

Finite Element Analysis of Natural Frequencies and Mode Shapes of The da Vinci Medical Robot Arm

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Abstract

This paper presents an analysis of the natural frequency and mode shapes of the arm and the working tip of the da Vinci robot, which is used in various types of surgical procedures. The survey was conducted using Autodesk Fusion 360. Using the da Vinci robot's construction data, a model was designed taking into account the characteristic dimensions and materials used. The obtained shapes of vibrations for natural frequencies allowed us to predict the influence of resonance phenomenon on the manipulator's arm. The movement of the tool along the wrong track, caused by an increase in vibration amplitude, may adversely affect the operation of the device. The results of the conducted research, therefore, provide information for which natural frequencies the values of these amplitudes increase.

Keywords: natural frequencies, mode shapes, finite elements method, medical robot arm

1. Introduction

Robots are used in many industries. They are characterized by high repeatability of work and particular precision of performed tasks. Although many people believe that human life cannot be entrusted to a machine, doctors and scientists are increasingly choosing to use robots in medical procedures, especially in surgery [1-3].

One of the most commonly used surgical robots is the da Vinci robot (see Figure 1), which was manufactured by Intuitive Surgical Inc.



Figure 1. View of the da Vinci robot [11]

All the actions to be performed by the robot are controlled and ordered by the surgeon who controls the machine. The robot does not make any decisions on its own - it is only an executive system. Scientists are still trying to program the robot to perform the entire operation fully automatically, without the intervention of a doctor. In the future, the da Vinci robot may be perfected to such an extent that it will be able to fully handle the surgeon [1].

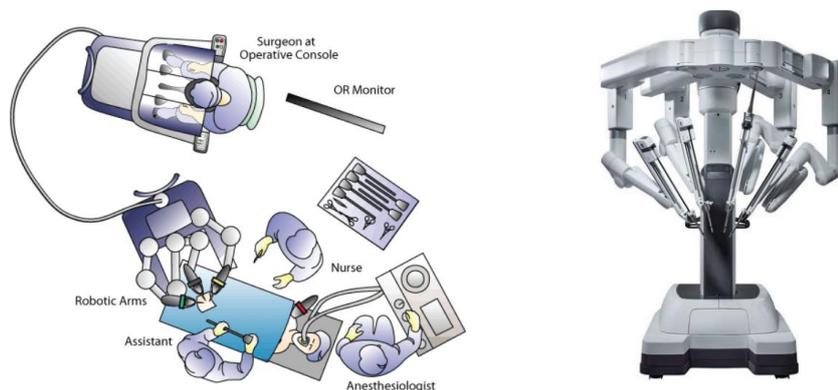


Figure 2. Pre-programming of the robot and the course of the procedure using it [9] (left) and patient's trolley [10] (right)

The da Vinci robot is a manipulator with the help of which, under the full control of a surgeon, it is possible to carry out the selected surgical procedure (Figure 2). It has seven degrees of freedom, which gives the doctor a great deal of power during control and makes the way of movement more natural. The manipulator, as part of the console available to the surgeon, records the movements of fingers, hands, and wrists. This makes it possible to map the doctor's movements through the robot's working tip. This end is inside the patient's body, at the end of the working arm. The robot's control system scales the surgeon's movements accordingly so that he can work freely, even with not very precise movements, because thanks to the scaling, the precision of the working tip movements will remain high and the dictated actions will be performed very precisely. The console used to control the robot, thanks to its appropriate location, allows the doctor to work comfortably - he performs the procedure sitting and not, as in the case of standard operations, standing [1]. The doctor can accurately observe the inside of the patient's body by introducing an endoscope equipped with a camera. The image appears on the operator console in a stereo way. It is the most important and necessary tool, because when the doctor does not see the body space undergoing the surgery - he is not able to give the robot the appropriate movements and activities, and consequently would not successfully perform the planned operation [1]. In addition to the console for the doctor, an important element is also the so-called "console" the patient's trolley, which is the robot's proper execution element (Figure 2). The four working arms are checked. They enable the manipulation of surgical instruments by the physician, who can perform all the necessary

procedures inside the patient's body [2]. A surgical instrument attached to the end of such an arm mimics the movements of the hand of a surgeon sitting at the console. The movement of the working tips is electronically controlled. The robot was specially programmed for this. The doctor, moving the controls on the console, does not drive anything in this way, but tells the computer what movement should be made. Electric motors in the robot's arms controlled by a computer (not the surgeon's hands) force the appropriate movement of surgical instruments [2].

