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GEOMETRIC OPTIMIZATION OF TRANSITION ZONES BASED ON BIOMIMETICS PRINCIPLES

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Abstract

The basic definitions and a history of the development of biomimetics as a discipline that considers nature-inspired design are presented in this paper. The discussion and the results of the application of principles of nature-inspired design in machine elements design are given. The fact that transition zones that Nature chose and designed on trees in many cases survived for more than a hundred years, resisting on the various and variable external loads and other external conditions, is considered. Presented case study used the nature-inspired transition shapes in the research of innovative design and geometric optimization of transition zones of high-loaded shafts. The comparative Finite Element Analysis is performed for a particular transition zone with traditional engineering design, as well as with nature-inspired design. The conclusions about the increase of load capacity that is obtained with innovative biomimetics design are discussed.

Keywords: Geometric optimization, stress-strain analysis, biomimetics, finite element analysis, high-loaded shafts

1. Introduction

The idea to imitate Nature was developed 3000 years ago, when the Chinese attempted to make artificial silk. Roughly at the same time, another imitation of Nature that most likely resulted from humans observing the spider using its web to catch flies occurred – fishing nets (Farzaneh and Lindemann 2019). However, it can be said that human beings have always been greatly inspired by Nature. Leonardo Da Vinci designed ships based on the shapes of fish, as well as planes based on the wings of birds, but it was not until the Wright brothers observed the phenomenon that birds glide and do not flap their wings repeatedly that a somewhat successful plane was designed (Eggermont 2008). Bushnan (2009) noted that since the 1980s the artificial intelligence and neural networks in information technology had been inspired by the desire to mimic the human brain. Examples of well-known precise calculations and high "commercial" innovations can be found by engineers everywhere around. The most important for these solutions is the fact that there is no price that has to be paid. They are always available for everyone, because Nature is the best innovator to be followed. This postulate is an explanation for a number of solutions to which old civilizations came without the use of modern computers and calculations. They simply looked to Nature.

Nature has developed various shapes, materials, objects and chemical compounds that interact and have specific functions in virtually all scales of magnitude. However, Nature never develops only one property as a dominant quality, rather have tendency to interconnect geometry and surface morphology and physical and chemical properties into one very efficient biological system (Bushnan 2009). A natural system evolves through generations only to be ‘good enough’ to survive and thrive in its prevailing group of boundary conditions. In other words, Nature prefers optimal solutions, very often opposite to human thinking in quest for maximal solutions. It should be possible in the future for an engineer to take any biological system from Nature as a starting point and inspiration, and improve in the way Nature does things (Vincent and Mann 2002).

In this paper, we would like to emphasize that understanding of nature-inspired design has a slightly broader sense. Biomimetics design is the application of knowledge of biological systems in research and development for technical inventions and innovations, particularly in the field of machine elements design (Farzaneh and Lindemann 2019, Lepora et al. 2013, Benyus 1997, Vincent et al. 2006, Atanasovska and Momčilović 2019). The engineers are realizing the benefits that can be gained by the biomimetics principles according with the new requirements in machine design such as size reduction, energy efficiency increasing and higher reliability. Therefore, biomimetics has intents to grow up in a new and progressive discipline widely used in machine elements design. The conclusions developed from studies presented by Mattheck (Mattheck 1989, Mattheck 1998, Mattheck and Tesari 2002, Mattheck et al. 2008, Mattheck et al. 2009, Baumgartner et al. 1992) on stress-relieving shapes in the adaptive growth of trees, give us an idea of the possible path to improve the shape of standard machine elements, particularly in reducing the influence of stress raisers at transitions zones of high-loaded shafts.

2. Biomimetics and Machine Elements Design

2.1 Biomimetics – definition and history

Biomimetics as a scientific discipline is an inter-disciplinary approach based on the bio-inspired design. Biomimetics literally means “the imitation of life”, the word coming from a combination of the Greek words: bios (life) and mimikos (imitation). This relatively new approach connects biology and technology, generating knowledge beyond the disciplinary borders. The approach or concept of using ideas from Nature to further technology has a number of names such as “Biomimetics”, “Biomimesis”, “Biognosis” and “Bionics” (Vincent 2001). Biomimetics as well as terms ‘biomimesis’, ‘biomimicry’, ‘bionics’, ‘biognosis’ and ‘biologically inspired design’ are phrases implying copying or adaptation or derivation from biological systems. This is thus a relatively young branch of science embracing the practical use of mechanisms and functions of biological science in engineering, design, materials, chemistry etc. Helms et al. (2009) defined biologically inspired design as an approach to using “analogies to biological systems to develop solutions for engineering problems”.

