A COMPREHENSIVE STATIC AND MODAL ANALYSIS OF"5R" KINEMATIC CHAINS USING VIRTUAL TECHNIQUES

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Abstract. An important characteristic for the field of industrial robotics is the positioning precision of end effectors. Due to the progress of the computer technologies and control systems, the accuracy has significantly improved in the last years. Still, there is a continuous need for machines to provide higher accuracy mechanisms and kinematic chains or to adjust the systems already built in order to adequate it to reach to a better precision of the tasks. The current paper shows the results of a comprehensive analysis applied for RRR-RR robotic system already build including two versions of static analysis and modal analysis, using the modern virtual instruments. The main stages pursued was: design of the mechanisms and kinematic chains for each rotation joint, in accordance with the real robot, modelling of the connections and the mesh for each element and surface, simulation and model analysis using FEM specialized instruments. A final indication about the characteristics to improve is presented.

Keywords: accuracy, stiffness, FEM, static analysis, modal analysis

1. Introduction

In the last years, remarkable performance of IT technologies has been revealed, concerning both hardware and software design. This helped to obtain increasing features of the products realized in the subsequent industries such as machine tool and robotics, mainly from the point of view of control units. Therefore, the units gained more precision and their behaviour can be optimized accordance with the desired criteria.

Still, for the mechanic system a continuous need to build accurate mechanism and kinematic chains is present. Moreover, the systems already built needs to be adjusted in order to adequate to reach to a better precision during the execution. In order to achieve this goal, this article aims to show the original results of a comprehensive analysis of a RRR-RR robotic system including all the mechanism and kinematic chains inside as well as the structure effect.

Such analysis has been performed using conventional techniques and theoretic approach for each mechanism and for several kinematic chains e.g. [1, 2, 3]. These approaches have been usually built on the basis of conventional methods or using FEM at the due moment. In the last few years, more powerful virtual instruments are available and such research can be easier obtained using an appropriate model.

An original analysis has been performed using these virtual techniques allows analyzing the behaviour of each mechanism and kinematic chain. Although this analysis is based on a comprehensive structure that involves a large information database regarding size, connections, mechanisms and kinematic chains, in the current paper we are focusing to show the part regarding the global system accuracy and the system behaviour as an ensemble.

The robot we have modelled is an "articulated arm" type of structure with the dimension completely defined in CAD (figure 1).

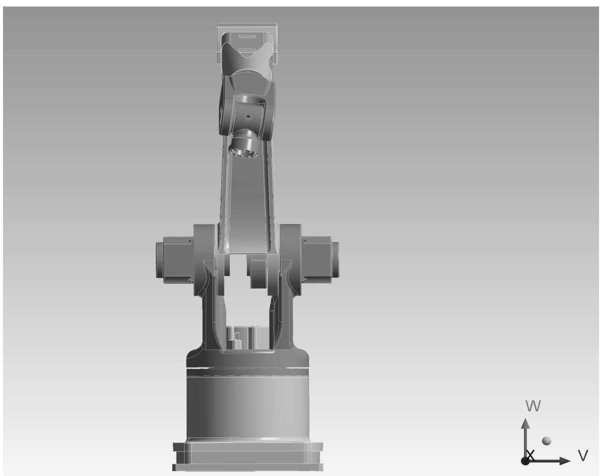

Figure 1. The robot structure

The model follows a real system functioning, therefore all the results are immediately applicable and a comparison using an alternative approach – the experimental research instruments. Such result allows building up any further optimization of the robotic system mentioned based on specific criteria.

2. The system model

2.1. General view

Following the original system in function, we have modelled an electronic version – CAD type introducing the parts, mechanisms and connections, actuators, harmonic drive and other similar components [4], linked to design the robot system mentioned. The file was done using an educational version of Solid Works.