The work tips are small in size and have different shapes, depending on the application for a particular treatment [2].



Figure 3. Examples of da Vinci robot work attachments [2]

The drive of the working tip allows seven degrees of freedom. The surgeon controls the two arms of the robot with both hands [2].

2. Mathematical model

In the analysis we have carried out, the characteristics of natural vibration are important. We assume that: the number of vibration frequencies is equal to the number of degrees of freedom of the system, and the natural frequencies are positive [4].

According to basic equations of linear elasticity, the harmonic equation of motion of linear elastic material fulfills a formula

$$-\rho\omega^2\mathbf{u} - (\mu\nabla^2\mathbf{u} + (\lambda + \mu)\nabla\nabla \cdot \mathbf{u}) = \mathbf{0}, \quad (1)$$

where ρ is the density, μ and λ are the Lamé constants and ω is the frequency of loading. The harmonic equation may be viewed as the eigenvalue equation.

The following matrix equation can be derived for the natural vibration of systems without damping:

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{f}(t), \quad (2)$$

where \mathbf{M} , \mathbf{K} denotes the inertia and stiffness matrices and \mathbf{q} denotes the nodal displacement vector.

The characteristic equation, whose solutions are the frequencies (ω) and the forms of vibration is in the form:

$$\det(-\omega^2\mathbf{M} + \mathbf{K}) = 0. \quad (3)$$

In systems with n degrees of freedom, n resonances may occur [4].

According to the above equation, it is possible to carry out strength analysis using the finite element method. The result of calculations with the use of the above-mentioned method depends on the accuracy of the adopted grid model with the structure coverage giving the correct result for the examined phenomenon [4-6]. The problem is solved using Autodesk Fusion 360 software.

3. Model of the robot arm

The designed model has been based on the dimensions from the Instrument & Accessory Catalogue for da Vinci devices [7] and the model [8]. The tip of the manipulator is used in human tissue surgery. It has an electric drive, the motor of which is located underneath the toothed gear of the pliers. Dimensions of the model of the robot arm are presented in Figure 4.

Stainless steel was used as the material for the workpiece, and the work-frame was made of aluminum 6061. Properties of materials were taken from Autodesk Fusion 360 (Table 1).

Table 1. Properties of materials used in the robot model

	Unit	Stainless Steel	Aluminum 6061
Density	[kg/mm ³]	8E-06	2,7E-06
Young's Modulus	[MPa]	193000	68900
Poisson's Ratio	-	0,30	0,33
Yield Strength	[MPa]	250	275
Ultimate Tensile Strength	[MPa]	540	310
Thermal Conductivity	[W/(mm·C)]	0,0162	0,167
Specific Heat	[J/(kg·C)]	477	897

