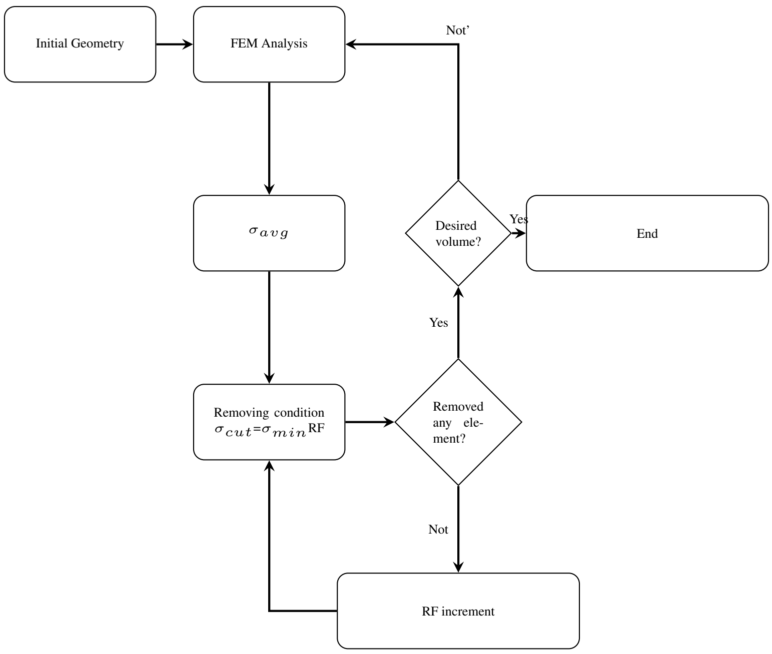

Figure 2. Evolutionary structural optimization algorithm

Figure 3. Optimization using a delay in the creation of cavities.

Algorithm 1: Genetic Algorithm

Generate individuals (random points x, y, ...) and compute cost $f(x, y, ...)$ for each;
Ascending rank population regarding cost function;
while *incomplete population* **do**
    Choose the best p individuals to be parents;
    while *iterator lt population size - number of parents* **do**
        Chance of mutation in the parent's chromosomes;
        Generate children using parent's chromosomes (*crossover*);
    end
    Append the new individuals to the population;
    for *each individual* **do**
        Compute $f(x, y, ...)$ for individual
    end
    Ascending rank population regarding cost function;
end

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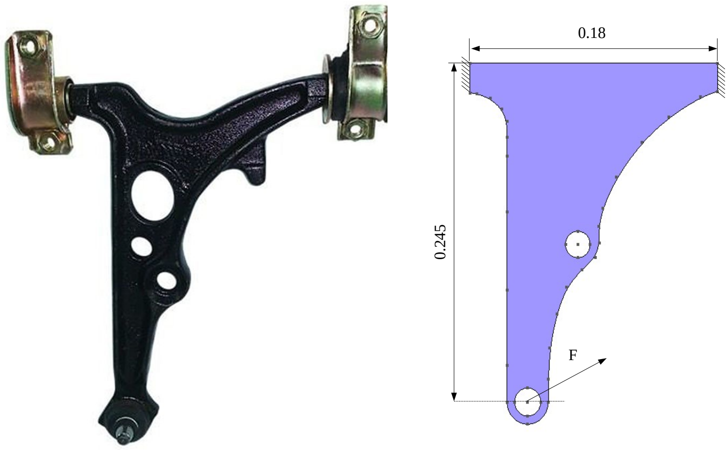
4 Numerical Application

The objective in this implementation is to get a replacing structure with mechanical properties very similar to the old one, without having prior knowledge of design loads. We consider that only the original geometry and material are known, and that the replacement part is going to be manufactured by a different process and in a different material. Alongside with the development of the structure a shape optimization is made, this is important to ensure optimum design. Optimization is made with regard to principles of manufacture (considering the part manufacturing feasibility) and geometric restrictions on the machine where the part will be assembled.

