Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 99 **2018**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2018.99.7

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Ilewicz, G., Harlecki, A. Multi-objective optimization of a medical robot model in transient states. *Scientific Journal of Silesian University of Technology. Series Transport*. 2018, **99**, 79-88. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2018.99.7.

Grzegorz ILEWICZ[1], Andrzej HARLECKI[2]

MULTI-OBJECTIVE OPTIMIZATION OF A MEDICAL ROBOT MODEL IN TRANSIENT STATES

Summary. The article describes the method for the multi-objective optimization of a proposed medical robot model, which has been considered in the form of a serial kinematic chain. In the assumed approach, the finite element method was used in order to model the flexibility of manipulator links. To speed up the optimization process, the response surface method was applied, defining the so-called metamodel. In order to uncover the optimal solution, a multi-objective genetic algorithm was used, guaranteeing the optimality of the manipulator model in the Pareto sense. The optimization process was carried out by analysing the selected case of the manipulator's dynamics. The proposed optimization method allows us to minimize the mass of the manipulator while additionally ensuring the highest possible stiffness of its structure and sufficient strength of its parts. Furthermore, it offers the possibility to eliminate the natural frequency of vibrations of the model close to the resonant frequency.

Keywords: medical robot; dynamics; transient state; optimization; genetic algorithm; finite element method

[1] Faculty of Mechanical Engineering and Computer Sciences, University of Bielsko-Biała, Bielsko-Biała, Willowa 2, Poland. Email: gilewicz@ath.bielsko.pl.
[2] Faculty of Mechanical Engineering and Computer Sciences, University of Bielsko-Biała, Bielsko-Biała, Willowa 2, Poland. Email: aharlecki@ath.bielsko.pl.

1. INTRODUCTION

Medical robots are used in human surgical procedures all over the world, in such a way that recovery is quick, postoperative scars are small and the surgery itself involves no problems associated with classic endoscopic operations. Due to the accuracy of positioning the endoscope, as well as the safety of the operation, which is of paramount importance, the complexity of endoscopic surgery has many technical problems, which remain unresolved and are constantly being contemplated scientifically.

Issues related to the dynamics of a medical robot (we can also include here the behaviour of the robot in transient states), and in particular the problem with vibrations in the effector (in the form of a surgical instrument), dominate medical practice. When designing such types of robots, the aim is to minimize their mass (this is tantamount to reducing the transverse dimensions of their parts, e.g., the thickness of their walls). On the other hand, the goal is to increase the value of the lowest (i.e., basic) natural frequencies of vibrations in the manipulators, which in turn should require an increase, not a reduction, in their mass. Thus, it can be seen that such set targets contradict each other. Therefore, the weight of the robot should only be minimized in such a way that its basic natural frequency of vibrations does not decrease beyond the permissible (real) value, while the transverse dimensions of the parts should not reduce their strength beyond the permissible limit.

Various models of the dynamics of a medical robot have been published to date. For example, the dynamics model of a robot was presented, which, including its control system, was developed in MATLAB/Simulink. A dynamics model based on the usage of the finite element method was also introduced. In [2], a model was presented, which takes into account the surgical instrument load coming from the operated tissue. Moreover, many other works have been published on the optimization of the medical robot by consideration of the various criteria; among them, we can indicate the following works: [1,3,4]. Meanwhile, equations used in finite element methods can be found in the following section [6].

This work aims to optimize the full model of the dynamics of the medical robot, taking into account such criteria as mass, first natural frequency and static stress, as well as stress in transient states with the adoption of restrictions on criteria in the form of a safety coefficient and value of the first natural frequency. The following dynamic equation is solved by using the finite element method:

$$[\boldsymbol{M}]\cdot\{\ddot{\boldsymbol{u}}\}+[\boldsymbol{B}]\cdot\{\dot{\boldsymbol{u}}\}+[\boldsymbol{K}]\cdot\{\boldsymbol{u}\}=\{\boldsymbol{F}\}, \tag{1}$$

where:

$[\boldsymbol{M}]$- is a mass matrix

$[\boldsymbol{B}]$- a damping matrix

$[\boldsymbol{K}]$- a stiffness matrix

$\{\boldsymbol{u}\}$- a displacement vector

$\{\boldsymbol{F}\}$- a vector of external forces

The solution to Eq. (1) enables us to show the full strength of the model, which is close to reality due to the consideration in subsequent iterations of transitional states from previous forces and impacts.