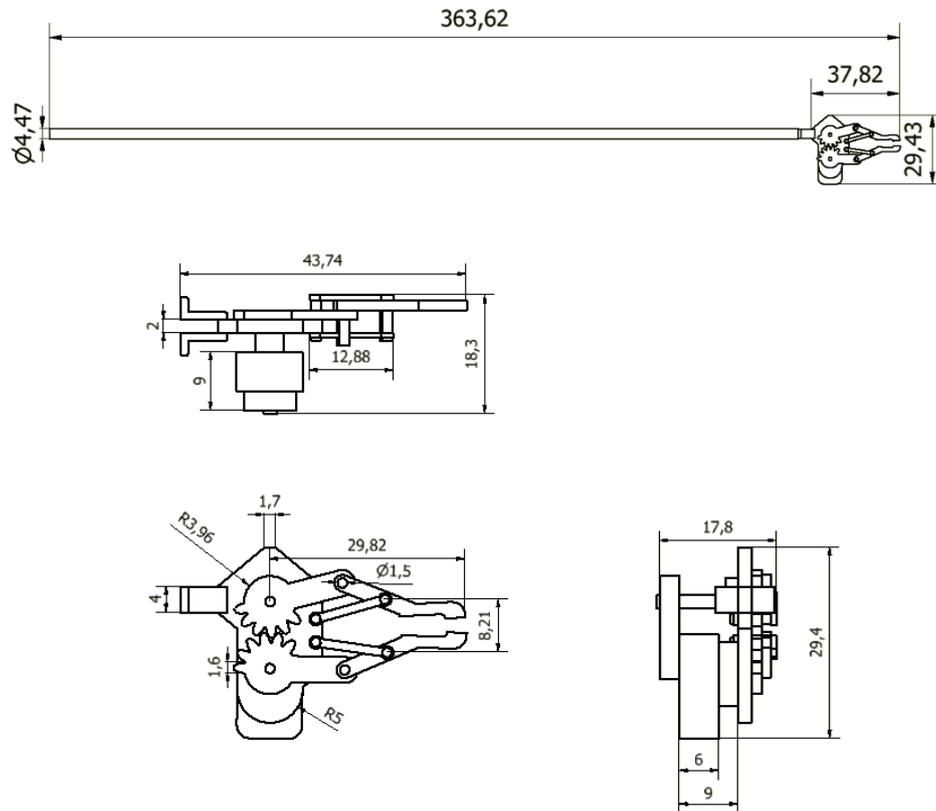


Figure 4. Characteristic dimensions of the model. The top figure presents the whole model and the three below present three views of the main part of the robot's manipulator.

4. Numerical results

The natural frequencies were compared, for the automatically generated grid with a discrete model with the number of degrees of freedom equal to 40972 with a grid with the number of degrees of freedom equal to 941156. The greater number of grid elements allows for more precise calculations, so the analysis of the grid in Figure 6 gives results closer to reality.

The simulation was performed on a superimposed grid (discrete model) with the highest density, made of 620266 elements and having 941156 nodes (Figure 6). Figure 7 shows the deformation mode shapes corresponding to the shown in succession eight natural frequencies of the model. There is a presentation of two plane bending vibrations and torsional vibrations of the manipulator tip.

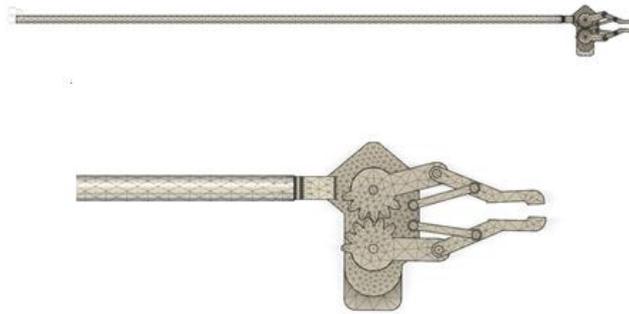


Figure 5. Mesh model with 40972 degrees of freedom and 22574 elements.

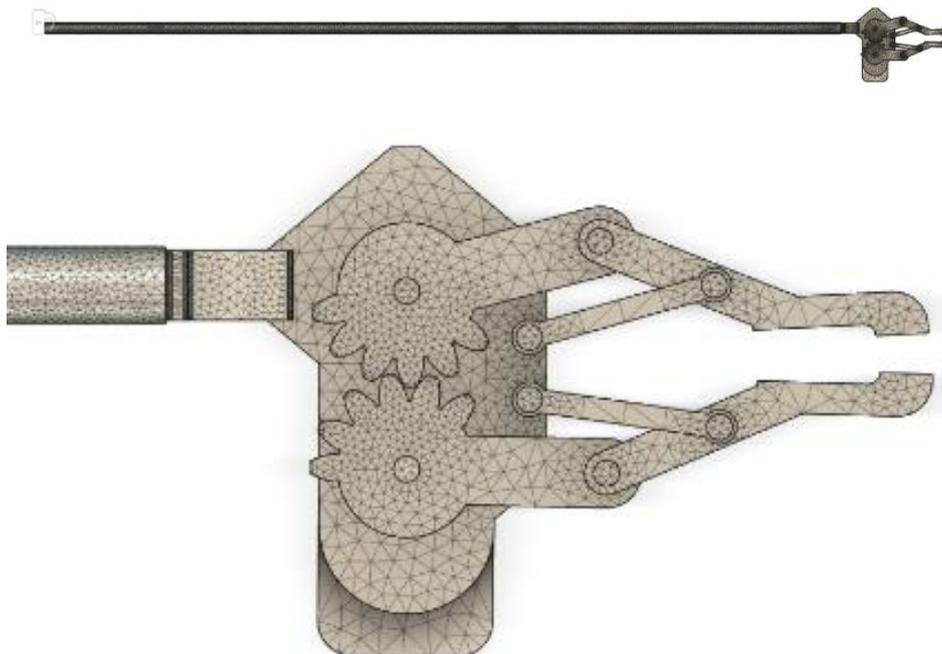


Figure 6. Mesh model with 941156 degrees of freedom, 620226 elements.

