ANALYSIS OF THE ACCURACY PARAMETERS FOR THE ARTICULATED ARM INDUSTRIAL ROBOT USING MODERN INSTRUMENTS AND SOFTWARE

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Tehnologiile IT şi de control a sistemelor tehnologice au sporit precizia de poziţionare prin controlul lanţurilor cinematice. Lanţuri cinematice de precizie ridicată sau reconfigurarea sistemelor in funcţiune pentru a asigura precizia corespunzătoare sunt în continuare solicitate în aplicaţiile industriale. Acest articol prezinta o abordare originală prin analiza preciziei unei structuri robotizate 5R, ce include lanţurile şi mecanismele acesteia. Sunt prezentate rezultatele corespunzătoare comportării întregului ansamblu precum şi indicaţii finale asupra caracteristicilor de îmbunătăţit. Analiza include evaluarea comportării din punct de vedere static şi a frecvenţelor proprii.

Computer and control system technologies have significantly increased the control of the kinematic chains in terms of precision of positioning. Highly accurate kinematic chains or adjustment of the functioning systems to achieve suitable precision are still required in actual applications. The paper presents an original approach using an analysis of accuracy of 5R robotic structure that considers its chains and mechanisms. The results corresponding to the entire structure are presented as well as the final indication about the characteristics to be improved. The analysis comprises the assessment from the static point of view and natural frequencies.

Keywords: accuracy, kinematic chain, FEM, static analysis, natural frequency

1. Introduction

The recent years have shown outstanding increase in informatics, hardware and equipments technologies. That helped all the industries connected to these, like the field of machine tools and robotics. The control units gains more accuracy and enhance their behaviour while it can be optimized in accordance with the desired criteria, even from the design stage [1]. Moreover, during the trajectory execution, the control loops provide an increased precision [2] required by many applications in flexible processing systems [3] while the modular conception simplifies the engineering work [4].

Despite all the improvements, the mechanical systems still needs inside accurate mechanisms and kinematic chains. Additionally, some systems already

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built have to be adjusted to reach the appropriate precision required by application. It is a target to obtain lighter structures to achieve high speeds and acceleration, but also to attain the target in very small tolerances. To reach this goal, a comprehensive analysis has to be performed in order to show the critical aspects and original results applied to an articulated arm 5R robot. Lighter structures have normally lower stiffness and are more flexible to the gravitational and inertial forces determined by an increased acceleration. An optimization of geometry – mass and stiffness - accuracy criteria is therefore useful. Such analysis has been performed on the basis of the conventional approach and theoretic model for each mechanism, contact surfaces [5], [6], [7], [8] or kinematic chains, usually built on the basis of conventional methods. It was proved that modern software and instruments based on the Finite Element Method (FEM) allow such research to be easier to perform using an appropriate model. Therefore, an analysis has been performed on a model of 5R robot arm. The analysed robot is defined in a CAD file. Particular models have been developed for each mechanism therefore this analysis includes large information database regarding dimensions, surfaces connections, mechanisms and kinematic chains. The current paper is focused to describe just a part of this research and to emphasize the accuracy of the robot as a system and to analyse its behaviour from the static point of view. The model follows a system actually functioning – Fig. 1; thus the results are immediately applicable. A comparison to validate the model, experimental research instruments and optimization by specific criteria of accuracy are prepared by the author but not detailed in this paper.

Fig. 1. The robot structure

2. The analyzed model

For the functional structure, a virtual model was built introducing all the parts and components [9], linked to model the robotic system. The influence of these parts on the general behaviour, considering a static approach, was analyzed using dedicated software for FEM analysis. The model was exported as parasolid file to the FEM processor, the geometry was updated and the structure meshed using 3D elements.

The robot architecture is formed by a positioning system of 3 degrees of freedom and other 2 degrees corresponding to the orientation system namely roll and pitch as rotational joints. Also, the degrees of the positioning system are rotational couples.