Then, on the basis of Eq. (2), we define the eigenvalue mechanical problem with frequencies:

$$([\boldsymbol{K}]-\omega^2\cdot[\boldsymbol{M}]\cdot\{\boldsymbol{u}\})=\{0\}, \tag{2}$$

where ω is the natural frequency. Eqs. (1) and (2) are solved by using the finite element method.

2. GEOMETRICAL MODEL OF A SURGICAL ROBOT

The open kinematic chain of a medical robot considered in this work is shown in Fig. 1. A medical robot has five links connected by three rotational joints and one spherical joint.

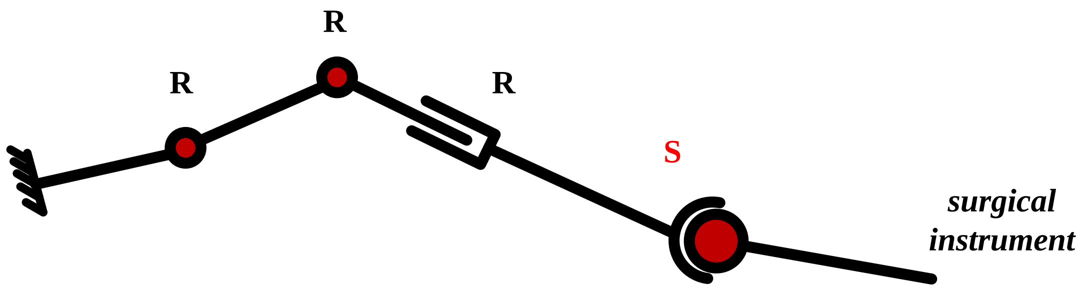


Fig. 1. Serial chain of a medical robot with revolute and spherical joints in the RRRS configuration

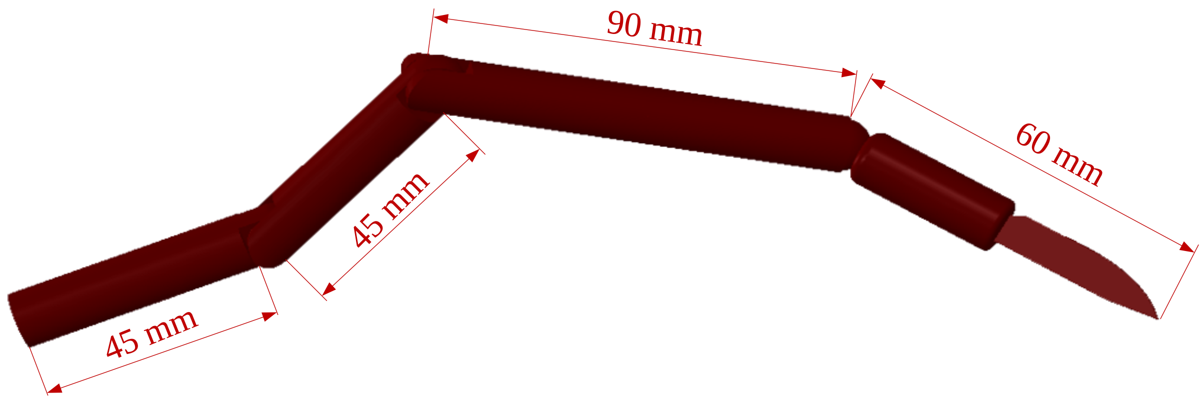


Fig. 2. Geometry model of a medical robot with a serial chain

Fig. 2 shows the geometry of the robot's kinematic chain whose dynamic is deliberated in numerical experiments. The robot's links are tubes, whose wall thicknesses may change in the optimization experiment. The kinematic chain with the presented configuration enables the tool to reach the back wall of the operated organ or the serviced artificial organ inside the human body.

