MODEL OF MEDICAL ROBOT WITH A NOVEL STRUCTURE OF KINEMATICAL CHAIN IN TUMOR OPERATION

MODEL ROBOTA MEDYCZNEGO Z NOWĄ STRUKTURĄ ŁAŃCUCHA KINEMATYCZNEGO DO OPERACJI ONKOLOGICZNYCH

Grzegorz Ilewicz[1, 2]

[1] Uniwersytet Rzeszowski, Wydział Matematyczno-Przyrodniczy,
Katedra Mechatroniki i Automatyki, 35-310 Rzeszów, ul. Pigonia 1

[2] International Society for Medical Robotics

*e-mail: gilewicz@ur.edu.pl

ABSTRACT

A model of medical robot for tumor operation is presented. To provide the possibility of changing the access port without moving the whole construction, one prismatic pair was added to kinematical structure. Two eigenvalue problems of mechanics were calculated using finite element method, to get information about possibility of resonance phenomenon for kinematical chain and the load factors that give information about dangerous values of external critical force. From stiffness point of view, presented construction is better than most popular da Vinci and Robin Heart. The structure of kinematical chain is also different from those occurring in these two robots.

Keywords: medical robot, innovation, finite element method, eigenvalue problems of mechanics

STRESZCZENIE

W pracy pokazano model robota medycznego do operacji nowotworowych. W celu umożliwienia zmiany portu dostępowego bez konieczności ruchu całej konstrukcji robota zastosowano dodatkową parę kinematyczną przesuwną. Dwa problemy własne mechaniki zostały obliczone używając metody elementów skończonych po to, żeby uzyskać informację o zjawisku rezonansu łańcucha kinematycznego i współczynnikach obciążeniowych, które dają informację o niebezpiecznych wartościach obciążenia krytycznego. Mając na uwadze sztywność konstrukcji, proponowane tu rozwiązanie jest lepsze od tego stosowanego w najbardziej popularnych robotach medycznych tj. da Vinci i Robin Heart. Struktura kinematyczna robota jest również odmienna od tych stosowanych w dwóch przytoczonych konstrukcjach.

Słowa kluczowe: robot medyczny, innowacja, metoda elementów skończonych, zagadnienia własne mechaniki

1. Introduction

Medical robotics is a modern medicine technique used in operations of the human body. There are many mechatronic devices, in such areas as cardio surgery, neurology, and joint replacement. There are also artificial organs which repair applications of medical robots [1, 2]. The most important, in the field of operation, is the structure of kinematical chain. One example is the Polish medical robot, called Robin Heart, which is used during heart operations with constant point mechanism and a closed loop structure of kinematical chain [3, 4]. Another example is ROCH-1 (also Polish construction), which has a serial chain structure different from Robin Heart's [5].

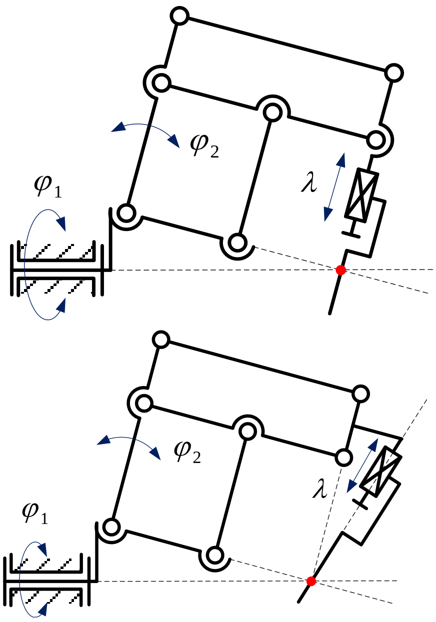


Fig. 1. The kinematical chains of a constant point mechanisms

An important area of operation is oncology, especially when the surgeon wants to remove the pathological soft tissue. In this work, kinematical chain of constant point mechanism with additional prismatic joint for improving the possibility of changing the access port (trocar) in laparo or thorax area is presented. Typical structures of constant point mechanisms are shown in figure 1.