Although Otto Schmitt defined the name of this discipline in 1957, when in his doctoral theses he developed and presented a physical device that mimicked the electrical action of a nerve (Vincent et al. 2006), it seems that now is the right moment for biomimetics. Momčilović et al. (2018) point up that this statement is especially valuable in the field of the machine elements design, because the processes of developing human awareness about the needs for returning to Nature and establishing harmony with the environment (expressed through the requirements for Sustainable Development, Ecology and Energy Efficiency), as well as high technological development in all spheres (Measuring Instruments, Mathematical Methods, Production

Technologies), achieve their peaks at the same point of time. In that sense, it is not surprising that this discipline tends to be among the top interests of scientists, primarily of those who deal with an inter-disciplinary approach. It is also important to underline that biomimetics does not usually mean the direct transfer or copying of an observation in Nature to the development of a product, but rather the creative implementation of biological concepts into a predefined goal. In general, the field of biomimetics addresses more than one issue (Ramachandra 2003, Eggermont 2008) and therefore our understanding of biomimetics is in its role as an inspiration.

2.2 A Role of Biomimetics in Machine Elements Design

The aim of the research presented in this paper is to point up the possibilities of biomimetics principles in the machine elements design. During last decades, the new requirements in machine elements design are placed in front of the experts. The optimization of machine elements is focused on the size reduction, energy efficiency increasing, as well as on the higher reliability. When it started to seem that the engineers were without inspiration, the disciplines returning us to Nature as an inspiration came into focus. Using biomimetics principles as an inspiration, fine optimization of present geometries of machine elements can be done, which will lead to longer and safer life of machines. The good example of solutions offered by Nature, with emphasize on design of geometry can be found in the references of few authors dedicated to research in this area (Mattheck 1998, Helms et al. 2009).

In machine elements design, biomimetics can be used in few different levels, from the low level, which includes the application of biomimetics principles in selection of only one of the characteristics of the designed machine element, up to the deep level of application, which leads to the multidisciplinary approach in design of almost all machine element characteristics by new and innovative nature-inspired design. That means that not only the geometry will be redesigned, but also the material, contact and joints, as well as maintenance will be the subject of a new approach.

The biomimetics principles application in machine elements design is at a very low level of development and application in today's engineering practice. Even we can say that there is no consistent use of these principles in the development of widely used machine elements. Although the example presented in this paper is the one of the low levels of biomimetics application, it is important to make an introduction for future research in this area.

2.3 Transition Radius on Trees Created by Nature

The transition zones that Nature chose and designed on trees in many cases survived for more than a hundred years, resisting on the various and variable external loads and other external conditions. Prof. Mattheck was one of the scientists who realized the potential in research of the way on which trees grow for engineering purposes (Mattheck 1989, Mattheck 1998, Mattheck and Tesari 2002, Mattheck et al. 2008, Mattheck et al. 2009, Baumgartner et al. 1992). Mattheck (1998) found that the transition zone created by Nature can be explain as a series of Isosceles triangles, in which each subsequent triangle has a leg equal to a half of the hypotenuse of the preceding one. The high loaded bolt is one of the first machine elements in which this principle of design is used. In this case, the biomimetics-inspired design is used for the transition zone between the head and the body of the bolt.

For the biomimetics-inspired design of the shaft to flange transition zone presented in this paper, the inspiration is found in the transition zones that Nature created on the real tree photographed and investigated in one of the parks in Belgrade, Serbia. Fig. 1 shows the examples of the transition zones on the Platanus in Topčider park (lat. Platanus acerifolia), which is a monument of Nature of the botanical character and is located in Topčider in front of Milošev konak, in Belgrade, Serbia. It is believed to have been planted around 1830. The transition zones shown in photos in Fig. 1 (a) grown up after the metal bars for supporting the very long branches of this tree are mounted. This transition zones are the excellent example how the Nature makes solutions. The schemas drawn on the photo in Fig. 1 (b) represent the transition zones simulated by series of Isosceles triangles, in which each subsequent triangle has a leg equal to a half of the hypotenuse of the preceding one, as Prof. Mattheck proposed (1998).

(a)

(b)

Fig. 1. Platanus in Topčider park, in Belgrade, Serbia (photo by D. Momčilović).

