Simpliefied Shape Optimisation Technique For The Design of Notched Machine Parts

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Abstract
In the last decade several methods for the optimal design of machine parts, based on bionic research results, were developed. These modern shape optimisation techniques based on finite element analyses may help to reduce stresses in notched machine parts significantly. But the geometries created by this procedures are very complex and in addition, the application of these methods is often very time consuming.

In this paper we investigate some new approaches for the optimal design of notched tension and bending rods based on the ideas of the German scientist C. Mattheck. The proposed methods are based on a simplified geometric design instead of iterative shape optimisation techniques. As a result it can be shown, that stresses can be reduced drastically. The procedure is demonstrated for the design of a connecting rod of a combustion engine.

Because of the simplicity of the method, it is also suitable for design education. Further-more we implemented the notch design procedure as a "user defined command" in the CAD program CATIA V5. This leads to a fast and reliable application in the industrial design environment.

Keywords: shape optimisation, notch stresses, finite element analysis, connecting rod

1 Introduction

Mechanical engineering often implies the design of complex shaped structures. A main concern will be stress concentration areas, also known as stress concentrators. Since they can not be always be avoided, it is important to find an optimal shape of the stress concentration area in order to minimize unwanted effects. This is not always a simple decision for mechanical engineer.

The classical solutions usually implies the use of a chamfer or a fillet. The efficiency of a such particular choice is not very easy to estimate. Modern simulation technology – based on numerical methods like Finite Element Analysis, FEA- usually make possible to optimize a shape based on a specific criteria (limits for stresses, strains, deformations, weight, etc.) This option is very efficient but implies performant software-hardware infrastructure and it is time consuming.

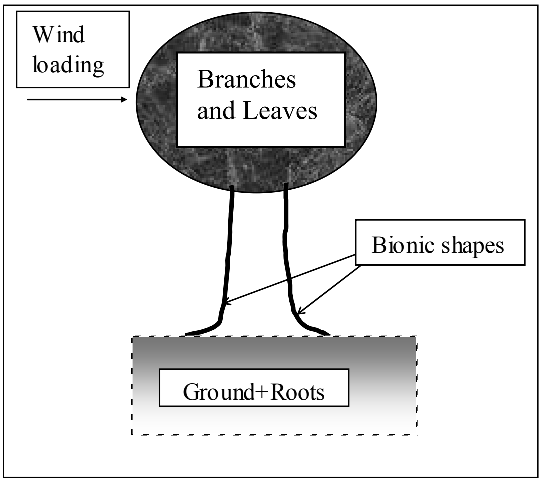

Fig. 1 Bionic shapes created by nature for trees.

An interesting alternative option is the use of bionics. Bionics, [www.en.wikipedia.org/ wiki], is the application of biological methods and systems found in nature to the study and design of engineering systems and modern technology. The word 'bionic' is possibly originating from the Greek word "βίον" - [b i o n]- meaning "unit of life" and the suffix -ic, meaning "like" or "in the manner of "like life". Figure 1 shows a tree whose branches and leaves are loaded by the wind. The roots of the tree are optimised during the growth-process of the tree. The result is an optimised bionic shape.

The transfer of technology between lifeforms and synthetic constructs is desirable because evolutionary pressure typically forces living organisms, including fauna and flora, to become highly optimized and efficient.

Professor Julian Vincent (University of Bath) estimated, [www.en.wikipedia.org/wiki], that "at present there is only a 10% overlap between Biology and Technology in terms of the mechanisms used".

Mattheck, [1], [2], suggested the use of some bionic shapes – found in natural “design” of some plants or animals - in order to optimise the mechanical behaviour of some parts used in mechanical engineering.

The most common example is the case of trees, fig. 1. Wind loading acting in an unpredictible way (intensity and direction) generates bending at the base, above the ground. In order to improve the behaviour to these conditions, the nature created some specific bionic shapes, fig. 1. Mattheck has suggested, [1], the use of these shapes in stress concentration problems.