The considered part is a control arm of a vehicle out of production, with its geometry described in figure 4. A control arm is an important component of the suspension kit, being the main link between the wheels and the vehicle body. As such, this component must endure several types of loading conditions. The component may develop some stresses concentration in the boundary between the two different regions, those stresses are not considered in this work, but we assume, based on Saint-Venant principle, that they are restricted to a local area only. Also, due to the limitations imposed by the chosen finite element implementation used for the technique development, we consider the load to act only in the plane of the structure, not considering effects of torsion, bending or buckling generating displacementes in the thickness direction. Figure 4 also presents the old and new material properties.



Mechanical Properties:

E_{old} = 205 GPa

E_{new} = 72 GPa

ρ_{old} = 7.85 g/cm3

ρ_{new} = 2.70 g/cm3

σ_{0old} = 450 MPa

σ_{0new} = 200 MPa

Figure 4. Lower control arm: dimensions and properties.

As a way to ensure best overall shape to different loading conditions, we initially create a set of optimum solutions. This process was carried out by varying the direction of the applied load and optimizing the structure. The superposition of the obtained shapes shall produce the best shape for all the possible loads. This process is shown in figure 5, where the last subfigure shows the shape obtained by the manual smoothing of the superposition of the optimized shapes.

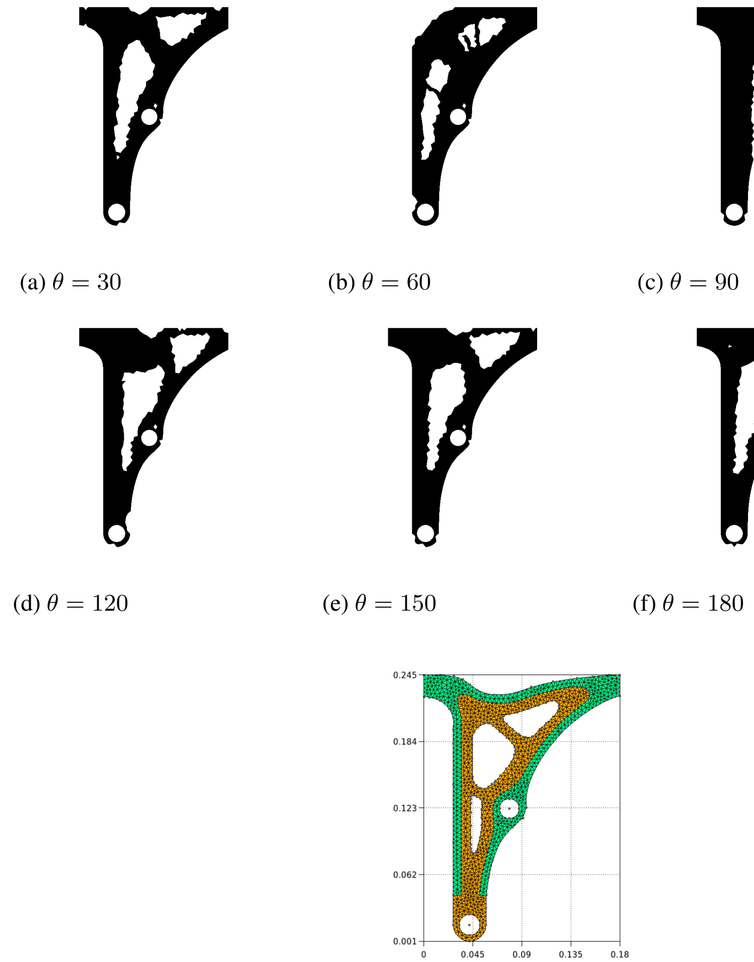
The final process of optimization seeks to ensure that the new part has similar mechanical properties as the original one, in this work:flexibility, strength (as a percentage of the yield VM stress) and the total volume are considered.

This last optimization is done by simulating the old part in the same conditions and then using its results as a reference to optimize the parameters of the new structure. The parameters considered in this optimization are the thickness of two areas: the inner region and the outer region depicted in the last figure of Figure 5.