There is a possibility to change the access port by using constant point mechanisms, similar to those used in da Vinci and Robin Heart, but it is difficult to construct the real mechatronic application and apply it in kinematical chain of a medical robot. In the work [6], a model of medical robot with mechanical (not mechatronic) device that gives this possibility is presented. The described virtual model with its working space is presented in figure 2.

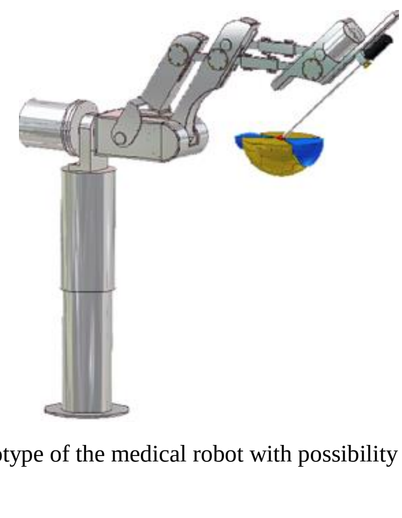


Fig. 2. Virtual prototype of the medical robot with possibility to change access port

The kinematical chain of robot with a possibility to change access port is shown on figure 3.

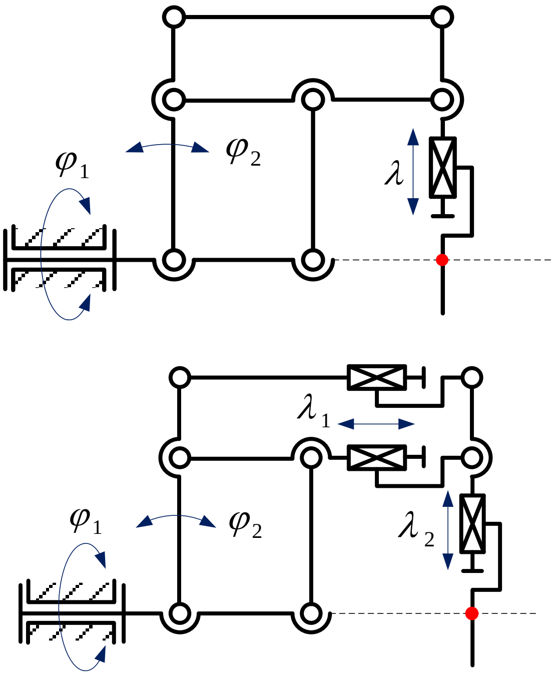


Fig. 3. Kinematical chain of medical robot with a possibility to change access port

A significant problem in constructing the constant point mechanism of medical robots (da Vinci, Robin Heart) is the accuracy of positioning the effector from the mechanics point of view. The main cause of it is the necessity to realize two rotational movements in order to obtain the spherical movement of the effector around constant point (access port to human body). The centers of masses of kinematical chain are far away from two axes of rotation due to the ergonomy of operation. And for this reason, inertia forces have large value, which may result in large deformation of kinematical chain. In the work [7], a possibility of another rotation of the effector of constant point mechanism is described. It allows to create mechatronic application in the construction of additional prismatic pair.

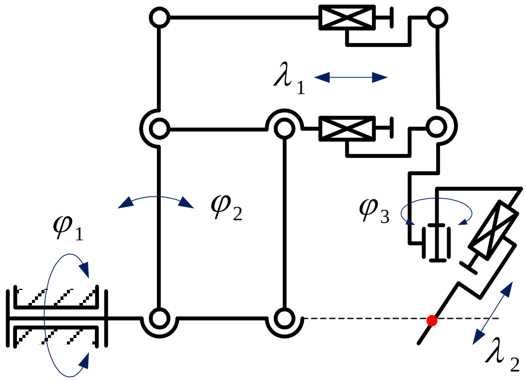


Fig. 4. Constant point mechanism with additional degrees of freedom

In this work, that solution is applied to the constant point mechanism of medical robot kinematical chain. This solution gives the construction a greater stiffness than in the classical constant point mechanisms used in da Vinci and Robin Heart because in their construction there are less kinematical pairs and no loss of stiffness associated with assembly inaccuracies.

The modern constant point mechanism with additional degree of freedom is shown in figure 5.