As the frequency increases, vibrations take on an increasingly complex form. At the first and second frequency, flexural vibrations predominate, at the sixth frequency, there are minimal flexural vibrations only in one axis. Torsional vibrations occur at other frequencies [5].

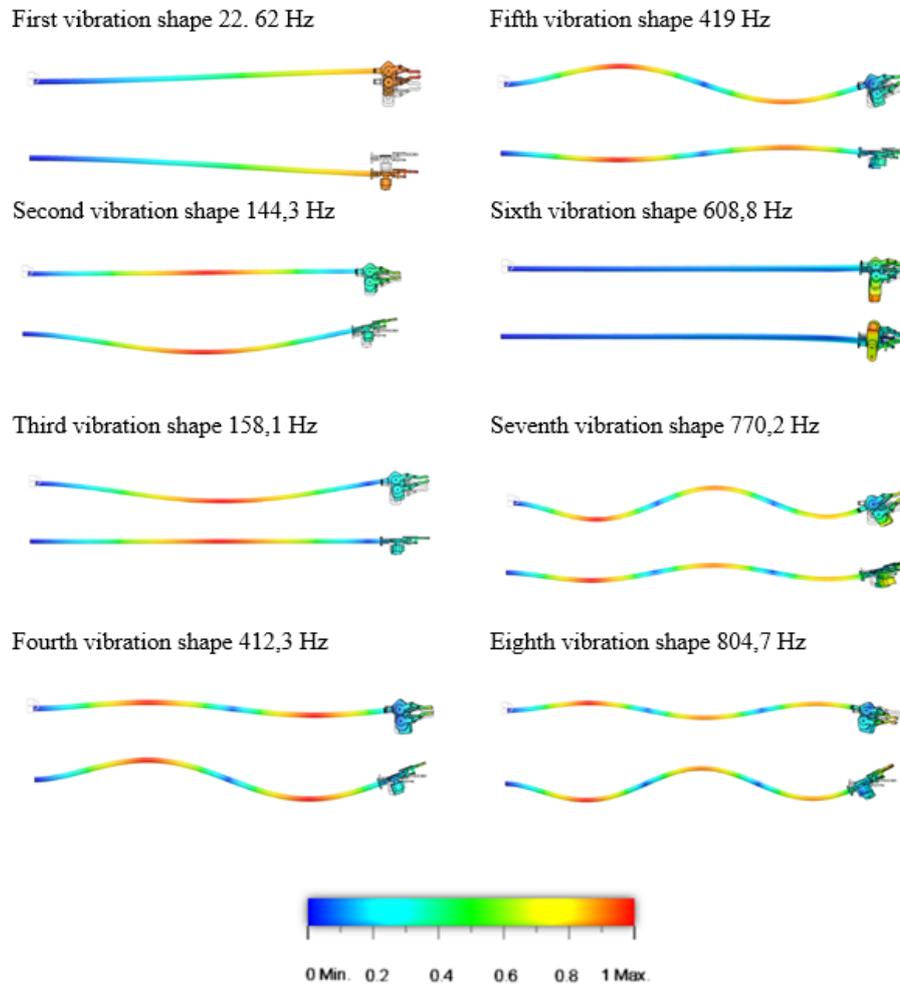


Figure 7. Mode shapes of the smallest eight frequencies.

5. Conclusions

The precision of both the working tip and the arm, in the case of the da Vinci robot, is very important. It guarantees that the procedure is carried out correctly and patient safety is guaranteed. Mathematical analysis, using the finite element method, allowed to determine the natural frequencies of the tool and to evaluate the vibration shapes during resonance. When planning the procedure and programming the robot, it is worth taking

into account the adverse effects of the resonance phenomenon, which are caused by a drive source located in the immediate vicinity. The observation of the shape allows the designer in the future to make appropriate modifications to the design of the arm and the tip of the manipulator. The test results could have been influenced by the dimensions of the analyzed part, selected on the da Vinci robot's data and materials proposed by us, also resulting from the design of this device.

Acknowledgments

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