3. MODEL OF THE FINITE ELEMENT METHOD

The geometric model of a medical robot was discretized by a tetrahedral element of Solid 186. The robot model was built of steel, due to its high strength as material of a real object. It is important to obtain the required safety factor in order to achieve the safety endurance of the robot. This task is extremely intricate due to the minimization problems. This was shown in [7], where, due to endurance reasons, the project of a Polish medical robot could not be completed. Fig. 3 shows a geometric model with a mesh of finite elements.

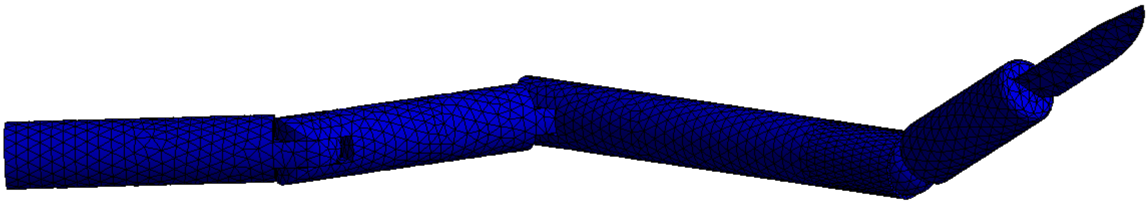


Fig. 3. Mesh model of a finite element method

The concurrence of the numerical solution with the correct values was gained for the 26,778 nodes of the mesh model. This concurrence was acquired by increasing the number of finite elements of the model until the value of the stress size stopped changing or was only slightly oscillated around this value. Fig. 4 shows a diagram of reduced stress according to the Huber-Mises hypothesis in the static state.

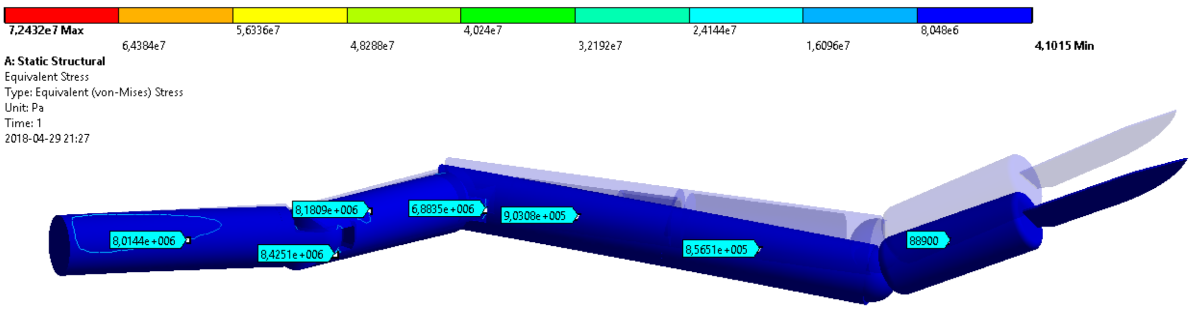


Fig. 4. The value of reduced stress according to the Huber-Mises hypothesis for a static load in the iso-tension chart

Fig. 5 shows the characteristics of tension for transient states. The system was forced to move in the first degree of freedom at a velocity of 1 [rad/s]. A 20 force [N] originating from the interaction with tissue was applied to the effector.