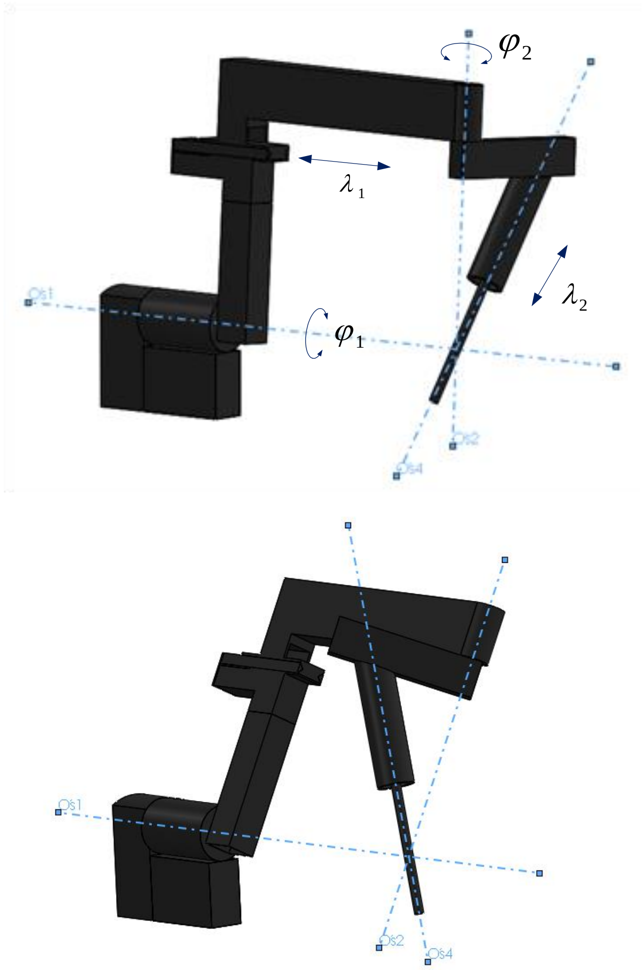


Fig. 5. Model of robot with additional degree of freedom

The above figure shows that axis of the three main degrees of freedom intersects in one point (constant point), which is the access point for minimally invasive effector. The model of robot for tumor operation with serial chain effector is shown in figure 6.

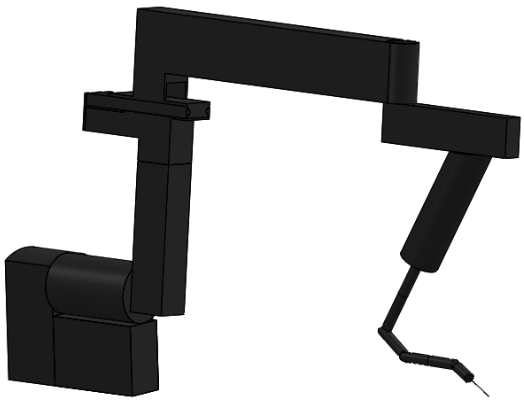


Fig. 6. Model of medical robot to tumor operation with serial chain effector

2. Eigenvalue problems of mechanics in construction of medical robot

There are two essential eigenvalue problems of mechanics in medical robots which can be solved by using the finite element method. First is the problem for natural frequency. This specific problem is described when large vibration, which appears during the resonance phenomenon, occurs in the construction of analyzed model. This is the first step to state a model of optimization in the robot construction.

Solving the eigenvalue problem of natural frequencies in medical robots with serial chain using finite element method is described in the work [8]. In that article, the numerical experiment of vectorial optimization for the criteria: first natural frequency and mass is also carried out. The problem of natural vibrations of Robin Heart's medical robot effector is described in other work [9]. The second important problem is an eigenvalue issue for load factors. This matter is described in the situation when the external force will have the value of Euler's critical force. Subsequently, the buckling phenomenon will appear and the construction will lose the stability. In the work [10],the problem of elastic buckling of Robin Heart medical robot, which has possibility to operate soft tissue, is described.