The behaviour of the kinematic chains and the way this influences over the general behaviour of the robot was analyzed using dedicated software for FEM analysis. The CAD model was imported into a compatible file for Ansys, the geometry updated and the structure meshed using 3D elements.

2.2. CAD model

The robot architecture consists from a main structure of 3 degrees of freedom and other 2 corresponding for the orientation unit namely roll and pitch. All five degrees are all rotational as well for positioning and orientation.

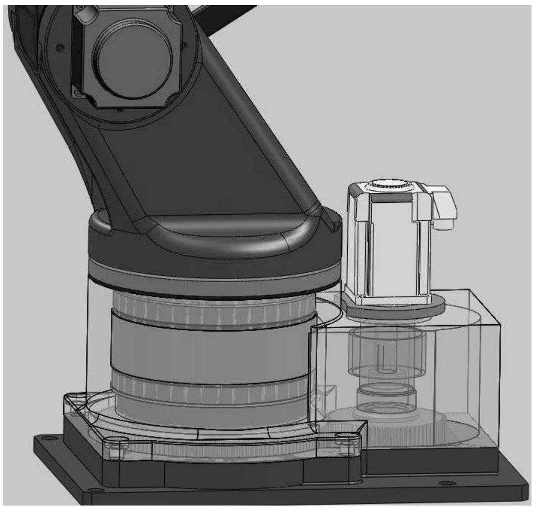

Figure 2. First rotation degree

A servomotor, figure 2, with coupling, actuates the first rotation and speed reducer and two toothed gears and the intermediary elements like radial – axial bearings, shafts or key (figure 3).

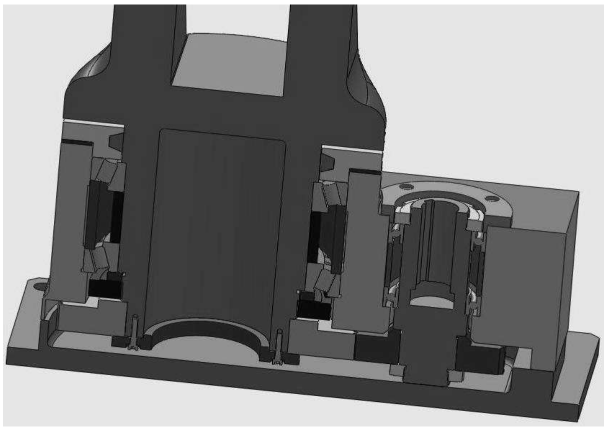

Figure 3. First rotation degree - components

The second rotation is direct drive actuated using a kinematic chain of servomotor coupled with the harmonic drive that assure the mobility of the second arm segment of the robot.

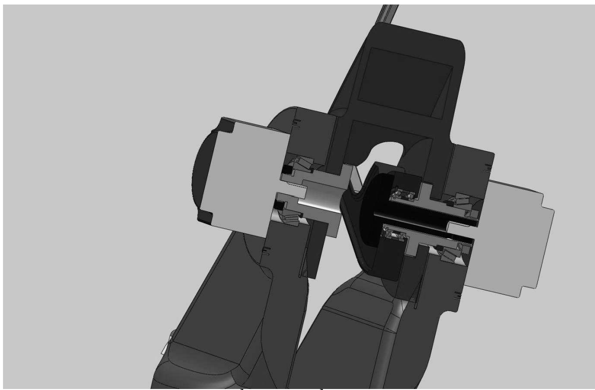

Figure 4. 2nd and 3rd rotation degree

On the opposite side of the jointed arm is located, also fixed to the second arm structure, the third degree which is realized using a closed kinematic chain – a jointed mechanism actuate by it’s correspondingly servo actuator on arm – as show the figures (4) and (5).