A significant issue for the construction of a medical robot is the work in the range of the resonance curve. It should be assumed that these vibrations are not suppressed. They can come from propulsion systems, extortions from tissue and functional activities, i.e., movements in the kinematic chain - in other words, an effector movement over a given trajectory, which can be displayed in T periods for a medical robot; as a function argument of a frequency calculated as a number of oscillations per second, it may have a resonant value in the quotient with an n. Therefore, it is important to illustrate the models (shapes of vibrations and their qualities) during resonance phenomena. Fig. 6 shows the first six shapes of vibrations for the next natural frequencies that would appear during resonance phenomena.

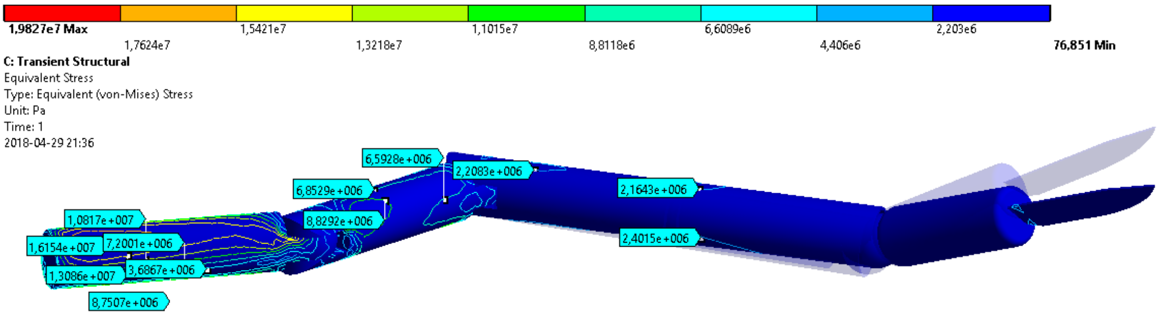
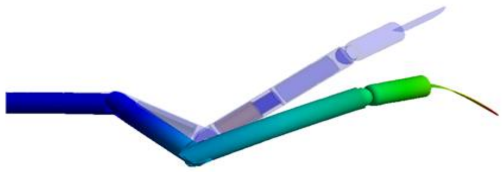


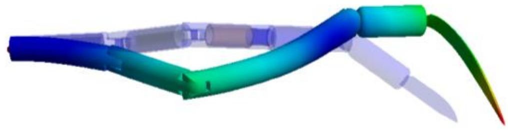
Fig. 5. The value of the reduced stress according to the Huber-Mises hypothesis for transient states in the iso-stress chart for movement in the first joint



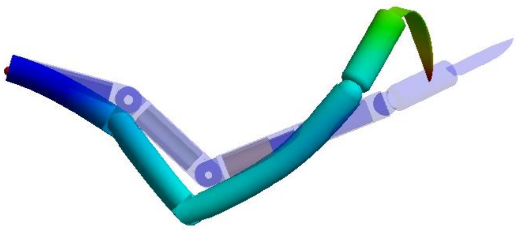
First natural frequency of 401.19 [Hz]

Second natural frequency of 479.3 [Hz]

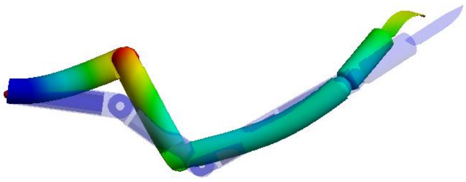
Third natural frequency of 517 [Hz]



Fourth natural frequency of 1,102 [Hz]



Fifth natural frequency of 1,398 [Hz]



Sixth natural frequency of 3,143 [Hz]

Fig. 6. Qualitative charts of displacements during resonance for the next natural frequencies looking from left to right side and from top to bottom

The first and second forms of vibrations define the lateral and longitudinal vibrations, as do the third and fourth, respectively. For higher frequencies torsional vibrations and vibrations with a more complex character appear. The numerical model of a medical robot is characterized by the tuning ability from the resonant curve.

