Engineering analysis of bionic prosthetic arm elements in Femap with NX

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Abstract. The study is divided into two principal parts. The first is devoted to the analysis of the structure of a hand prosthesis based on the principle of electromyographic sensor. The second part of the study is devoted to the analysis of the strength of the prosthesis structural element with its further modification. The study deals with the most loaded structural elements of bionic hand prosthesis made using 3D printing. The engineering analysis was carried out while specifying various variants of prosthesis load taking into account their approximation to real conditions.

1. Introduction
The wide possibilities of additive technologies make them relevant in the modern world of digital production. At present, their functionality has significantly increased from prototyping to structures that perceive workloads. It includes such high-tech production areas as aircraft engineering, shipbuilding, instrument-making, medical engineering. In this regard, the assessment of the strength of such structures becomes ever more relevant.

A good example here is the assessment of the strength of the bionic prosthetic arm structure.

The staff and students of Irkutsk National Research Technical University (INRTU) are developing a bionic hand prosthesis for disabled persons without a wrist joint. The demand for this product is high. In addition to providing a wide functionality of the prosthesis, one of its main advantages is the affordable price. It was decided to make prosthesis parts using the additive technology – extrusion printing with plastic. Inexpensive parts that are available to a wide range of consumers are implied for the manufacture of prosthesis: ABS plastic (Striplast; ABS plastic (REC); PetG plastic (ABS Maker).

The performance characteristics of the hand bionic prosthesis make it necessary to be responsible for its strength reliability. The prosthesis design (Figure 1) represents a complex structure, which elements are simultaneously in different strain-stress states. For obvious reasons, these states change during the operation of the prosthesis.

The designed prosthesis consists of a body, a worm-type mechanism and elements that move fingers. Figure 1 shows the main features of the mechanical worm gear.

The user tenses one of the preserved muscles on a stump. An electromyographic sensor installed in the stump sleeve receives an electric pulse from a muscle and sends a signal to a microcontroller. In accordance with the control program, the microcontroller sends a signal to drives (1) on the rotation of their shafts and, accordingly, worms (2) fixed on them to one direction or another. While rotating the worms intermesh with a toothed sector on middle phalanx (4) and turn it perpendicular to a palm at bending and parallel to it at extension. Note here that the middle phalanx (4) pulls the extreme phalanx (6) pinned therewith. At the same time the rocker (5) pinned on the rack (3) and extreme phalanx (6)
rotates the extreme phalanx relative to the middle one thus ensuring the hand grasp. Figure 2 shows the extreme bending position of the hand fingers.

![Figure 1. General inside view of the prosthesis: 1 – drive; 2 – worm gear; 3 – rack; 4 – middle phalanx of a finger; 5 – rocker; 6 – extreme phalanx](image1)

![Figure 2. Grasp of prosthesis hand](image2)

2. Materials and Methods
Since the analysis of the whole design behavior is complicated by differences in material and links of the structure, it is necessary to analyze the most loaded elements. The analysis of the most loaded elements will give a general conclusion on the strength properties of the structure, since with sufficient strength of the most loaded and least strong elements, the rest of the structure will withstand the load with lower stresses. Since the main load is on the rocker element, further calculations will be made regarding this element only.

The task includes the analysis of loading options on the part of bionic prosthesis, determination of stress distribution along the structure of prosthesis elements at various loads selected during the analysis, conclusions on possible and permissible methods of prosthesis loading, recommendations for prosthesis users.

In this study, the authors completed the following main stages:
- modeling of objects for tests;
- selection of the optimum calculation scheme;
- engineering analysis of an artificial limb design for the calculation of tension and deformations;
- analysis of obtained results.

The geometry and shape modeling was performed through Siemens NX10 program. To analyze the
stress-strain state of the selected element, the geometry was imported into Femap NX Nastran environment.

Figure 3 shows the general view of the model.

![Figure 3. Prosthesis rocker geometry in Femap](image)

The boundary conditions were defined before calculation:
1. design elements of bionic prosthesis finger are made of different materials – plastic for 3D printing PETG (main design elements) and steel (binding elements – fingers);
2. printing is made in layers in different directions, the whole finger represents a mechanism (necessary to determine speed and acceleration of design points in order to highlight the most loaded elements);
3. selection of the method of applying forces, the points at which the specified load will be distributed depend on the actual conditions of the prosthesis use;
4. it is necessary to identify some elements of the structure and gradually transfer the load to them, as this method allows moving from the mechanism to static loads of each element.