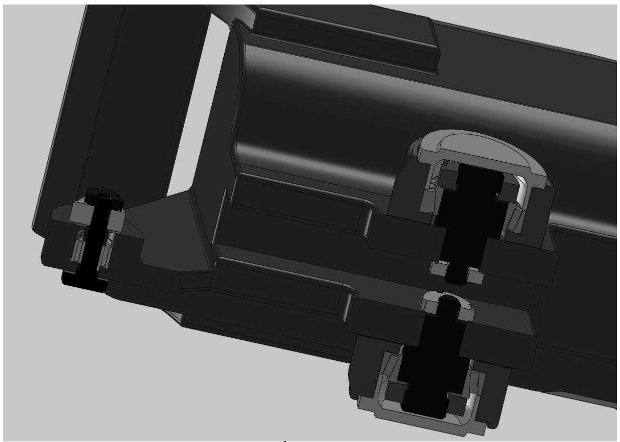

Figure 5. 3rd rotation degree

As for the two mobility degrees for orientation, the mechanism for roll is actuate by a servomotor and harmonic drive and pitch type rotation is driven by actuator, intermediate drive and timing belt and two belts in direct contact with a rotational shaft and case where the gripper is fixed (figure 6).

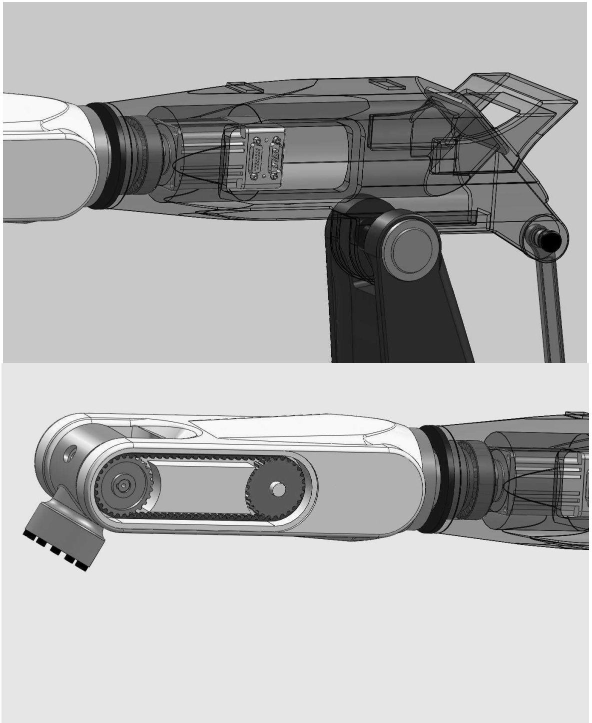

Figure 6. Orientation system: roll and pitch degrees

The geometry previously mentioned was introduced in Ansys 12.01 software where we have run all the simulations. All the objects, faces and the contact regions have been controlled in order to their complete definition.

The mesh model of the mechanisms and kinematic chains finally included a high number of elements - over 350,000 and nodes – over 700,000, 0.5 to mass and a volume of approximately 6.39 m^3. The model above described has been considered as appropriate in order to obtain reliable results.

3. Kinematic chain analysis

3.1. Theoretical basis

The analysis of the stiffness is based on the calculus of the stiffness equation (1) which gives the results $\{P\}^{(e)}$ defined as the equivalent nodal forces. The approximation include 3D finite elements and the calculation of the element stiffness matrix $[k^{(e)}]$ (2) and (3). The other parts of the relation includes the matrices $[B]$ and $[D^e]$ constant throughout the material and the equivalent nodal forces due to initial strains (4), and body force (5) as the literature shows – [5]:

$$\{P\}^{(e)} = [k^{(e)}]\{\delta\}^{(e)} + \{F_{\varepsilon 0}\}^{(e)} + \{F_F\}^{(e)} \qquad (1)$$

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

$$[k_{ieje}^{(e)}] = \iint_D [B]^T [D^e][B] t dx dy \qquad (3)$$

$$\{F_{\varepsilon 0}\}^{(e)} = -\iint_D [B]^T [D^e][\varepsilon_0] t dx dy \qquad (4)$$

$$\{F_F\}^{(e)} = -\iint_D [N]^T \{F\}^e t dx dy \qquad (5)$$

3.2. Loads and input data

All the geometry of the robot is defined and all the mechanisms and kinematic chains modelled accordingly with the real model. Such model is similar to IRB type produced by ABB (figure 7).