Optimization is carried out by coupling the fem analysis with an genetic algorithm that finds the best thickness to reduce the objective function composed of the desired characteristics: the flexibilities in x and y direction; resistance, as a fraction of the maximum tensile strength; and the structure volume.

$$\begin{aligned}
\alpha_1 &= \frac{v_{ref_x} - v_{opt_x}}{v_{ref_x}}, \\
\alpha_2 &= \frac{v_{ref_y} - v_{opt_y}}{v_{ref_y}}, \\
\alpha_3 &= \frac{\sigma_{ref_i}}{\sigma_{ref_0}} - \frac{\sigma_{opt_i}}{\sigma_{opt_0}} \text{ e} \\
\alpha_4 &= \frac{V_{opt} - V_{ref}}{V_{ref}}
\end{aligned} \tag{2}$$

Flexibility and the strength are calculated for directions ranging from 0 to 180 degrees, with step of 18 degrees; so



(a) $\theta = 30$ (b) $\theta = 60$ (c) $\theta = 90$

(d) $\theta = 120$ (e) $\theta = 150$ (f) $\theta = 180$

(g) Final shape.

Figure 5. Optimization (as 75% of the original volume) shapes obtained for different loading conditions.

n = 10.

$$O(\alpha_1, \alpha_2, \alpha_3, \alpha_4) = \sum_{i=1}^{n} \alpha_{1_i}^2 + \sum_{i=1}^{n} \alpha_{2_i}^2 + \sum_{i=1}^{n} \alpha_{3_i}^2 + n\alpha_{4_i}^2 \tag{3}$$

A genetic algorithm implementation was carried out to obtain the thickness parameters that minimize the mechanical differences between the two structures as described in Table 1.

Final structure has 2 different thicknesses, the outer thicker region with 40.75 mm, and an inner thinner region with 16.88 mm. The original part is thinner in general, the simulated reference structure has 20 mm in the outer region and 10 mm in the inner region; however, since the material used in the second is lighter, the optimized structure weights 949 g while the original weighs 1599 g. There was a volume increase, mostly because the outer region of the optimized structure is much thicker than the original: 351.5 cm^3 in the optimized, versus 203.6 cm^3 in the original. An important achievement, however, was to reduce peak stress: optimized structure has a lower Von-Mises stress than the original for an identical loading condition.

5 Conclusions

This work proposed a strategy to make the structural design of a replacement part without knowledge of design criteria adopted to the original one and with different material and manufacturing process. The proposed technique starts with the basic shape definition, which is based on the superposition of different optimized shapes considering the loading acting in different admissible directions. Based on the manufacturing process, seeking a

Generation	t1 [m]	t2 [m]	O
1	0,03164	0,01595	13,69833
2	0,04212	0,01697	10,57555
3	0,04212	0,01697	10,57555
4	0,04212	0,01697	10,57555
5	0,04171	0,01646	10,53837
6	0,04113	0,01659	10,52753
7	0,04110	0,01664	10,52692
8	0,04087	0,01678	10,52498
9	0,04071	0,01681	10,52494
10	0,04082	0,01682	10,52476
11	0,04066	0,01691	10,52476
12	0,04072	0,01691	10,52470
13	0,04078	0,01685	10,52468
14	0,04074	0,01689	10,52467
15	0,04075	0,01688	10,52466

Table 1. Parameters and objective for the best individuals in each generation.

more economic design, different thickness areas are defined. Those thickness are optimized using genetic algorithms to result in a structure with mechanical properties optimally close to the ones of the original part. From the application example, where this technique is successfully applied to the design of an automotive part, we can conclude that this technique has potential to be applied to several practical problems. In order to do so, as a continuity of this work, more general finite elements should be implemented (3D shell and solid elements) in order to be extended to 3D problems, including most of the machinery components.

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(a) Optimized structure stress field.

(b) Original structure stress field.

Figure 6. Observed stress (Von-Mises) due to an identical loading condition.

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