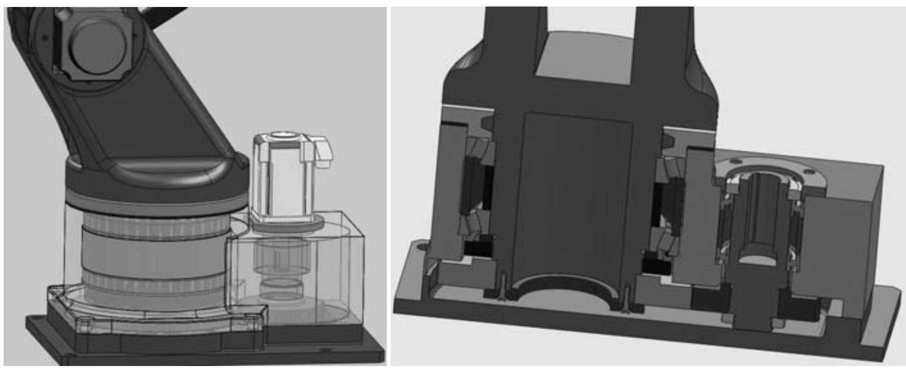


Fig. 2. The positioning system – first rotation joint

The first joint is actuated by a servomotor, Fig. 2, with coupling and speed reducer and two gears and the intermediary elements with radial – axial bearings and shafts.

Fig. 3. The second and third degree of the positioning system

The second rotation is direct drive actuated using a servomotor coupled with the harmonic drive that assures the mobility of the second arm segment of the robot. To the upper side of the second arm, a shaft with radial bearings eccentrically located, ensures the mobility of the third degree of positioning of the third arm. This is actuated using a closed kinematics chain jointed structure coupled with servo actuator to the bottom of the second arm and connected to the end of the third arm, as in Fig. 3. The first mobility degree of orientation is a mechanism of direct drive “roll” type actuated by a servomotor with harmonic drive. The “pitch” type rotation is driven by an actuator controlled by the command equipments linked to transmission elements comprising a main shaft – first belt and timing belt transmission with the second belts in direct contact with the structure to be rotated where the gripper is installed (Fig. 4).

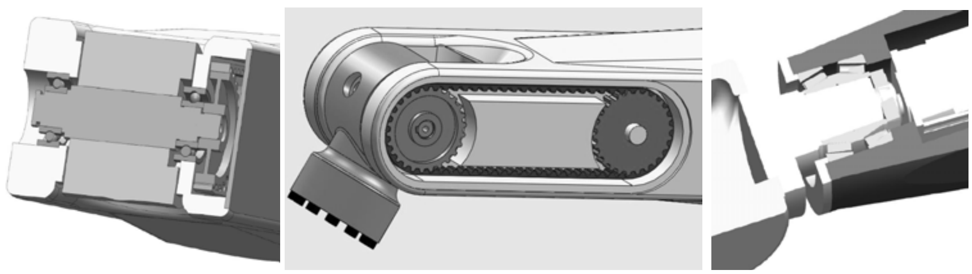


Fig. 4. Orientation system: “roll” and “pitch”

The robot was considered fixed to the ground in four points where displacements were constrained. The previously mentioned geometry was imported in FEM software where we have run all the simulations. All the objects, faces and the contact regions were controlled in order to be geometrically defined. The materials were also defined with specific parameters: most of the component are made of steel or iron while the belt is of reinforced polyurethane. The actuators were considered with a specific weight but no other parameters were taken into account. More details are listed in Table 1 bellow.

Table 1

The main parameters of the model

Specification	Type	Description
Five actuators	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, no thermal or nonlinear effects
Different bearings	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, iron, no thermal or nonlinear effects
Structure parts	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, iron, no thermal or nonlinear effects
Differet covers	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, iron, no thermal or nonlinear effects
Different shaft types	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, iron, no thermal or nonlinear effects
Assembly parts	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, usual material of steel, no thermal or nonlinear effects
Different gear	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour,

Specification	Type	Description
types		structural steel, no thermal or nonlinear effects
Timing belt	Parts	Introduced with bounding box, inertia, flexible stiffness behaviour, reinforced polyurethane, no thermal or nonlinear effects

The contact regions between parts were fully defined by faces with bonded type definition and symmetric behaviour and normal stiffness controlled by the program. The resulted model includes over 350,000 elements and more than 700,000 nodes with a total of 0.5 tonnes mass and a volume of approximately 6.39 m^3. The model was considered as appropriate in order to obtain reliable results.