The generation of the profile in this case is described in fig. 2, and it uses a simple geometrical algorithm recommended by Mattheck, [1]:

- AB represents the classical solution: a chamfer 45x45°. P1 equally devides the segment AB.
- An arc (center in B; radius=B-P1) is drawn up to P3´ (The intersection with the vertical through O).
- P2 is the middle of P1P3´ segment.

- A new arc (center in P3´; radius=P3´-P2) is sketched up to P4´ (the intersection with vertical in O).
- This process continues and points P1, P2, P3, P4, etc. are defined successively.

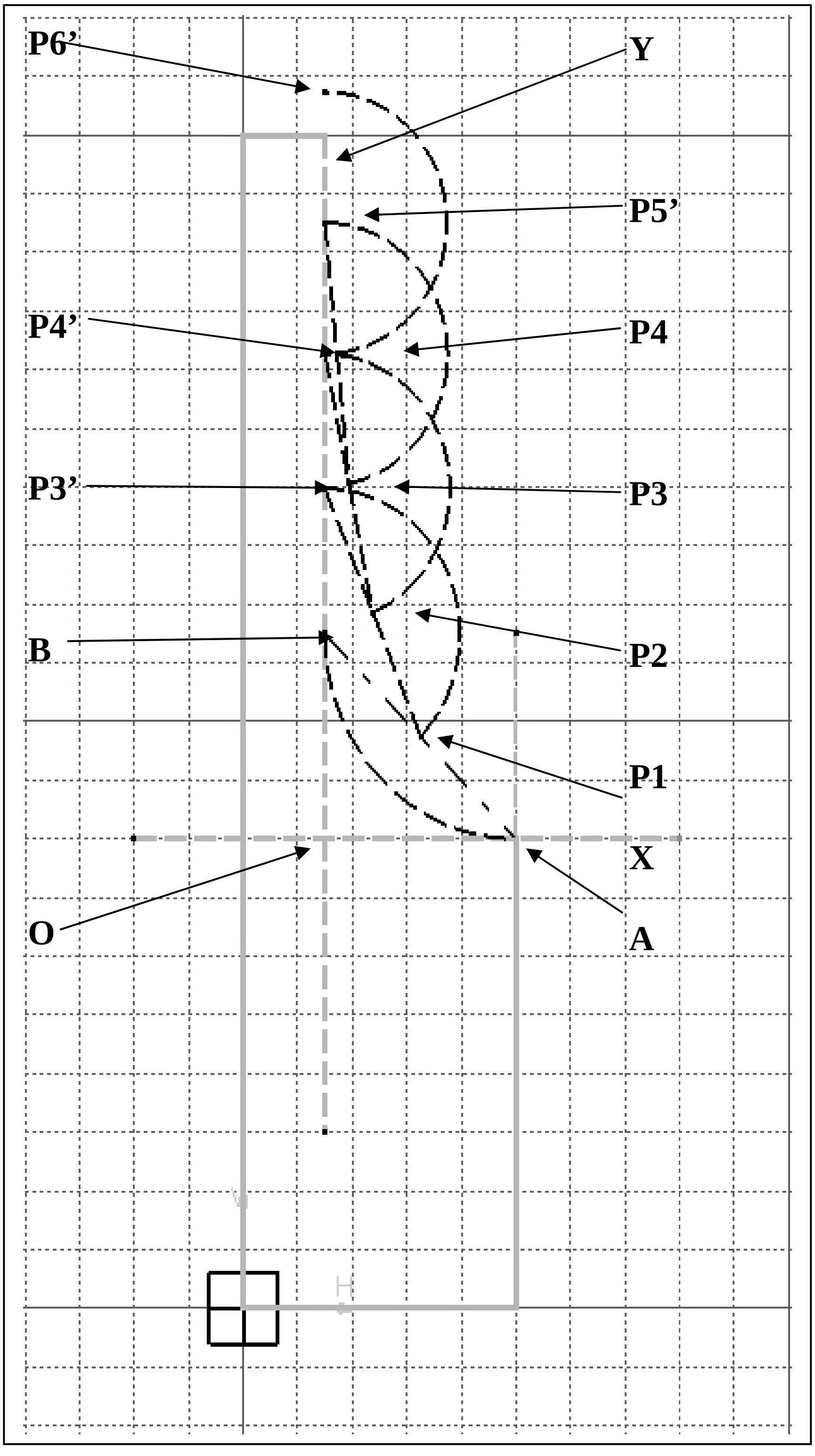

Fig. 2 Simple geometrical algorithm suggested by Mattheck, [1], [2], for modelling the bionical shape.

Originally Mattheck proposed to create the shape of the notch using arcs concatenated by tangency constraints. This approach results in a set of small CAD surfaces, which can create inconsistent finite element mesh densities during the FE meshing procedure.