The eigenvalue problem for natural frequencies arises from (1), if Rayleigh damping and external forces can be omitted:

$$[\boldsymbol{M}]\cdot\{\ddot{\boldsymbol{u}}\} + [\boldsymbol{K}]\cdot\{\boldsymbol{u}\} = \{\boldsymbol{0}\} \tag{1}$$

where:
$[\boldsymbol{M}]$ – structural matrix of mass,
$[\boldsymbol{K}]$ – structural matrix of stiffness,
$\{\boldsymbol{0}\}$ – displacement.
The general solution of the equation (1) can be specified as:

$$\{\boldsymbol{u}\} = \{\boldsymbol{u_A}\}\cdot\cos(\omega t) + \{\boldsymbol{u_B}\}\cdot\sin(\omega t) \tag{2}$$

The second derivative of the displacement vector (2) can be written as:

$$\{\ddot{\boldsymbol{u}}\} = -\boldsymbol{\omega}^{2}\cdot\{\boldsymbol{u}\} \tag{3}$$

Substituting (4) to (2) we receive:

$$-\boldsymbol{\omega}^{2}\cdot[\boldsymbol{M}]\cdot\{\boldsymbol{u}\} + [\boldsymbol{K}]\cdot\{\boldsymbol{u}\} = \{\boldsymbol{0}\} \tag{4}$$

Transforming equation (4) we have equation that describe generalized eigenvalue problem for natural vibration:

$$([\boldsymbol{K}] - \boldsymbol{\omega}^{2}\cdot[\boldsymbol{M}])\cdot\{\boldsymbol{u}\} = \{\boldsymbol{0}\} \tag{5}$$

where:
$\boldsymbol{\omega} -$ vector of eigenvalues which gives natural frequencies of the model,
$\boldsymbol{u} -$ eigenvector which gives shapes of vibrations of the medical robot during resonance.

The eigenvalue problem for elastic buckling is giving by equation:

$$([\boldsymbol{K}] + [\boldsymbol{K_G}])\cdot\{\boldsymbol{u}\} = \{\boldsymbol{F}\} \tag{6}$$

where:
$[\boldsymbol{K_G}] -$ stress-stiffness matrix,
$\{\boldsymbol{F}\} -$ vector of nodal forces.

During the loss of the stability for equal loads are possible other states of equilibrium:

$$([\boldsymbol{K}] + \boldsymbol{\lambda}[\boldsymbol{K_G}])\cdot\{\boldsymbol{u}\} = \{\boldsymbol{F}\} \tag{7}$$

$$([\boldsymbol{K}] + \boldsymbol{\lambda}[\boldsymbol{K_G}])\cdot\{\boldsymbol{u} + \boldsymbol{\delta u}\} = \{\boldsymbol{F}\} \tag{8}$$

After subtracting the equations (7) and (8), the symmetrical problem, that defines the stability of the substitutional system, is obtained to solve:

$$([\boldsymbol{K}] + \boldsymbol{\lambda}[\boldsymbol{K_G}]) \cdot \{\boldsymbol{\delta u}\} = \{\boldsymbol{0}\} \tag{9}$$

where:
$\boldsymbol{\lambda}$ − vector of eigenvalues which gives load factors of the model,
$\boldsymbol{\delta u}$ − eigenvector which gives shapes of buckling.

The system of equation (9) is solved by using the Lanczos method [11] for large symmetrical systems. In this work, the finite element method is used to solve the defined eigenvalue problems.

3. Discrete model of medical robot solved by using the finite element method

The discrete model of the medical robot is presented in figure 6. The model aluminum geometry was simplified in order to reduce the time of computation. The Boolean operation was used for this purpose and the name of this operation is called the cleaning geometry. Without this operation, there are many computational errors and the time of computation is very large. The model has an excellent number of degrees of freedom which is equal to 350231 and gives correct numerical solution. The ten-node tetrahedral element was used to discretize the continuum.

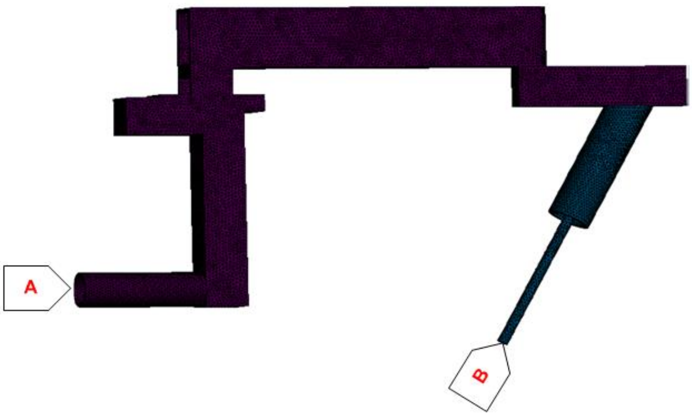


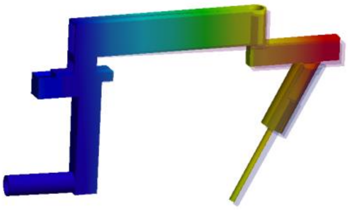
Fig. 7. Discrete model structure of the medical robot