3. The approach used for the kinematics chain in analysis

The main considerations related to the stiffness and mechanical design model are presented in the literature including the general equation of the model 1, [10]. The static analysis considers only the [k] matrix from the mentioned formula. For computational reasons, equation (2) is used which gives the result noted with {P} defined as the vector of equivalent nodal forces with the calculation of the element stiffness matrix [k] as in equations (3) and (4). The matrices [B] and [D] are constant throughout the material and the equivalent nodal forces due to initial strains and body force are obtained with equation (5), [11].

$$\{F(t)\} = [k]\cdot\{u\} + \{c\}\cdot\{u'\} + \{M\}\cdot\{u''\} \quad (1)$$

$$\{P\}^{(e)} = [k^{(e)}]\{\delta\}^{(e)} + \{F_{\varepsilon 0}\}^{(e)} + \{F_F\}^{(e)} \quad (2)$$

$$[k_{\mathrm{ieje}}^{(\mathrm{e})}] = \begin{bmatrix} k_{1e1e}^{(e)} & k_{1e2e}^{(e)} & k_{1e3e}^{(e)} \\ k_{2e1e}^{(e)} & k_{2e2e}^{(e)} & k_{2e3e}^{(e)} \\ k_{3e1e}^{(e)} & k_{3e2e}^{(e)} & k_{3e3e}^{(e)} \end{bmatrix} \quad (3)$$

$$[k_{\mathrm{ieje}}^{(\mathrm{e})}] = \iint_D [B]^T [D^e][B] t dx dy \quad (4)$$

$$\{F_{\varepsilon 0}\}^{(e)} = -\iint_D [B]^T [D^e][\varepsilon_0] t dx dy$$
$$\{F_F\}^{(e)} = -\iint_D [N]^T \{F\}^e t dx dy \quad (5)$$

4. Loads and input data

For the model with the previously mentioned geometry, several potential configurations were analyzed. The most disadvantageous load configuration was considered when the third arm segment is horizontally extended (Fig. 5), [12].

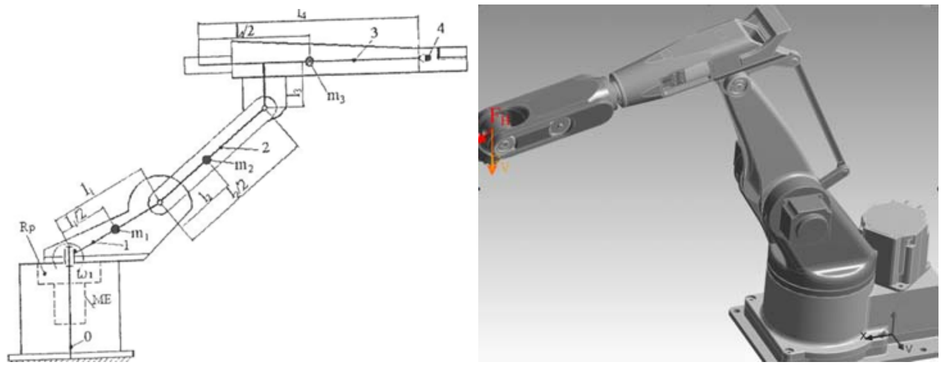


Fig. 5. The input data and loading scheme

The gravitational and inertial forces were introduced in the current model with the maximum values required by the application. The loads were applied at the end point of the 5th joint as vertical load (Ow axis) considering the application requires the robot should carry a maximum 100 kg. The inertial effect was introduced but separately assessed to a maximum value of 500 N applied as a force by the horizontal axis (Ox axis) in the above mentioned point, considering the acceleration of 5 m/s^2 in accordance with the specific parameters of the robot. A normal temperature distribution of 22° C was considered and it was assumed that no other conditions influence the environment. Considering the above mentioned data, a static analysis was carried out for the entire system, in order to obtain the main parameters of stiffness and accuracy. For a primary assessment of the dynamical behaviour a modal analysis was run, considering the same conditions as for static analysis.

4. Results

The static analysis comprises an assessment of the total deformation and directional displacement, shear stress, principal stress and equivalent (von Mises) stress under the loads mentioned above, [13]. Preliminary, an analysis of non operational robot was done only considering the gravitational forces. The inertial forces were introduced as well, to show a complete static analysis of the operational robot. The analysis was considered separately to determine if the inertial forces have any proper effect over the structure. The main diagrams are listed below.