In our investigation we used a spline curve (passing succesively through the points A, P1, P2, P3 and P5) which determines the new contour for the stress concentration area. In addition two tangency constraints were defined: a first one acting vertical in point P5 and a second one acting in point A in the direction of segment AB. But other choices of “troughpoints” and tangencies are possible (see chapter 4). The final shape depends of the number of points chosen or the real geometrical conditions in which the algorithm is implemented.

2 Application to a tension rod

Figure 3 shows the parametric geometry of a tension rod. The radius R could be replaced by a bionic shape according to chapter 1.

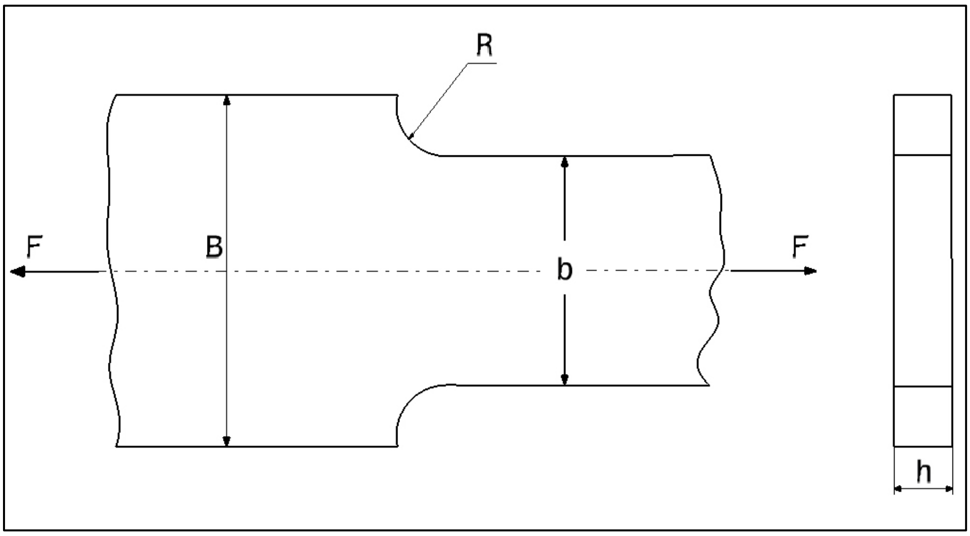

Fig. 3 Dimensions of the tension rod

Based on the CAD geometry a FEA model was developed (Fig. 4). The mesh density was adjusted to solve the numerical convergence problem [3].