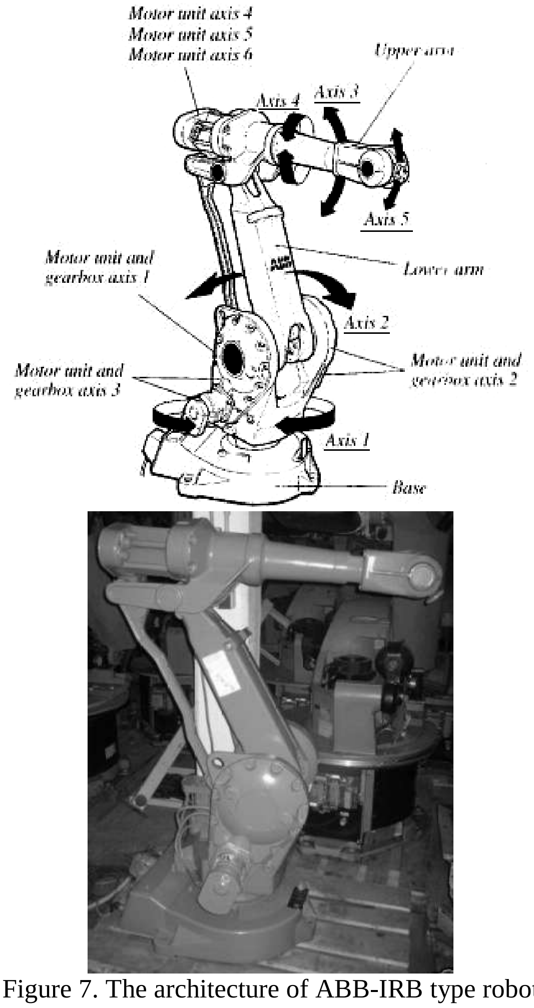

Figure 7. The architecture of ABB-IRB type robot

On the basis of the geometry and considering and the higher load configuration (figure 7), we have calculated the extreme loads determined by the gravitational and inertial forces. This represents the input data to perform the first test of static analysis.

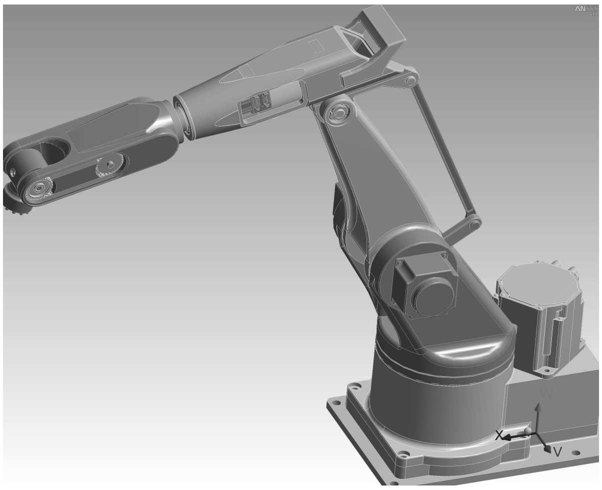

Figure 8. The higher load configuration

A normal load of gripper according to specific application of the robot was calculated on the basis of the kinematic model to 1000 N maximum force applied at the end point of the 5th joint as vertical load (*Ow* axis) (figure 8).

On this basis we have prepared the first assessment and the static analysis. Any influence of temperature distribution is considered, only the normal 22 °C in entire environment.