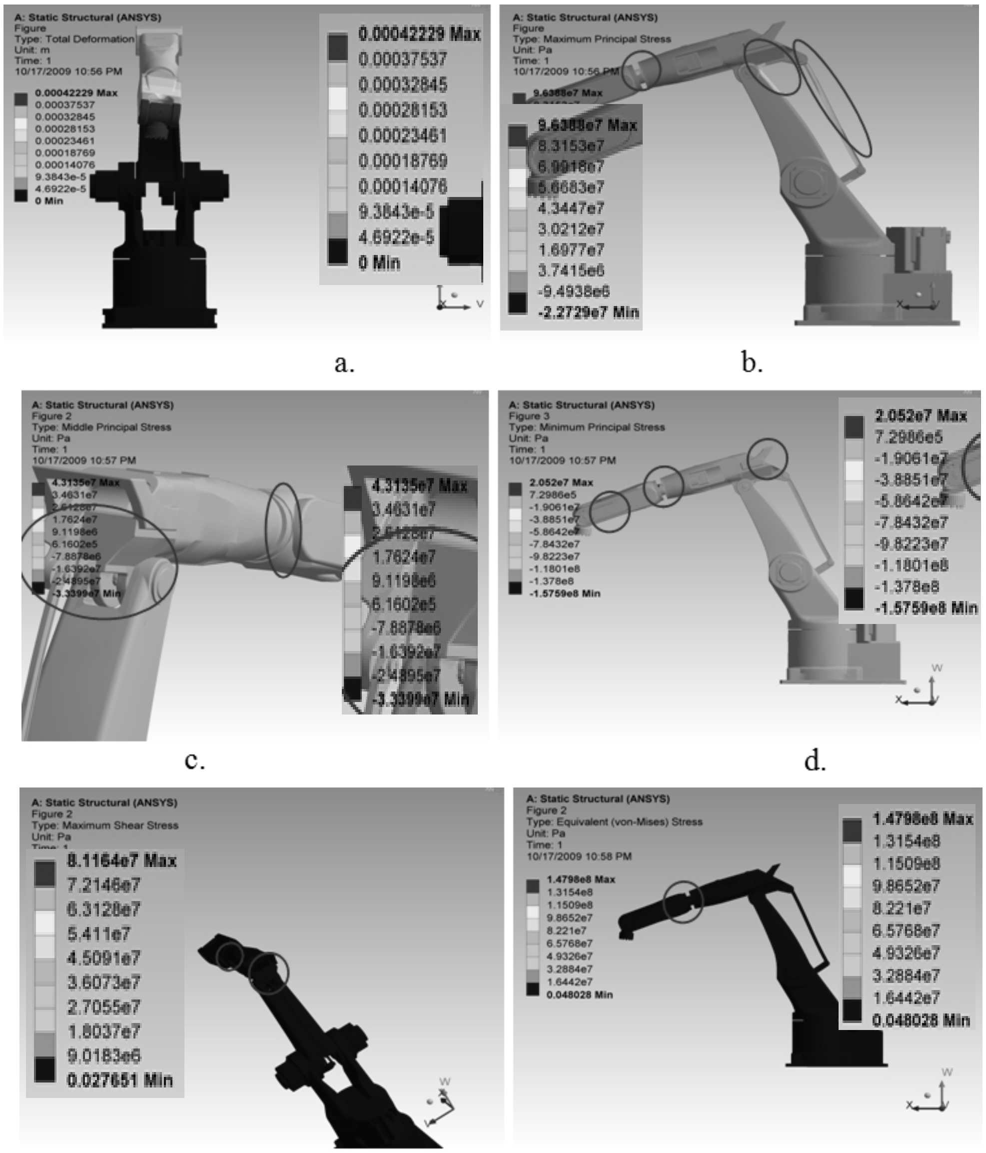
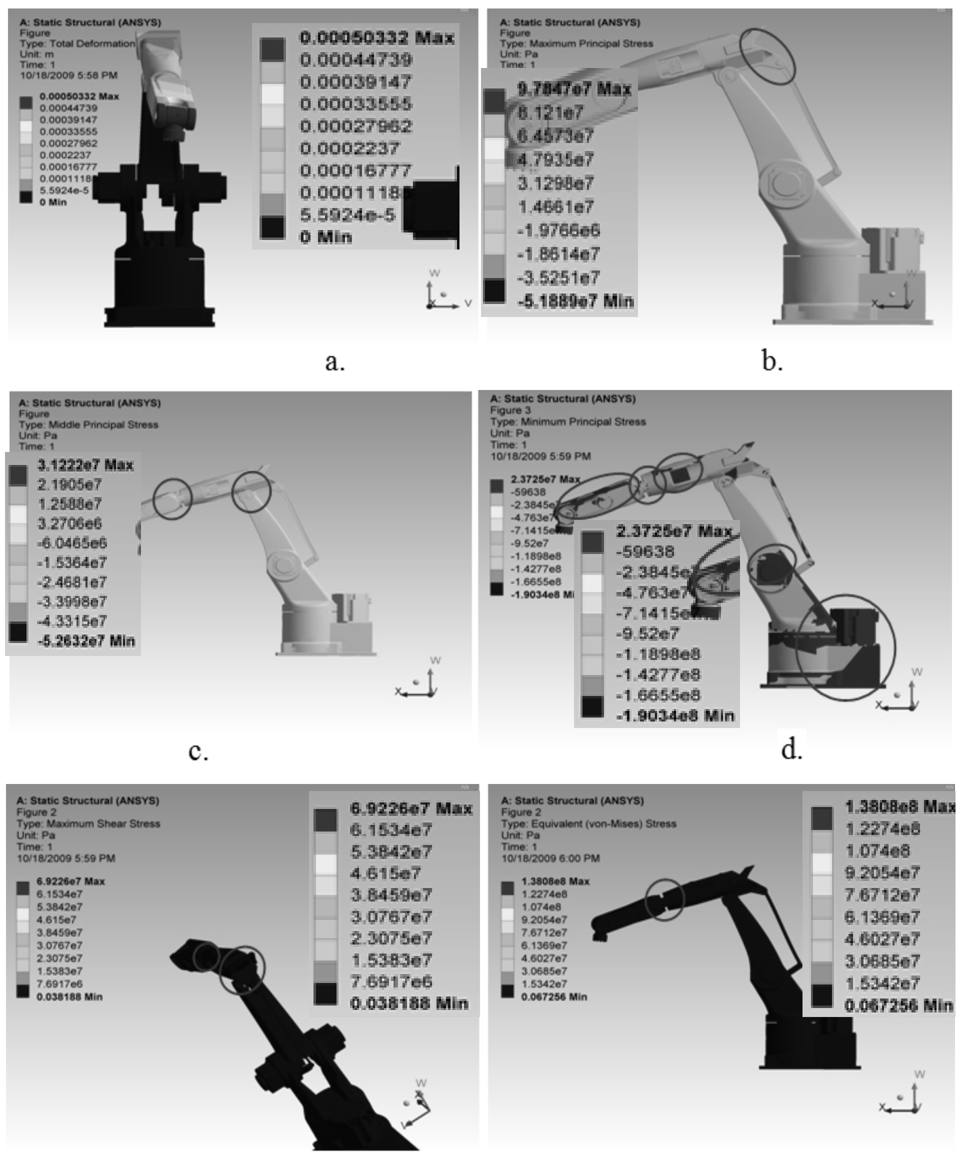