3. Biomimetics-inspired design of transition zones on shafts

In the case study presented in this paper, the biomimetics principles are used in research of the innovative design for transition zones of high loaded shafts. The inspiration is found in the geometry solutions of the Nature in the case of trees (Mattheck 1998, Momčilović et al. 2018). For the presentation of the innovative design by biomimetics principles, a particular shaft with flange is chosen. This shaft is a real horizontal hydro turbine shaft with significant radius change at transition zone from shaft to runner flange, which was the cause of failure (Momčilović et al. 2012a). Fig. 2 shows the 3D model of this shaft with the traditional engineering design of a shaft to flange transition zone. Before the end of the guaranteed working period, a failure of the shaft appeared. Momčilović et al. (2012a) concluded that it was caused by cracks on shaft to flange radius. This failure initiated comprehensive research of the deformation and stress state of the traditional design of the particular shaft in the real loading conditions. The main characteristics that make this shaft very interesting for innovating its design is the macro scale dimensions - very large diameter, which is over 2 m, and length over 7 m, and the ratio of the diameter of shaft and the diameter of flange, which is out of standard engineering ratios for which some recommendations for optimal design existed.

3.1 Transition Zone on Turbine Shaft to Flange

The geometric biomimetics principle mentioned above is used for the new design of the transition zone of this particular turbine shaft shown in Fig. 2. The traditional engineering design of shaft to flange transition zone is characterized by single radius arc with r=80 mm, as Fig. 2 shows. The Finite Element Model (FEM) is developed for this design solution. The Finite Element Analysis is performed by Momčilović et al. (2012b) in the previous phases of research for load variation, as well as arc radius variation. The conclusions about the disadvantages of the traditional design option of the shaft to flange transition zone are discussed and the obtained conclusions defined the requirement for new innovative design that will solve the existing problems about the critical stress distribution.

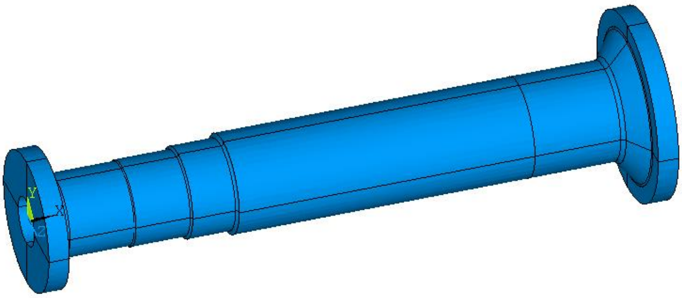
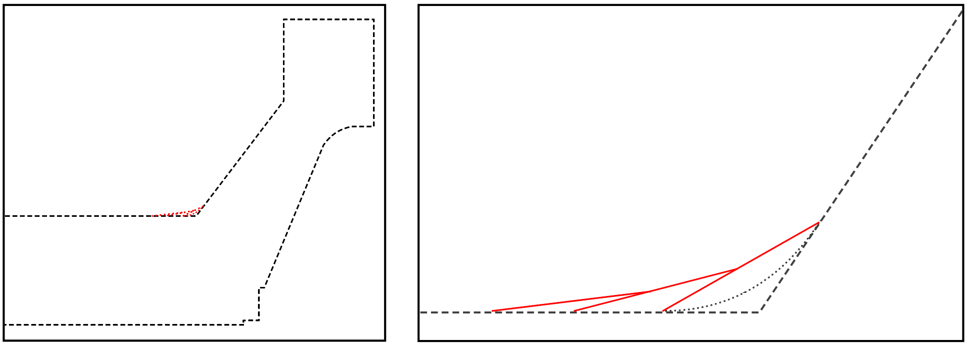


Fig. 2. 3D model of a particular hydro turbine shaft.

For the development of the new design of a transition shaft to flange zone inspired by biomimetics, the principle of the creation of generatrixes in transition zone by series of Isosceles triangles is used in accordance with above-described procedure. The detail of the new design of the transition shaft to flange zone inspired by biomimetics in correlation with traditional one is shown in Fig. 3 for the case when the hypotenuse of the first triangle has the end points in the points which matched with the end points of the arc transition in traditional engineering design. In the presented research, this case of the biomimetics design is marked as “case 1”.