For the eigenvalue problem of natural frequency, the model was fixed in point A (shown in figure 6). Whereas for the problem of elastic buckling, the boundary conditions were such that the model was fixed in point A with and external force of 10 N, while the compression of medical robot construction was applied in point B.

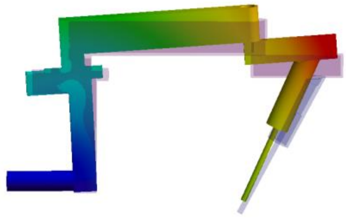
The model was calculated using the i5 third generation processor with 2.5 GHz frequency and the computer had 8 GB RAM. The time of calculations was 397 seconds for natural vibration problem and 3491 seconds for linear buckling problem.

4. Results

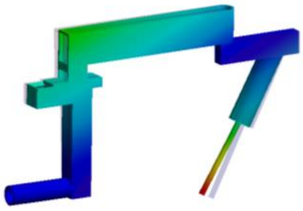
In figure7, different shapes of deformation during resonance phenomenon in six subsequent natural frequencies are presented. In the first natural frequency, which equals to 28.4 Hz, the construction is in bending vibration during the resonance phenomenon in the plate that is horizontal to the ground. In the second natural frequency, which equals to 34.7 Hz, the construction is in bending vibration in the plate of the robot that is perpendicular to the plate where the vibration occurred in the first shape of medical robot. The third and fourth shapes of vibration have similar character respectively to the first and second shapes. The fifth and sixth modes are complicated bending aspects.



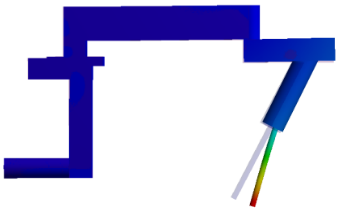
The 1st mode for frequency: 28.4 Hz



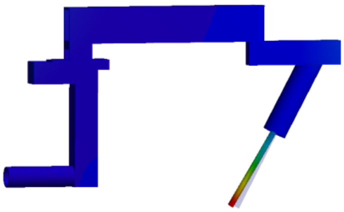
The 2nd mode for frequency: 34.7 Hz



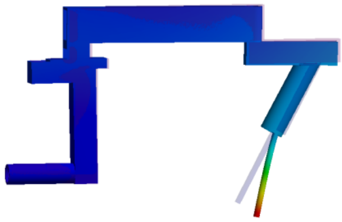
The 3rd mode for frequency: 85.3 Hz



The 4th mode for frequency: 133.5 Hz



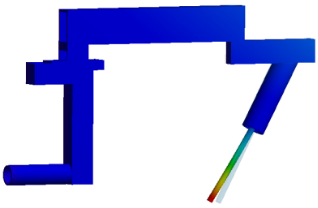
The 5th mode for frequency: 144.5 Hz



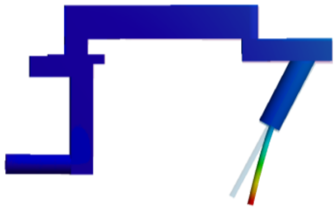
The 6th mode for frequency: 163.6 Hz

Fig.8. Shapes of deformation in the next six modes of natural vibrations

In figure 8, various shapes of deformation during elastic buckling in the six subsequent load factors are depicted.