Fig. 6. The results of the static test – first analysis

The preliminary static analysis results are shown in Fig. 6. The final analysis concludes with results shown in Fig. 7. Here we can find the regions exposed to the highest stress. Therefore, we have to focus our attention on these parts for further improvement of the kinematics chains precision and mechanisms as well as for the optimization of the structure. We observe the highest deformations are in the area of 5th articulation –“roll” type. This is determined from geometrical restrictions.



a. b.

c. d.

e. f.

Fig. 7. The results of the static test – second analysis

Table 2

Total deformation and stress parameters

Specification	Preliminary analysis	Final analysis
a. Total deformation (mm.)	0.4223	0.5033
b. Maximum principal stress (MPa.)	-22.7 .. 96.3	-51.8 .. 97.8
c. Middle principal stress (MPa.)	-33.3 .. 43.1	-52.6 .. 31.2
d. Minimum principal stress (MPa.)	-157.5 .. 20.5	-190.3 .. 23.7
e. Maximum shear stress (MPa.)	81.12	69.23
f. Equivalent (von-Mises) stress (MPa.)	147.98	138.09

The comparative results analysis presented in Table 2 show that there are no improvements due to the inertial forces, the final analysis also showing the highest deformations and stresses. In terms of global of positioning precision, the accuracy has depreciated due to the inertial forces with around 20%. All the stress parameters and the equivalent stress are above the material limits. The biggest impact due to the inertial forces is observed in relation with the principal stress while the equivalent von-Mises stress has just a small increase of 8%. Also, the direction of the stress is not influenced.