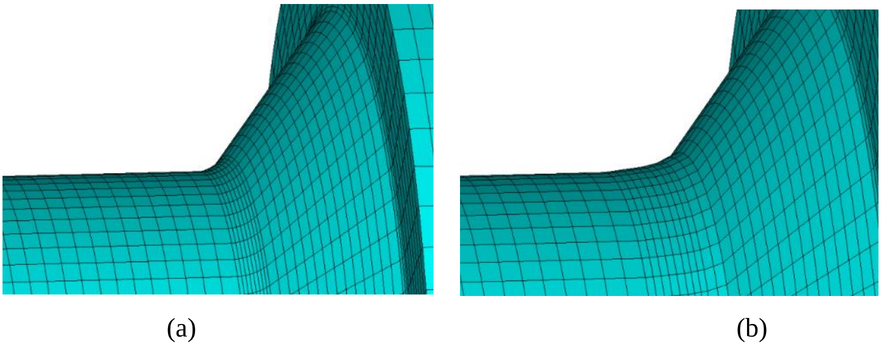
Both of the variants of the transition zone design are modeled as a part of the whole shaft model and the corresponding Finite Element Models (FEMs) are developed. The details of these models in the area of the subjected transition zone are shown in Fig. 4. The models are made with continuum discretized by the 3D structural solid finite elements defined by 8 nodes that had three degrees of freedom at each node (translations in the nodal x, y and z directions) (Momčilović et al. 2012a, Momčilović et al. 2012b).

Finite Element Analysis (FEA) is performed for both of the developed FEM models for the critical case of the external load, defined in accordance with the real operation conditions defined by Momčilović et al. (2012a, 2012b) as the regime during starting. The static load during start of the operation and change of the operating runner's blades position is defined by following load components: the maximum axial hydraulic force of F_a=5542.65·10^3 N, pressure in servomotor q=40 bar, own shaft's weight, runner's weight of G=1·10^6 N and the torque on the runner of M_t=4280.5935·10^3 Nm. The total axial hydraulic force F_a is simulated by the forces in axial direction (the x-axis direction) at points of connecting the shaft flange to the runner. The pressure in servomotor is simulated by surface pressure inside of the flange and axial force $F_p=p\cdot\pi(R^2-r^2)$, where the values of servomotor cylinder radius R=925 mm and servomotor toggle radius r=190 mm were taken over from the original turbine manufacturer's documentation. The shaft's own weight was simulated by gravitational acceleration. The runner's weight was reduced to the connection points of the flange to the runner. The torque was simulated by concentrated forces at radial direction in all the nodes at the shaft flange perimeter, so that the total torsion moment from these forces represents the torque, while the bending moments of these forces as well as the forces themselves are mutually cancelled. The results obtained for the normal tensile stresses in the direction of the axis of rotation are shown with contour plot in Fig. 5 for both of the developed models: a model with traditional mono-arc design of the transition zone and a model with innovative design of the transition zone inspired by biomimetics, which is defined previously as "case 1".



(a) (b)

Fig. 3. The new design of the transition shaft to flange zone inspired by biomimetics (case 1) in correlation with traditional one (a) and zoomed detail (b).



(a) (b)

Fig. 4. The detail of the FEM of shaft to flange transition zone: a) traditional design, b) design inspired by biomimetics (case 1).

The component of normal stresses in the direction of shaft axis defines the critical fatigue load for the considered transition zone (Momčilović et al. 2012a). Therefore, this component of the stress state results is selected for comparison and discussion. On the basis of the analysis of the results shown in Fig. 5, it is obvious that the maximum value of this component of normal stresses obtained for a new design solution is lower than the maximum value of the same component of normal stresses obtained for the traditional design.