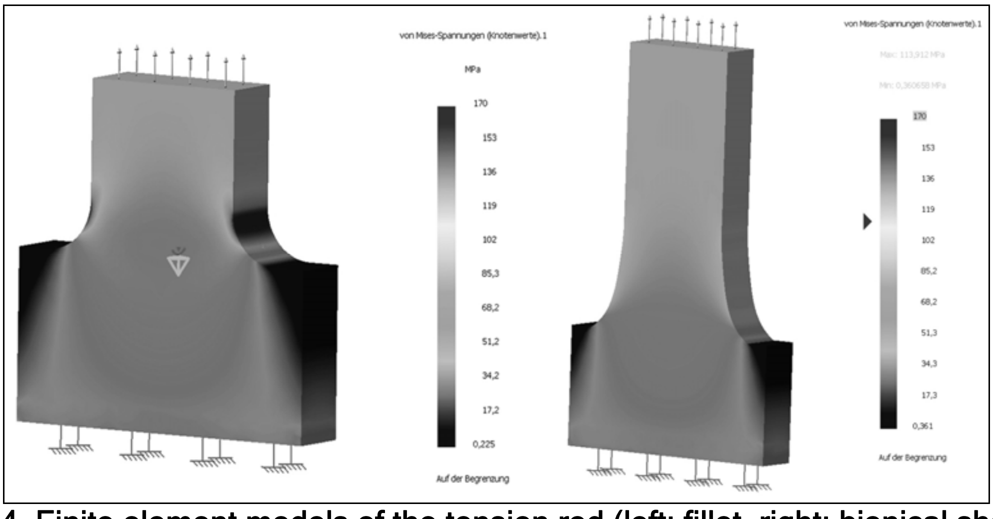

Fig. 4 Finite element models of the tension rod (left: fillet, right: bionical shape)

Stresses and deformations were computed for different geometrical parameters. The maximum Von Mises stress S_{max} and the nominal stress S_{nom} were used to calculate the stress concentration factor K_t:

$$K_t = S_{max} / S_{nom} \qquad (1)$$

For the geometric model using a fillet radius, the calculated stress concentration factors should be the same as these from textbooks [4] (Figure 5, curves B and C). If the bionical shape is used instead of the fillet radius, the stress concentration factor reduces significantly [3] (Fig. 5, curve A).

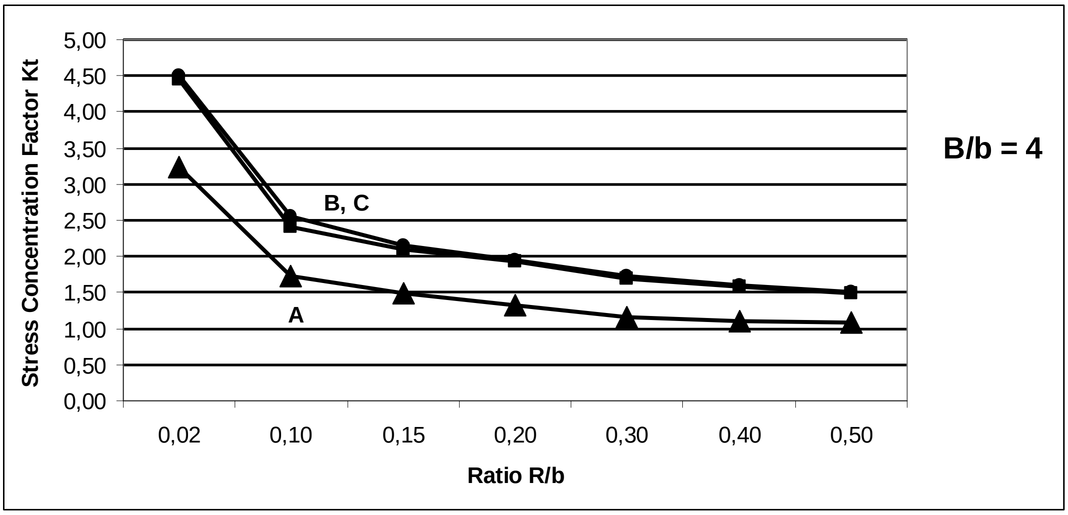

Fig. 5 Stress concentration factor K_t as a function of the ratio R/b (A: bionical shape, B: textbook, C: fea analysis)