4. STRUCTURAL OPTIMIZATION MODEL

The multi-objective optimization problem is defined in terms of finding the Pareto front for such criteria as mass, first natural frequency, safety factor, and stress in static and dynamic states. The optimization model is used to control the mechanical parameters in order to achieve the optimal properties desired in the design process. The major values are safety factor (the most important value due to the most vital criterion for the medical robot; also for any other construction), safety, balanced stiffness by its own frequency as a measure of an accurate positioning of the robot and repeatability, and stress at rest and in transient states, in which we know there are reactions inside the structure and displacements. The limitation in the first natural frequency, from which results the inflexibility of the construction, is said to be 60 [Hz] (12.5 [Hz] is the smallest natural frequency, which was found for the clinically used PUMA 560 medical robot).

The optimization function can be described as:

$$\boldsymbol{f}(\{\boldsymbol{d}\}) = \{\boldsymbol{f}_1(\{\boldsymbol{d}\}), \boldsymbol{f}_2(\{\boldsymbol{d}\}), \boldsymbol{f}_3(\{\boldsymbol{d}\}), \boldsymbol{f}_4(\{\boldsymbol{d}\})\}. \tag{3}$$

The restrictions of the model can be specified as:

$$4 \le d_1 \le 9{,}5\ [\mathrm{mm}],$$
$$4 \le d_2 \le 9{,}5\ [\mathrm{mm}].$$

In addition, other restrictions must be met:

$$\boldsymbol{f}_2(\{\boldsymbol{d}\}) \ge 60\ [\mathrm{Hz}],$$
$$\boldsymbol{f}_4(\{\boldsymbol{d}\}) \ge 4,$$

where:

$\boldsymbol{f}_1(\{\boldsymbol{d}\})$ - mass vector

$\boldsymbol{f}_2(\{\boldsymbol{d}\})$ - vector of the first natural frequency

$\boldsymbol{f}_3(\{\boldsymbol{d}\})$ - stress vector in the static state

$\boldsymbol{f}_4(\{\boldsymbol{d}\})$ - stress vector in transient states

d_1, d_2 - dimensions, resulting in the wall thickness of the first and second links

Limitations to the geometrical dimensions have a functional character, i.e., it is assumed that a space must be left inside the structure for mechanical linkages causing the movement. The optimization model is solved by using the multi-objective genetic algorithm (MOGA) [5].

To speed up the optimization process, the response surface method was used to define the so-called metamodel, which is specified through the matching of approximating functions to a set of points originating from a numerical experiment. There are statistical functions that verify the accuracy of this match (the basic one is the correlation coefficient R^2, which should reach a value close to 1 in the case of a proper match). In general terms, the response surface is the approximate analytical dependence between input and output values, which replaces the complex calculation algorithm. The response surfaces are identified by using the so-called Kriging method (also called as the spatial interpolation method). Finding the optimal solution is achievable thanks to the use of the MOGA. The applied algorithm includes optimality in a Pareto sense, based on non-dominated solutions, and provides a result in the form of a global Pareto front. In the accepted procedure, such variable and decisional values as d_1 and d_2 are searched, where the objective function $f(\{\boldsymbol{d}\})$ will guarantee the smallest mass of the manipulator, the maximum value of the first natural frequency, and sufficiently low values of equivalent stress in the case of the static and dynamic load of the manipulator.

4. RESULTS

Figs. 7-9 show the response surfaces for mass, the first natural frequency and the equivalent stress (transient state), depending on the dimensions of the medical robot links. A very good fitting of a metamodel was gained in relation to the data from numerical experiments, i.e., the coefficient of correlation R^2 was equal to 1 for all criteria.