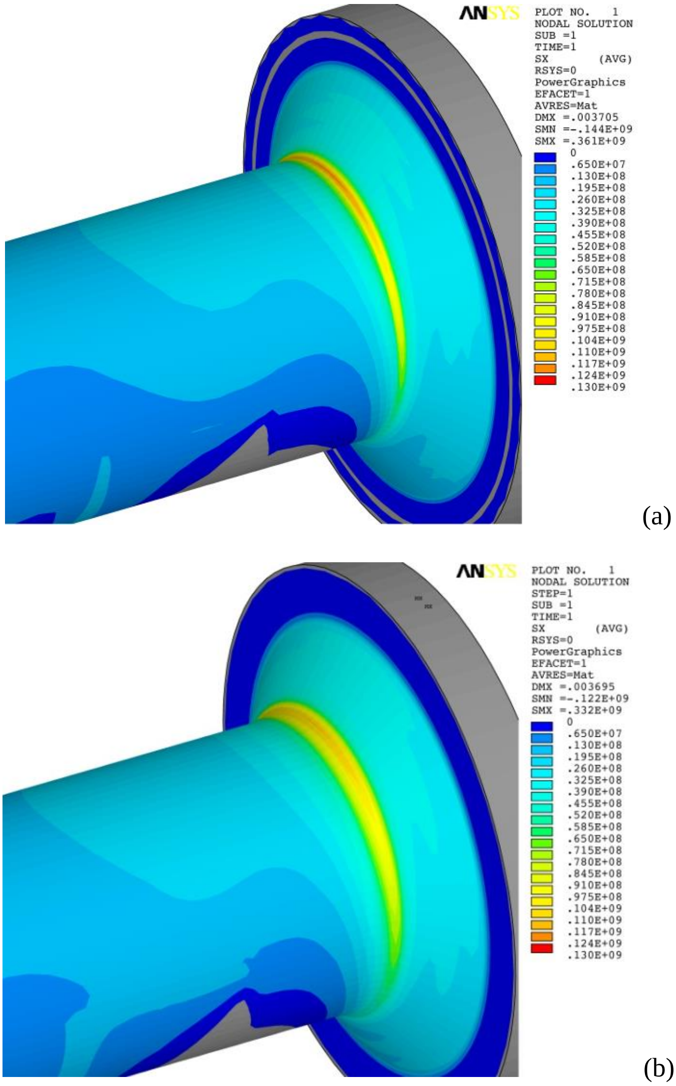


Fig. 5. FEA results for normal tensile stresses - in the direction of the axis of rotation: a) traditional design, b) design inspired by biomimetics (case 1).

4. Geometric optimization of shaft transition zone based on biomimetics design

The previous discussion has inspired further research in this direction, which is focused on the optimization of the dimension of the first triangle during the bio-inspired design (Atanasovska and Momčilović 2021). For this purpose, two additional dimensions of the first triangle are chosen and the modeled designs are marked as “case 2” and “case 3”. For the “case 2” the leg of the first triangle has a length for a quarter less than in the “case 1”, while for the “case 3” the leg of the first triangle has a length for a quarter more than in the “case 1”. The simulations of these cases of the nature-inspired design are shown in comparative drawing given in Fig. 6 (a). The obtained generatrixes for all considered cases of the transition shaft to flange zone is shown on the common drawing in Fig. 6 (b). In Fig. 6 (b) the following labels are used: (a) - for the traditional engineering design, (b) - for the design by biomimetics “case 2”, (c) - for the design by biomimetics “case 1” and (d) - for the design by biomimetics “case 3”.

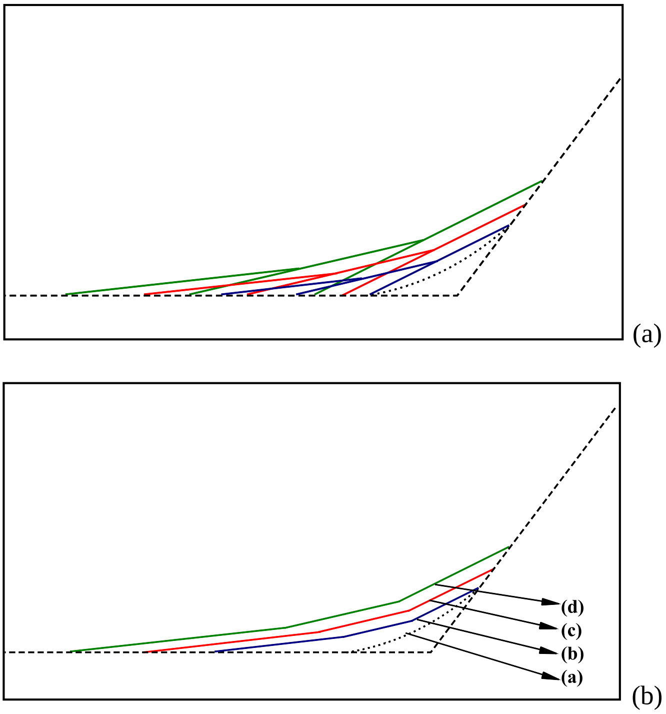


Fig. 6. Comparative drawn of traditional design and designs simulated by biomimetics principles (a) and the obtained generatrixes at the transition zone (b).

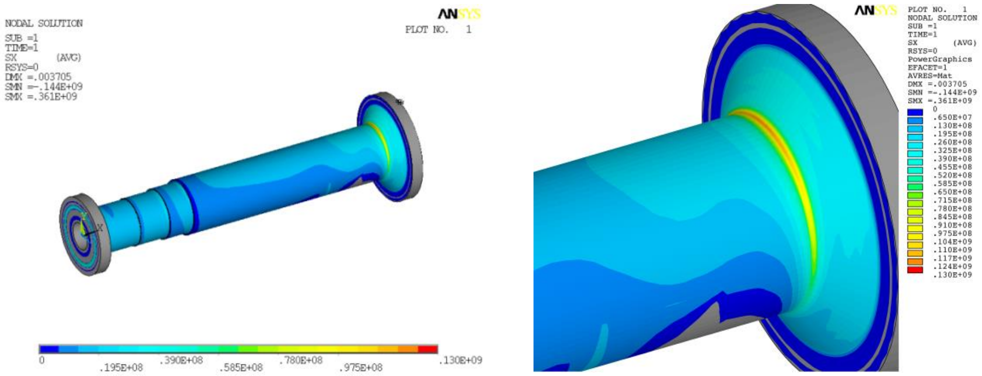
4.1 The Comparative Analysis of the Results and Discussion

