TWO-DIMENSIONAL TOPOLOGY OPTIMIZATION APPROACH FOR DESIGNING BICYCLE FRAMES

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ABSTRACT

This paper describes, the use of the topology optimization method for designing a bicycle frame depending directly on the forces applied to it, and not only on the aesthetic parameters. For this, BESO 2D software (Bi-directional Evolutionary Structure Optimization) was used for doing FEM simulation of the frame structure seen by the side, and the topology optimization in itself. Two different approaches for extrapolating the two-dimensional results into three-dimensional designs were proposed, and these results were finally shown by using freeCAD software. The results show four different bicycle frame designs obtained by defining in the topology optimization algorithm two different percentages of volume (area) reduction. Finally, to make it easier the future manufacturing these last designs were re-interpreted using pipes like the regular bicycle frames.

KEYWORDS: Finite Element Method, Bicycle Frame Design, 2D Topology Optimization

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1 INTRODUCTION

The most of cases, the designs of the mechanical components of machinery and vehicles obey to aesthetic guidelines instead of its own mechanical requirements, this especially happens in simple vehicles such as bicycles in which the structure is always visible. In the design of car chassis, it is able to use optimization approaches without being worried about the aesthetic aspect because the chassis in most of cases is totally covered by the bodywork. For the optimization of chassis design for vehicles and robots, some algorithms have been used such as genetic algorithms (Huang & Wang, 2007), generative design optimization (Pinto Peñaherrera, 2019), morphogenesis (Meng & Jin, 2011) and topology optimization (Deng & Suresh, 2016; Linhua, Yong, & Wei, 2011; Mantovani, Campo, Ferrari, & Cavazzuti, 2018; Zegard & Paulino, 2011) among others (Scappaticci, Bartolini, Guglielmino, & Risitano, 2017). Specifically, the topology optimization method has been widely implemented for doing optimized designs of chassis and frames of vehicles such as regular cars (Meishi, Huaixian, & Tiezhu, 2017), racing cars (bin Ab Razak, bin Hasim, & bin Ngatiman, 2017), trucks (R. & Acero, 2012; Ruiz-Rosas, Forero-Casallas, & Bohórquez-Ávila, 2014), motorcycles (Kashanian, Shah, Pamwar, Sangha, & Kim, 2020; Manios, Lagaros, & Nassiopoulos, 2019), quad bikes (Vdovin, Levenkov, & Chichekin, 2019), regular bicycles (Huang & Pan, 2003; MOISSIADIS & ALLILOMIS, 2019) and electric bicycles (Wu, Wu, Lu, & Lin, 2003; Xiao, Liu, Du, Wang, & He, 2012). Additionally, this method has been used for optimizing not only the complete chassis or frame but also individual parts like swing arms (Rankhambe & Nhaichaniya, 2018), crank arms (Ismail, Na, & Koo, 2020), or even wheels (Ballo, Gobbi, Massera, & Mastinu, 2014; Joshi, Powar, Khuley, & Yesane, 2016). A large amount of the found works about the use of topology optimization of chassis and frames

for vehicles implement a 3D approach, due to the three-dimensional character of them, however, some 2D topology optimization approaches have been explored (Zeleny & Cadek, 2015). On the other hand, a bicycle frame is less tree-dimensional than a car chassis or even than a motorcycle chassis, having a three-dimensional character mainly in the wheels axis, then it is possible to consider the rest of the frame as flat. The work reported in this paper proposes a two-dimensional approach of topology optimization for optimizing a bicycle frame and how this 2D design is extrapolated to a 3D one.

2 METHODOLOGY

The organization of this work is presented as follows. First, a brief description of the Finite Element Method (FEM) or Finite Element Analysis (FEA) is shown as an introduction of the Topology Optimization method applied to mechanical structures, likewise, the software tool used to compute this optimization is referenced. The next section presents the definition of the problem to optimize (bicycle frame) and its parameters in terms of the two-dimensional FEM simulation. After that, the 2D FEM results and therefore the 2D topology optimization ones are shown. After that, a three-dimensional extrapolation approach is described and finally, the different obtained structures are implemented on a 3D CAD software to show the final designs.

2.1 Finite Element Method (FEM)

The topology optimization is based on the Finite Element Method (FEM) or Finite Element Analysis (FEA), which basically consist of dividing a big problem that involves partial differential equations in single nodes in order to reduce the complexity of solving it, this method is applicable to many of physical problems including Force-Stress over mechanical structures, which is the type of problem developed in this work. The steps to follow to obtain a FEM simulation start by defining the working area for the optimization, in this case, it corresponds to the basic mechanical design. After, the boundary conditions and constraints are defined and located on the working area, in the case of a Force-Stress problem they refer to the forces, fixed points, and material features. Then, a mesh is generated on the working area to subdivide it into nodes, this mesh could have different shape and spacing depending on the necessities, taking into account that a dense mesh implies more nodes and therefore a high computing time.

Figure 1: Steps to follow to obtain a FEM simulation.

Finally, the differential equations are solved for each node taking into account its connectivity. The final result is commonly shown with a color palette related to the value of the output variable, also it is possible to indicate the resultant

torsion or bending deforming the original mesh. Figure 1 shows an example of a cantilever (a basic mechanical structure) which is fixed in the left edge and it is applied a force on 1 N in the node correspondent to the bottom right vertex, this one shows graphically the steps described previously.