For the second case, we have keep the conditions above mentioned but introduced the inertial effect separately assessed from a kinematic model, to a maximum value of 500 N as force, applied in the same point but at the horizontal axis (*Ox* axis), while the temperature is normal in entire environment.

On this basis, we have prepared the second assessment and the static analysis. No other influences - such as temperature, have been included.

3.3. Running analysis – the main static tests

The static analysis comprises an assessment of the total deformation and directional displacement, shear stress, principal stress and equivalent (von Mises) stress – see [6].

Running this analysis for the first case considered, the results are shown in the graphics from figure (9) while for the second case concludes with results shown in figure (10).

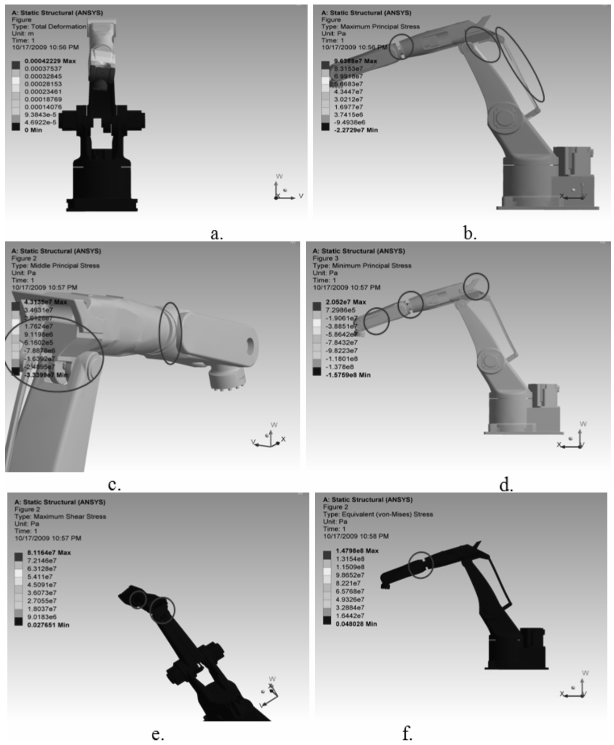

Figure 9. Static analysis – first case

Here we can find the main location exposed to the biggest stress. Therefore, in these parts we have to focus our attention for further improvement of the kinematic chains precision and mechanisms as well as for the optimization of the structure.

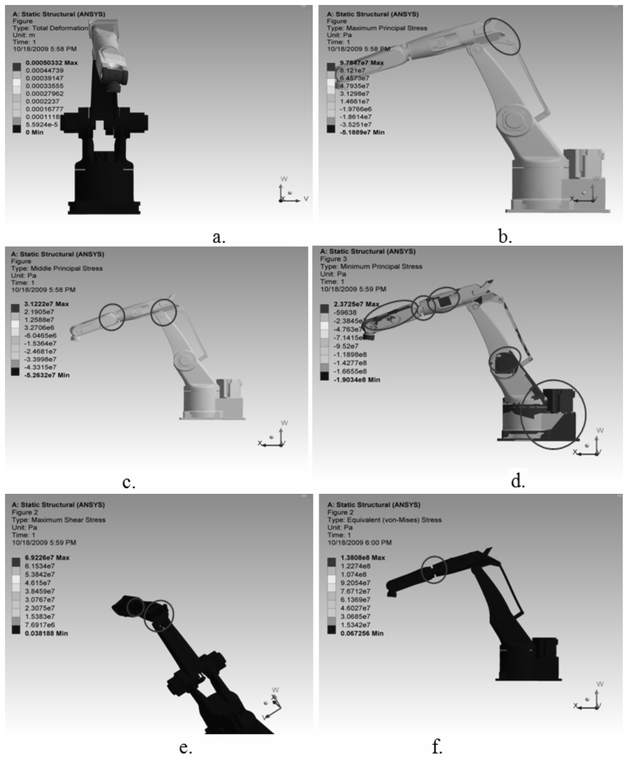

Figure 10. Static analysis – second case

Comparative results analysis presented in table (1) show increasing of stress when the horizontal load is introduced.