In order to analyze all modeled design variants of the investigated particular shaft to flange transition zone, the Finite Element Models are developed for all cases in accordance with previously defined procedure. The FEA is performed for all designs in accordance with the selected critical external load conditions, defined in accordance with the real operation conditions as the regime during starting. The obtained results for the normal tensile stresses in the direction of the axis of rotation are shown with contour plots in Fig. 7 for each of four developed models. The results obtained for maximal normal stresses, as well as for maximal equivalent Von Mises stresses are given in Tab. 1.

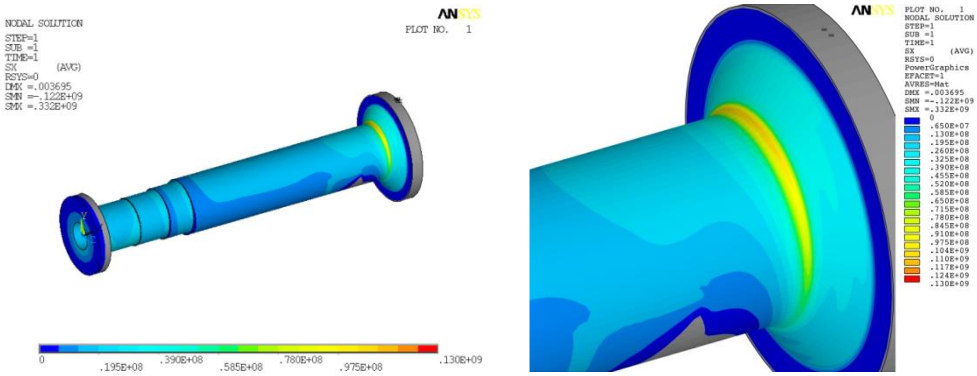
The analysis of the obtained results shows that the stress distribution has been changed with the variation of transition zone design, and the obtained differences are not only reflected in the area of the investigated transition zone but through all volumes of the studying shaft. Undoubtedly, the new design by biomimetics can bring improvement and increase in load capacity, but the results show that not all cases of biomimetics design can provide these improvements. Therefore, the deep analysis and optimization is required in order to point up the improvement for a real machine element.

The comparative contour plots shown in Fig. 7, as well as the results presented in Table 1 lead to the conclusion that the significant decrease in the maximal value of normal stresses can be obtained with the new design marked as “case 3”. This design is characterized by the extension of the transition zone. In the analyzed particular real shaft, this design is simulated with the first triangle with leg extended for a quarter, in comparison with the one in the “case 1”, as the basic biomimetics design obtained when the hypotenuse of the first triangle has the end points in the points matched with the end points of the arc transition in traditional engineering design. The finally obtained decrease in the normal tensile stresses is about 11%, while the less critical equivalent stresses remain almost the same. This represents the significant reduction and can lead to important increasing in load capacity and efficiency.

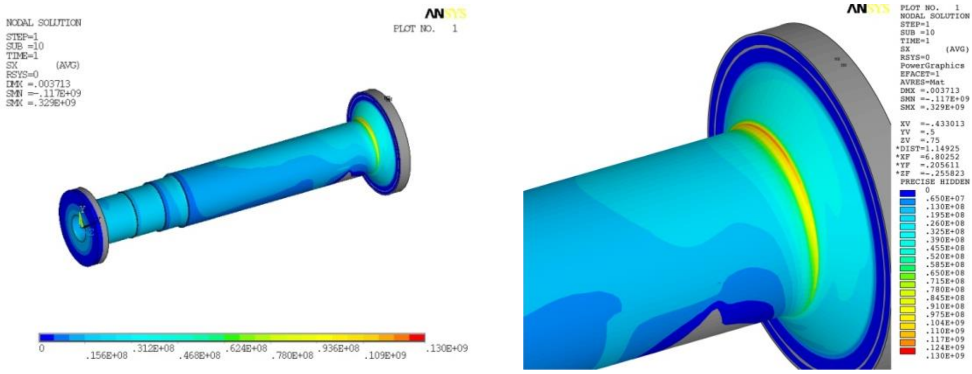
Moreover, it is very important to emphasize that the important changes are obtained in the stress gradients along material depth in the analyzed critical zone, given in Fig. 8. These gradients also give the increased fatigue resistant in the case of the design variant marked as “case 3”.