The deformations exceed the desired tolerances of 0.05-0.10 mm with even 400% which means the system needs an optimization and improvements in terms of mechanisms to provide a better accuracy or to allow a superior tolerance. As seen, decreasing the acceleration does not have a big influence over the general accuracy - we expect less than 20%. A mixed solution of the above criteria could also be applied.

Generally just a static analysis is not enough to validate the model as previously mentioned. Considering a flexible - lighter structure, as the stiffness decrease, the natural frequencies decrease too. On the contrary, increasing the mass the structure will generate an improvement in terms of stiffness but not in benefit of the inertial forces which will impact over the dynamic parameters. Any optimization has at the basis a modal analysis to offer the parameters used for updating finite element models using experimental results. The paper presents the results of this analysis, using the finite element method; the natural frequencies and the modal shapes of the mechanical system are on the same conditions as defined and modelled for the static analysis.

The analysis of natural frequencies and eigenmodes of vibration can give indication in order to perform an optimisation of the structure to provide better dynamic behaviour. A modal analysis shows if any dangerous frequency can affect the system, knowing the natural frequency are operational.

The following steps have been followed: modelling the system geometry, loads estimation and apply in accordance with the above mentioned. In theory, if the term $\{F(t)\}$ from the equation (1) is equal to zero the natural frequencies result. The classic equation of the eigenvalues is:

$[k]\{\phi_i\} = \omega_i^2 [M]\{\phi_i\}$, where: (6)

- [k] is the stiffness matrix;
- $\{\phi_i\}$ is the shape vector of the mode “i”;
- ω_i is the natural frequency;
- [M] is the mass matrix.

An analysis of precision parameters is usually performed with a correct understanding of the stability of the system. The diagram of frequencies is presented in Table 3.

Table 3

Natural frequencies

Specification	Natural frequency (Hz)
1st frequency	51.8
2nd frequency	55.3
3rd frequency	122.3
4th frequency	133.5
5th frequency	275.5
6th frequency	300.3
7th frequency	326.4
8th frequency	362.1
9th frequency	474.6
10th frequency	502.1

Usually, the first natural frequency has the highest amplitude, dangerous for systems. Considering the natural frequency of the components is usually in the range of 20-30 Hz, corresponding to 1.200-1.800 rotation per minute there is a low probability that the robot system having the first natural frequency of 51.8 Hz, will get into resonance during service.

5. Conclusions

The target to obtain lighter structures to achieve high speeds and accelerations but also to reach the target in very small tolerances is possible only by considering optimization criteria. Lighter structures have normally lower stiffness and are more flexible structures to the gravitational and inertial forces determined by an increased acceleration. An optimization of geometry – mass and stiffness - accuracy criteria is therefore useful. Such analysis was performed on the basis of the conventional approach and theoretic model for each mechanism, contact or kinematic chains and structures usually built on the basis of conventional methods. It was proved that modern software and instruments based on the FEM make such research easier if using an appropriate model. The current paper indicates the results of an analysis of the mechanical system of the articulated robot 5R arm, performed using state of the art software and virtual instruments. Similar new research methods analyses from other perspectives similar robotic structures e.g.: introducing a magneto-rheological damper to choose the optimal value of the vibration field to avoid some spectrum resonances, [14]. The scope of our work is to examine if an optimization is needed for a specific robotic structure to work in a different application from the one for which it was designed and to investigate which are the regions to be optimized. A specific parameter of the new application is a maximum load of 1,000 N. The analysis was performed using FEM in order to assess the accuracy of positioning and stiffness parameters. To establish the load, the forces were reduced and the most disadvantageous position was considered.

The results have shown the highest stress when the inertial load of 500N is introduced and the accuracy of the positioning are lower. The deformation in this case is up to 0.5033 mm. Therefore, for an application that requires better accuracy (in the region of 0.05-0.10 mm), the system is not suitable and it becomes compulsory to complete the second stage – an optimization analysis.

Regarding the dynamic analysis, the analysis shows a first frequency of 51.8 Hz, the result validate a low probability to get into resonance during the operations.

Therefore, one of the directions to improve the behaviour is to use the timing belt transmission instead of numerous gears of the speed reducers. A recent investigation performed by the author showed a favourable damp effect introduced by this transmission, [15].

The current work continues other previous researches of the author - [15] while further work should be focused to check the results of the present study and find a solution to improve the system accuracy: experimental research applied for the analyzed model in order to validate the virtual model used and virtual instruments and equipments as LMS to use for the optimization analysis by accuracy vs. dynamic behaviour criteria.

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