2.2 Topology Optimization

Starting from the FEM results, the topology optimization algorithm reduces the number of nodes of the working area depending on their values. Topology optimization consists of an iterative algorithm that reduces the amount of material of the working area maintaining the boundary conditions previously defined. As shown in figure 2, The FEM results show areas of low stress (blue and near colors) and areas of high stress (Red and near colors), so it is possible to optimize the area by removing the nodes of low stress keeping the connectivity between the constrains and the nodes where the force is applied. After several iterations, the algorithm gives a structure with a similar average stress value to the original one but reducing its area in a specific percentage (50% in the case of figure 2).

Figure 2: Example of a topology optimization based on the FEM results.

For all of the simulations done for this work BESO 2D software was used (Xia, Xia, Huang, & Xie, 2018), this one uses the Bi-directional Evolutionary Structural Optimization method. This software is a powerful tool which as its name implies works for two-dimensional topology designs. BESO 2D allows using only square meshes (as shown in examples of figures 1 and 2).

2.3 Problem Definition and Design Criteria

The work reported in this paper is to design a bicycle frame based on the structural necessities instead of following aesthetic directives. The main idea is defining the constraints and forces which the bicycle frame will deal with, to continue with the rest of the steps described previously, assuming that all of the structure is two-dimensional and it is seen from the side. First, the fixed structures of the frame design are defined, it means the mechanical structures that do not have to be changed by the topology optimization algorithm, these are shown by the software in dark yellow as is shown in figure 3. These fixed structures are the handlebar base pipe (left-up), the bike seat pipe (center-up), the anchor point for the rear wheel (right), and the pedal axis pipe (center-bottom). Besides, the working area was defined as a rectangle between the fixed structures previously established, this is shown in green in figure 3.

Figure 3: Work area for the optimization algorithm.

After that, the constraints are defined as the handlebar base pipe and the anchor point for the rear wheel, these two elements will work as support points for the forces applied to the structure, in the figure 3 these are shown as red triangles. On the other hand, the forces were applied to the seat pipe and the pedal axis pipe, corresponding to 443 N and 243 N respectively. The value of these forces correspond to a biker height of 70 kg distributed approximately 35% at the pedals and 65% at the seat, these are shown as light green arrows in figure 3. After, aluminum was chosen as the building material, so its mechanical features were established in the algorithm as shown in table 1.

Table 1: Material mechanical features

Material	Young's modulus	Poisson's ratio	Density
Aluminum	$6,65 \cdot 10^{10} \text{ N/m}^2$	0,34	$2698,4 \text{ kg/m}^3$

Additionally, a square mesh with 1653 nodes was defined for the design, this low number of nodes was selected to reduce the total computing time of the algorithm. Finally, the FEM was applied to the model obtaining the result shown in figure 4, where the stress values are from 1,062 MPA for the blue nodes to $2.973 \cdot 10^3$ MPA for the magenta nodes. The results of figure 4 graphically show big areas with very low resultant stresses such as 3 of the 4 corners and the middle of the rectangle, which are susceptible to be removed during the topology optimization process.

Figure 4: Finite element method applied to the work area with the boundary conditions.

3 RESULTS

For applying the topology optimization algorithm to the working area previously defined, it is necessary to set up some parameters, those are shown in table 2. The only parameter that was used as a variable design criterion was the Objective volume fraction which changes the size of the desired final area. The volume fraction was varied and tested from 50% to 25% obtaining some different resultant designs. Figure 5 shows two results (A and B) corresponding to the volume fractions of 38% and 27% respectively.

Table 2: Definition of the topology optimization software

Parameter	Value
Evolutionary volume ratio	2%
Filter radius	0,3
Convergence tolerance	0,1%
Max iteration number	200

After obtaining the topology optimization results, it is necessary to extrapolate them into three-dimensional designs, for that, freeCAD software was used as 3D design tool. Two different extrapolation approaches were proposed, in the first one the two-dimensional design is extrapolated by extruding the shape as a complete volume, and the second one approximates the shape using pipes more similar to a regular bicycle frame. For the first approach, the obtained shape is extruded in a specific thickness from the handlebar base pipe to the pedal axis pipe and the seat pipe. On the other hand, the structure shape from both the pedal axis and the seat to the anchor point for the rear wheel is extruded into two branches generating the cavity for the wheel, those branches have the half of thickness of the rest of the structure. Figure 6 shows the three-dimensional representation of both designs using the first three-dimensional approach.

Figure 5: Topology optimization applied to work area, 38% (A) and 27% (B) of the original area.

(A) (B)

Figure 6: Three-dimensional extrapolation of both designs using the first approach.

In order to make it easier the possible manufacturing of the obtained designs a second approach was proposed, this one approximates the shape obtained by the topology optimization by using pipes like the regular bicycle frames. Two different kinds of pipes were used in the designs, the ones of circle profile for the slimmer shapes and the ones of oval profile for the thicker shapes. The radius of the circle pipes and the minor radius of the oval pipes never exceed 36 mm. For the structure shape from both the pedal axis and the seat to the anchor point for the rear wheel, oval pipes were used, which have as major radius the half of the width of the two-dimensional correspondent shape. Figure 7 shows the three-dimensional representation of both designs using the second three-dimensional approach.

(A) (B)

Figure 7: Three-dimensional extrapolation of both designs using the second approach (pipes).

As shown in the obtained designs in figures 6 and 7, it is possible to design this kind of bicycle frames based on mechanical criteria instead of following aesthetic guidelines and previous design. Topology optimization not only can produce optimal designs based on mechanical parameters but this works as a source of inspiration for industrial designers for looking for new and different designs as shown in this paper.

4 FUTURE WORK

It is important to do 3D FEM simulations to corroborate that the obtained three-dimensional structures accomplish the mechanical parameters of the design. Additionally, it is possible to use directly a three-dimensional approach of topology optimization, which can produce other different kinds of 3D design without the interpretation inserted by the designer during the 2D to 3D extrapolation process.

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