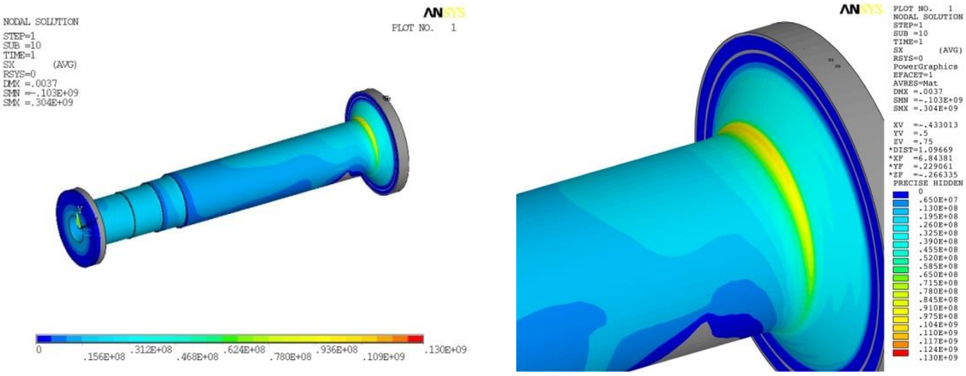
(a) traditional mono-arc design



(b) design by biomimetics - “case 1”



(c) design by biomimetics - “case 2”

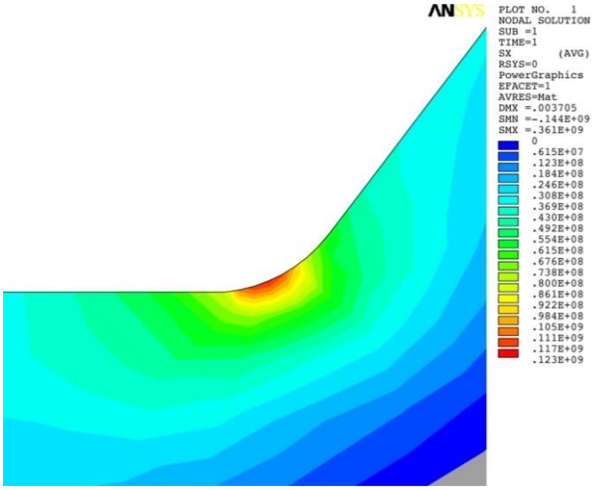


(d) design by biomimetics - “case 3”

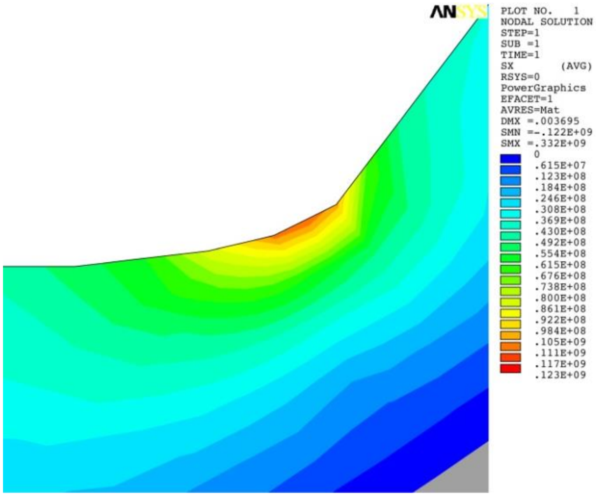
Fig. 7. FEA results for normal tensile stresses - in the direction of the axis of rotation: a) traditional design, b) design by biomimetics - case 1, c) design by biomimetics - case 2, d) design by biomimetics - case 3.

Design variant	**σ_x [MPa]**	**σ_x reduction**	**σ_{VM} [MPa]**
traditional design with *r*=80mm	119	/	127
design by biomimetics - case 1	111	6.7%	128
design by biomimetics - case 2	122	-2.52%	144
design by biomimetics - case 3	106	10.93%	129

Table 1. Comparison of the obtained normal tensile stresses (σ_x) and equivalent VonMises stresses (σ_{VM}) for considered design variants.