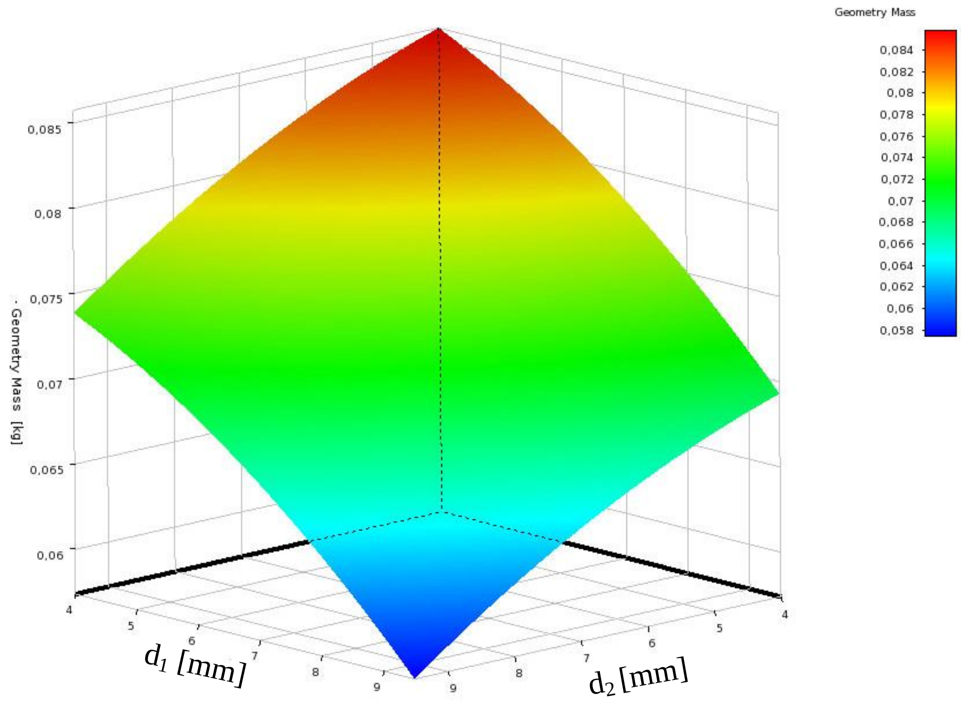


Fig. 7. The response surface for mass and dimensions

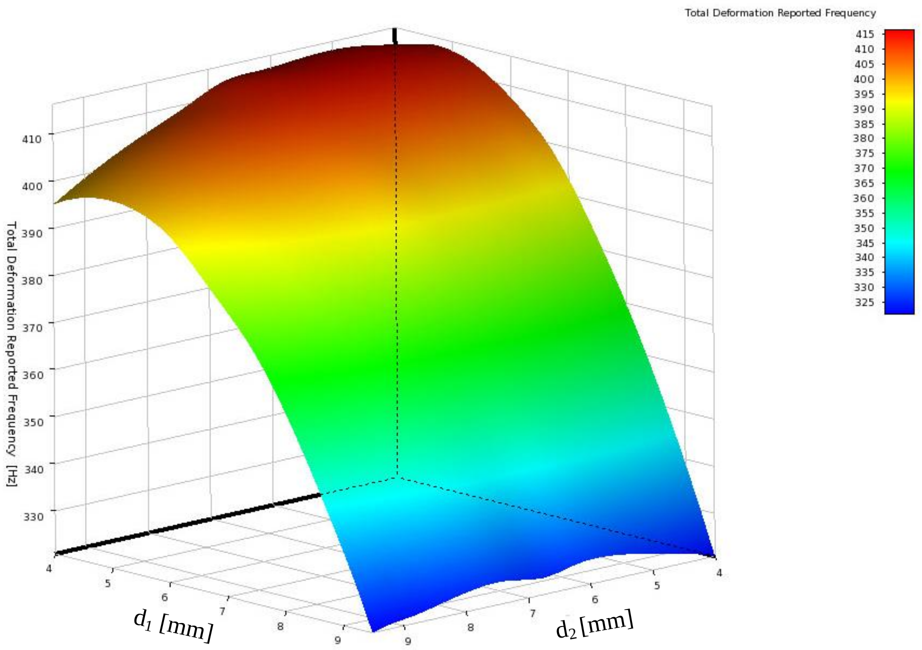


Fig. 8. The response surface for frequency and dimensions

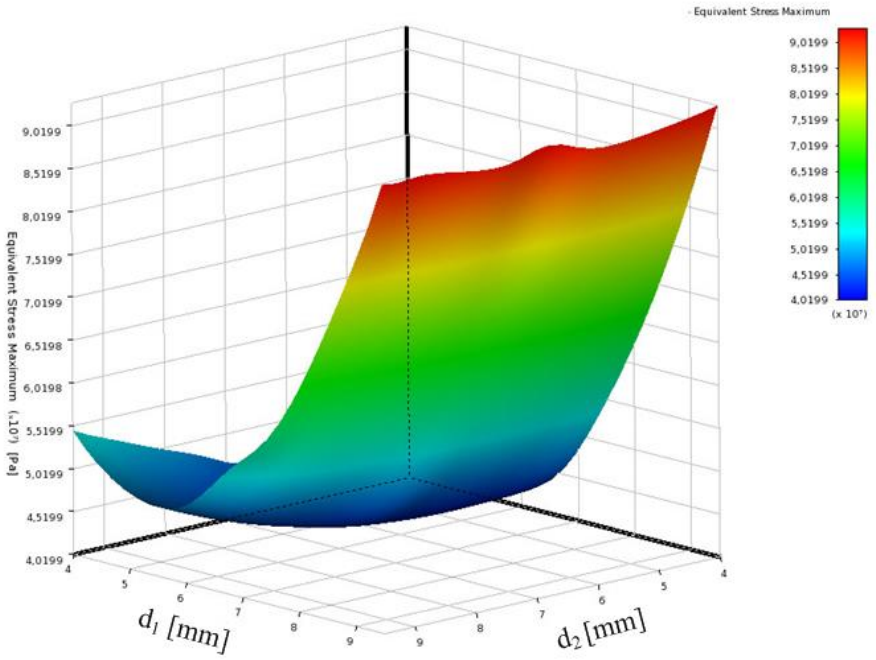


Fig. 9. The response surface for equivalent stress (transient state) and dimensions

Fig. 10 shows a graph of sensitivity towards criterions when changing the geometric dimensions for the optimal obtained solution. The graph should be read in such a way that each criterion field is composed of the percentage effect of a dimensional variable marked in colour on its value.

After obtaining the metamodel, a genetic algorithm was used to select the optimal non-dominated solution on the basis of the Pareto front.