In order to analyze the existing design, the experiments were previously performed to determine the printing characteristics of layers in different directions from several materials. Figure 4 shows the experiment itself.

![Figure 4. Tests of PETG samples](image)
3. Results and Discussion
As a result of these experiments, one material (PETG) was selected and its approximate printing properties were determined, which in turn will be used in software modeling.

The analysis of the general view of the structure revealed that the rocker is the most loaded element of the structure.

The first version of rocker calculation was performed taking into account the connection with a finger element (Fig. 5). The calculated position was selected to tilt the rocker 45° in the XY plane (the position of the bent prosthesis hand). The material properties were not considered in calculations, standard anisotropic material ($E=2.1\times10^5$ MPa, $\eta=0.3$, $\rho=7.89$ g/cm$^3$) – this neglect will allow defining the correctness of the calculation scheme to choose its optimal option for further calculation of layered orthotropic material. The graphic image of deformation results is shown in Figure 6.

![Figure 5. The view of rocker and finger model computational grid](image)

![Figure 6. Loading result: a – undeformed display of stress fields, b – deformed state](image)

The stresses in the area of crushing the rocker material take the values of $7.27\pm0.4$ MPa in the nodes of the hole surface.

In order to understand how much a finger-free rocker model can be used for further calculations, an analytical calculation was made.
In order to perform the analytical calculation during static loading, it was necessary to highlight the
direction of the load action on the rocker.
Since the system is movable, there is a need to specify the position of the element in space. The
rocker position at 45° was selected for the calculation, but the geometry for the calculation is somewhat
complex because the load is distributed over the surface of the Finger element. When drawing up a
simplified loading diagram, the presented structure is schematized and beam theory is used – the design
is simplified to the beam diagram, the load is represented as a central tension throughout the section.
Figure 7 shows the original dimensions of the rocker element.

![Figure 7. Rocker dimensions, mm](image)

Schematizing the loading into received 10 kg, the final simplified diagram is shown in Figure 8.

![Figure 8. Model conversion](image)

The presence of the load distribution over the finger surface, possible bending of the rocker due to
the bending moment, influence of oblique loading are neglected in simplification.
In the approximate analytical calculation, it is obtained that the stresses at the central tension have
the following value:

\[ \sigma = \frac{P}{A} = \frac{100 \cdot \cos 45}{10 \cdot 10^{-6}} = 7.071 \text{ MPa}. \]

Since the calculated value in the simplified approach is close to the value obtained from the analysis
of the model in Femap NX Nastran, namely the difference is 2.7 % of the average value, this calculated model (Fig. 3) can be used for further analysis. Therefore, it is possible to use only the rocker model in further calculations, ignoring the interaction with the finger element, as bending moments do not strongly affect the resulting stresses.

there is a need to specify a material when analyzing a real 3D printing polymer plastic design. Material characteristics are given in MPa (Fig. 9).

![Figure 9. REC ABS material properties](image)

When printing, the rocker was set to 10 layers with the thicknesses of 0.2 mm and the alternating angles of 45° and –45° respectively (Fig. 10).

Next, a static calculation was performed. Figure 9 shows the graphical results.

The maximum stress values of the model were 14.625 MPa, and the strains of the extreme nodes of the model at the place of loading were 3.7 mm. These values are not valid at only 100N loading. Therefore, it was decided to make this responsible element from steel semi-finished product.

This calculation with selected load values was also made for the rocker made of steel semi-finished product (30XGSA). Stress and displacement values were obtained – 8.23 MPa and 0.016 mm, respectively.
4. Conclusion

The tests revealed an interesting fact that the samples printed with a linear pattern and a filling density of 60% and the samples printed with a triangular pattern and a filling density of 100% have equal values of the average tensile force of the samples. A similar pattern is observed for hardness. In other words, it can be assumed that in order to achieve the required strength and hardness characteristics provided the filaments are saved, several influence parameters shall be combined in a certain way.

![Figure 10. Specifying plastic layers](image-url)
It should be noted that the volume of experiments carried out during the study does not allow drawing unambiguous conclusions on the strength and hardness of samples, and, as a result, at the moment does not allow assessing the strength of the hand bionic prosthesis. However, the results of experiments provide an opportunity to see the trends in the development of this topic and require further research with a large number of samples.

![Image of the tension pattern of the Rocker element](image)

**Figure 11.** Image of the tension pattern of the Rocker element

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