ANSYS
PLOT NO. 1
NODAL SOLUTION
SUB =1
TIME=1
SX (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003705
SMN =-.144E+09
SMX =.361E+09
0
.615E+07
.123E+08
.184E+08
.246E+08
.308E+08
.369E+08
.430E+08
.492E+08
.554E+08
.615E+08
.676E+08
.738E+08
.800E+08
.861E+08
.922E+08
.984E+08
.105E+09
.111E+09
.117E+09
.123E+09

(a)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STEP=1
SUB =1
TIME=1
SX (AVG)
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PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003695
SMN =-.122E+09
SMX =.332E+09
0
.615E+07
.123E+08
.184E+08
.246E+08
.308E+08
.369E+08
.430E+08
.492E+08
.554E+08
.615E+08
.676E+08
.738E+08
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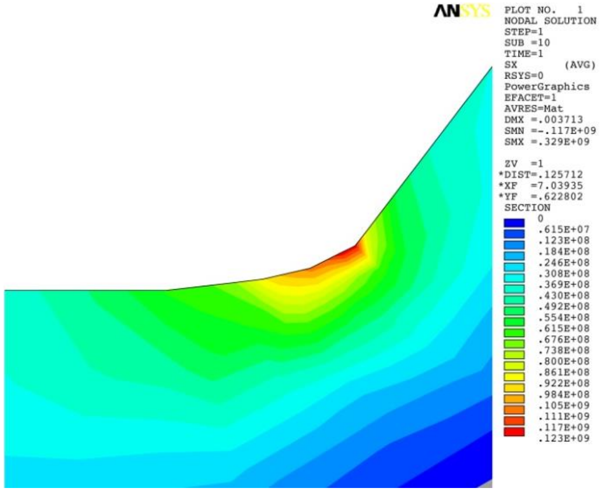
(b)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NODAL SOLUTION
STEP=1
SUB =10
TIME=1
SX (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.003713
SMN =-.117E+09
SMX =.329E+09
ZV =1
*DIST=.125712
*XF =7.03935
*YF =.622802
SECTION
0
.615E+07
.123E+08
.184E+08
.246E+08
.308E+08
.369E+08
.430E+08
.492E+08
.554E+08
.615E+08
.676E+08
.738E+08
.800E+08
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.984E+08
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.117E+09
.123E+09

(c)

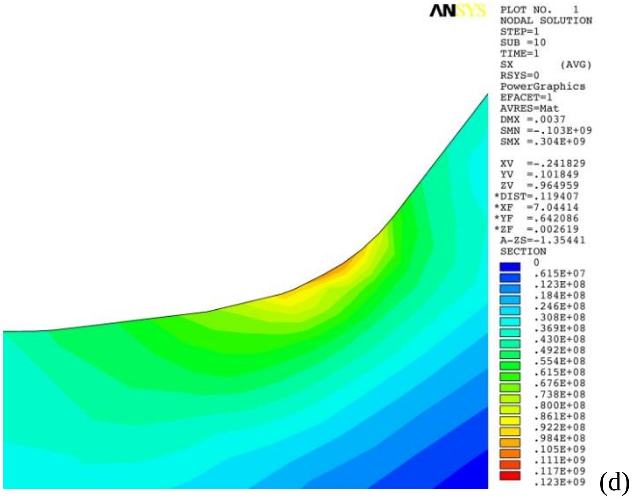

Fig. 8. The cross section plots of FEA results for normal tensile stresses - in the direction of the axis of rotation: a) traditional design, b) design by biomimetics - case 1), c) design by biomimetics - case 2), d) design by biomimetics - case 3.

5. Conclusions

The basis for application of biomimetics-inspired design in machine elements design is given in this paper in order to underline this new and prospective future frame for machine elements design and improvements. It is important to point out that this new approach is interdisciplinary and requires broad and specific engineering education.

The high loaded turbine shaft to flange transition zone is used for the new biomimetics approach presentation. The comprehensive research of stress and strain state of the few new variants in transition zone design inspired by natural solutions in trees is performed. All design variants are modeled by FEM and Finite Element Analysis is performed for the critical load case. The analysis of the obtained results leads to the conclusion that in this example the biomimetics design can provide significant increase in load capacity of the critical zones during machine element design. The decrease of about 11% of the critical tensile normal stresses is obtained, while the rest characteristics remain almost unchangeable (equivalent stresses, mass etc.). However, the presented research shows that some variants of the design by biomimetics principles can at the same time lead to the lowest load capacity of the machine element. Therefore, it is obvious that the application of the nature-inspired solutions must be done carefully and with appropriate engineering calculations and analysis. Optimization is necessary in some cases in order to finally obtain the improved design. In some cases, the future research can be required in order to obtain the optimized design for the particular machine element, such as analysis of the total mass changes, eigenmodes of oscillation changes, possibilities of the machining and production of new designed elements and so on. In many cases, not only the geometry can be redesigned, but also material, contact and joints, as well as maintenance will be the subject of the new approach.

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