In terms of global of positioning precision, the accuracy has depreciated in the second case with 20% compared with the first one.

The highest differences are observed in relation with the principal stress while the equivalent von-Mises stress registers a small increasing of only 8% within the limit above mentioned. Also the direction of the stress is not influenced.

Table 1. Statical analysis results

Specification	1st case	2nd case
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

3.4. Natural frequencies analysis

This paper presents the results of a modal analysis, by finite elements method; the natural frequencies and the modal shapes of the mechanical system previously defined and modelled.

This analysis is important because the parameters of natural frequencies and own modes of vibration can give indication in order to perform an optimisation of the structure and better dynamic behaviour. A modal analysis will show if any dangerous frequency can affect the system.

The following steps have been followed: modelling the system geometry, loads estimation and apply in accordance with the above mentioned, expanding the vibration modes and generating the results. To determinate the natural frequencies and own modes of vibration we have used the modern virtual techniques offered by Ansys. In theory, the classic equation of the eigenvalues:

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

- $[k]$ 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. Running this set of analysis, we have obtained the results shown in the figure (10).

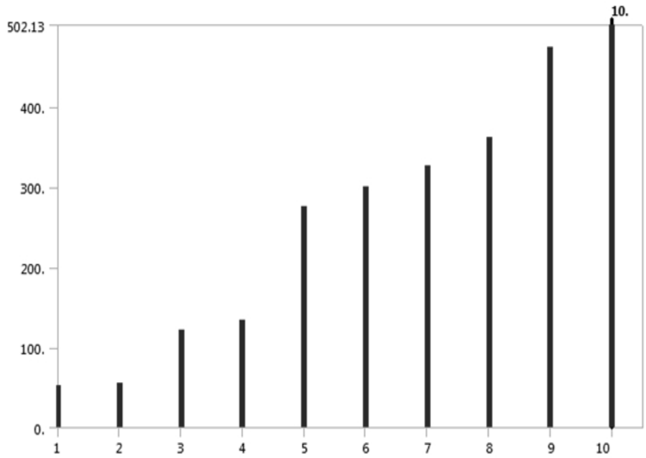

Figure 10. Frequency analysis

The diagram of frequencies is presented in table (2). This reveals that the first natural frequency of 51.8 Hz, which confirm a fair parameter of stiffness and a low probability to get into a resonant frequency during the execution.

Table 2. Frequency analysis results

Specification	Range of 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

4. Conclusions

The current work shows the results of a comprehensive analysis of the mechanical system of the articulated robot arm type "RRR-RR" which has been carried out using virtual techniques and modern software.

The research was performed using Ansys 12.0 in order to assess the accuracy of the kinematic chain as well as its stiffness and dynamic parameters of the entire robot.

Considering the static analysis, an increasing stress is observed when a horizontal load of 50% from vertical load is applied in gripper and the accuracy of position suffers depreciation in terms of deformation of 20%. If the aim is to achieve a better accuracy for the application where the system is functioning, it needs definitely an optimization and the figures (9) and (10) help in identifying the main parts where the parameters have to be improved.

From the perspective of dynamic study, the natural frequencies analysis shows a first frequency at 51.8 Hz, which is not dangerous for the system. Such results confirm a fair parameter of stiffness and a low probability to get into a resonant frequency during the execution.

All the results mentioned, can be confronted with the one obtained from the experimental research in progress of the real model.

Then, an optimization solution, organized by criteria is recommended to be carried out in order to improve the parameters mentioned. A “sensitivity analysis is also needed in order to optimize the parameters in correspondence with the desired performances criteria such as: accuracy vs. stiffness and dynamic analysis.

The current work continues other previous researches of the authors - [7] while the further work is focused to check the results of the present study and find a solution to improve the system accuracy.

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