The use of a bionical shape results in a reduced stress concentration factor K_t*. Based on this factor an improvement can be defined:

$$\text{Improvement} = \text{abs}(\ (\ Kt^* - Kt\ )\ /\ Kt\ ) \qquad (2)$$

From the data calculated by Hoppe [3] it can be shown, that for ratio values B/b greater than 1.3 an improvement of at least 9.5% is achieved. This means, that no finite element analysis is needed in these design cases. But in most cases the improvement is even greater and increases values of 20 to 30%. But in this cases the improvement must be verified by a FEA analysis.

3 Application to a connecting rod

In the following, the use of a bionic shape will be demonstrated on the design of an automotive part. We implemented the notch design procedure as a “user defined command” in the CAD program CATIA V5 for simple and reliable application.

Originally the connecting rod (fig. 6) was designed using fillet radii. The maximum stress S_{max} was determined to 146.6 MPa. Afterwards the fillet radii were replaced by bionical shapes [3]. As a consequence the maximum stress value was reduced to 121.8 MPa.

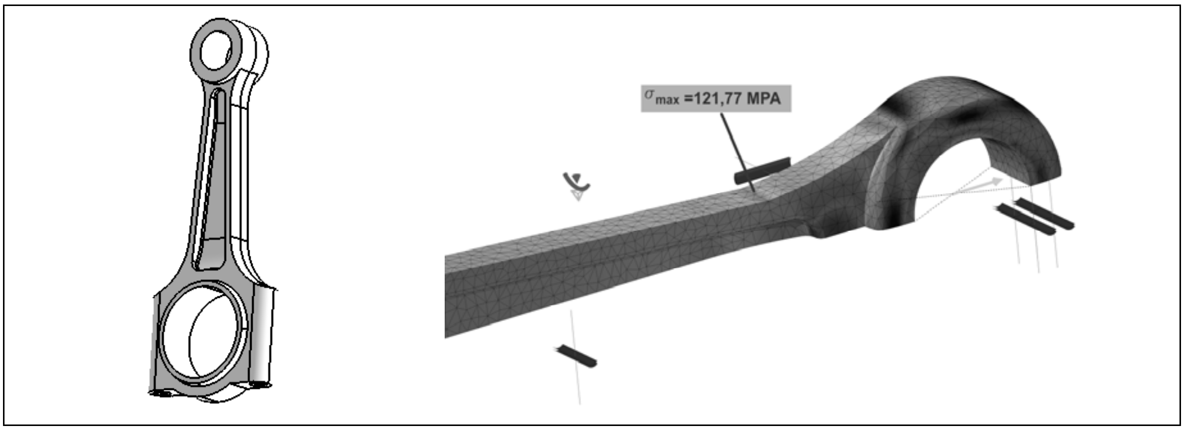

Fig. 6 Optimisation of a connecting rod of a combustion engine
(left: CAD model, right: fea analysis using symmetry boundary conditions)

4 Summary and future work

In this paper we investigated the use of a bionical shape to reduce stress concentrations. This bionical shape was suggested by C. Mattheck. Two mechanical systems were investigated: a tension bar and a connecting rod of a combustion engine. In both cases a considerable reduction of mechnical stresses was achieved using this bionical shape.

In our future work we will invesigate bending behaviour of the rod instead of tension. The first results show that even in this case the stresses decrease significantly. Furthermore we analyse round bars loaded by tension forces, bending forces and torsional moments, respectively. A first quick look at the results shows, that also in these cases the proposed method is very efficient.

As mentioned in chapter 1 modified shapes could be created from figure 2 using a spline curve. Currently, we analyse the use of a spline curve through the points A, P1, P2, P4', resulting in a shorter fillet and suboptimal stress behaviour. In addition the proposed method will be compared to older approaches discussed by Peterson [5].

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