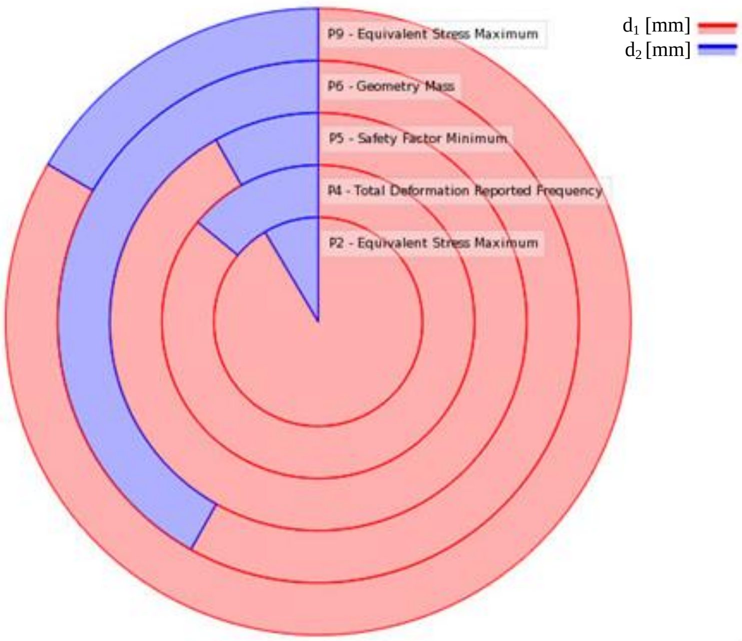


Fig. 10. The graph of sensitivity dimensions towards criterions

It was agreed that the solution would be a Pareto point, for which the mass is minimal, the first natural frequency is maximal and greater than 60 [Hz], and the safety factor is greater than or equal to 4. Using the genetic algorithm, the following values of mechanical quantities were achieved: first natural frequency of 408.33 [Hz] and mass of 0.075 [kg]. At the same time, a minimum static stress of 3.1E7 [Pa] and a minimum stress in transient states equal to 4.1E7 [Pa] were gained. These were acquired for the geometric dimensions d_1=5.2 [mm] and d_2=6.2 [mm] and a safety factor equal to 7.8.

5. CONCLUSIONS

This work proposes a model of dynamics including the solution for a full Newton's equation for the deformable block in the non-inertial system. The finite element method has been applied, which is characterized by a good approximation of actual dynamics states in a numerical manner, as well as being the basic method of choice for the structural analysis of systems with complex geometry and load condition, taking into account the forces appearing in the motion. Deformations from previous states were included in each subsequent iteration of the analysis. To date, this medical robot model has not been reported in the literature for which a multicriterion optimization experiment has been carried out. The results of optimal mass and stiffness for a medical robot were obtained for the given limits. The achieved numerical model allows for the real object to be tuned from the resonant ranges. In further works, the numerical model will be applied to a model with a DC motor and a control system based on the PID regulator.

References

1. Grebenişan G., N. Salem. 2017. "The multi-objective genetic algorithm optimization of a superplastic forming process, using Ansys". In: *Proceedings of the International Conference IMT Oradea*. 27-29 May 2017. Baile Felix, Romania. ISSN: 2261236X. DOI: 10.1051/matecconf/201712603003.
2. Yang J., L. Yu, L. Wang, Z. Wang, W. Wang. 2017. "Dynamic modeling and analysis of the instrument arm based on the physical properties of soft tissues". In: *Proceedings of the Institution of Mechanical Engineers Part C*: article in press. ISSN: 09544062. DOI: 10.1177/0954406217715661.
3. Li Jianmin, Shuxin Wang, Xiaofei Wang, Chao He. 2010. "Optimization of a novel mechanism for a minimally invasive surgery robot". *International Journal of Medical Robotics and Computer Assisted Surgery* 6 (1): 83-90. ISSN: 1478-5951. DOI: 10.1002/rcs.293.
4. Miroir M., J. Szewczyk, O.Y. Nguyen, S. Mazalaigue, A.B. Grayeli, O. Sterkers. 2009. "Mechanical design and optimization of a microsurgical robot". In: *Proceedings of Eucomes 08, The Second European Conference on Mechanism Science*: 575-583. 17-20 September 2008. Cassino, Italy. ISBN: 978-1-4020-8914-5. DOI: 10.1007/978-1-4020-8915-2_69.

5. Wang Wei, Weidong Wang, Wei Dong, Hongjian Yu, Zhiyuan Yan, Zhijiang Du. 2015. "Dimensional optimization of a minimally invasive surgical robot system based on NSGA-II algorithm". *Advances in Mechanical Engineering* 7 (2): 83-90. ISSN: 1687-8140. DOI: 10.1177/1687814014568541.
6. Zienkiewicz Olek, Robert Taylor, J.Z. Zhu. 2013. *The Finite Element Method: Its Basis and Fundamentals*. Oxford: Elsevier Ltd. ISBN: 9781856176330.
7. Leniowska Lucyna, Leniowski Ryszard. 2016. "Technological limitations of surgical robotics on the example of a robot Roch-1". *Acta Bio-Optica et Informatica Medica* 2(3). ISSN: 1234-5563.

Received 29.02.2018; accepted in revised form 30.05.2018