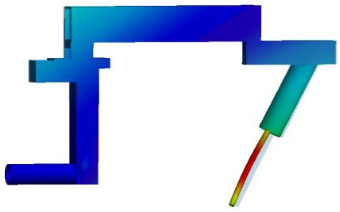


The 1st mode for load factor: 160

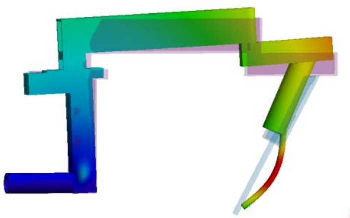


The 2nd mode for load factor: 164.6

The 3rd mode for load factor: 1430



The 4th mode for load factor: 1453



The 5th mode for load factor: 1483

The 6th mode for load factor: 1526

Fig. 9. Shape of deformation during elastic buckling phenomenon in the six subsequent load factors

In the first mode of elastic buckling, where the load factor is equal to 160, the deformation is in the plate horizontal to the ground. However, when the load factor is equal to 164.6, the deformation is in the plate of medical robot. The other states of loss stability in the construction have very large values of the load factors.

5. Conclusions

The new construction of medical robot for tumor operations was presented in this article. To create the possibility of changing the access port, one prismatic joint is needed to be added to kinematical chain. This allows a larger mobility of the robot without changing the position of the whole robot, as it is done in the two most popular clinically used constructions: Polish Robin Heart and American da Vinci. Due to the difficulties of building mechatronic devices with good functionality, like it is shown in the work [5], other configuration of kinematical pair of constant point mechanism was applied.

From the inaccuracies point of view, during the montage of construction, which result from the numbers of kinematical pairs, the presented solution will be characterized by a better accuracy of positionning and repeatability.

The mechanical analysis of natural frequency for a given geometry was carried out to check how stiffness is constructed for given dimensions of kinematical chain profiles. The information about the appearance of resonance phenomenon is also obtained.

It was also proven by using the numerical model that presented construction will not lose stability as a result of elastic buckling, because values of obtained load factors are large. It is helpful to have such information before clinical usage of the construction because of the safety during the operation. The next step of a numerical analysis will be a creation of structural and steering optimization model.

REFERENCES

[1] G. Ilewicz: *Modeling and controlling medical robot for soft tissue surgery and servicing the artificial organs*, Proceedings of the 17th Mechatronika 2016, IEEE, s. 102–107, Prague 2016.

[2] M. Habib: *Handbook of Research on Advancements in Robotics and Mechatronics*, Engineering Science Reference, 2015.

[3] Z. Nawrat: *State of the art. In medical robotics in Poland: development of the Robin Heart and other robots*, Expert Reviews Medical Devices, vol. 9(4), 2012, s. 353–359.

[4] Z. Nawrat, P. Kostka: *Polish cardio-robot „Robin Heart. System description and technical evaluation”*, International Journal of Medical Robotics and Computer Assisted Surgery, vol. 2(1), 2006, s. 36–44.

[5] L. Leniowska, R. Leniowski, J. Cieślik, R. Pajda: *Manipulator Chirurgiczny*, Opis patentowy, pp. 391263

[6] G. Ilewicz: *Modification of parallel mechanizm geometry to increase operative ability of cardiosurgical telemanipulator.* (in Polish), Advances in Biomedical Technology, 2007, s. 355–365.

[7] G. Ilewicz: *Movements optimization of ardiosurgical teleoperator effector*, PhD dissertation (in Polish), Gliwice 2011.

[8] G. Ilewicz: *Natural frequencies nad multi-objective optimization of the model of medical robot with serial kinematical chain*, Advances in Inteligent Systems and Computing, vol. 519, 2017, s. 371–379.

[9] G. Ilewicz, Z. Nawrat: *Vectorial optimization of medical robot tool using finite element method (in Polish)*, Acta Bio-Optica et Informatica Medica Inżynieria Biomedyczna, s.234–244, vol. 22, nr 4 2016

[10] G. Ilewicz, Z. Nawrat: *The linear buckling phenomenon of medical robot structure calculated using finite elements method* (in Polish), Materiały konferencyjne Międzynarodowej Konferencji Medical Robots, Fundacja Rozwoju Kardiochirurgii, Zabrze 2014.

[11] L. Bostic, S. Lanczos: *Eigensolution method for high-performance computers*, National Aeronautics and Space Administration Memonardum, Langley Reserch Center 1991.

otrzymano / submitted: 01.06.2017
zaakceptowano / accepted: 12.12.2017