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BEHAVIOUR ANALYSIS OF ROBOT ARM

Construction of robots arm with drives placed in the base requires the use of inserted shafts that transfer the torque to individual joints of the robot. These shafts are supported on ball bearings of several levels. As these constructions are very complicated, it is necessary to perform verification of deflection of individual shafts to prevent undesirable collisions. Furthermore it is necessary to check the tilt angle of bearing rings which must be no bigger than the value specified by producer. The article deals with the methodology of computational models creation and the ways of calculation results interpretation.

Introduction Mass minimization of moving parts belongs to basic requirements to manipulation subsystems of service robots. The one of possibilities how to achieve that is placing of drives nearer to the base or directly to base of the manipulation subsystem. The transfer of torques is made with the help of the inserted shafts. This type of construction requires not only high manufacturing accuracy, but also sufficient stiffness of individual subassemblies, to avoid collision among single shafts. Therefore it is necessary to make strength analyses not only of single components of subassemblies, but also analyses of whole assemblies.

1 The description of analyzed subassembly

Within the framework of project FT-TA3/014 it is dealt with a manipulation subsystem of the service robot with drives placed nearer its base, the Figure 1. The subassembly of the arm 2 was chosen as an example of analyses. The design scheme of arm, can be seen in the Figure 2. From the scheme it is evident, that it is an assembly of three shafts, whereas one shaft is inserted in the second shaft by the aid of ball bearings and second shaft is inserted analogously in the third shaft. For the right function of the all assembly it is necessary to make strength analyses, whose goal is:

– to detect the deformation of single shafts in order to avoid collision of single shafts or related components,

– to detect the tilt angle of bearing rings not to exceed allowed value that is prescribed by producer.

2. Computational models of bearings

To be able to create a suitable computational model, whereon it would be possible to simulate behavior of rotating parts, it is necessary to make an analysis of possible cases of models, which present rolling bearings. This analysis is carried out on common ball bearing. In the following figures are displayed models presenting ball bearing.
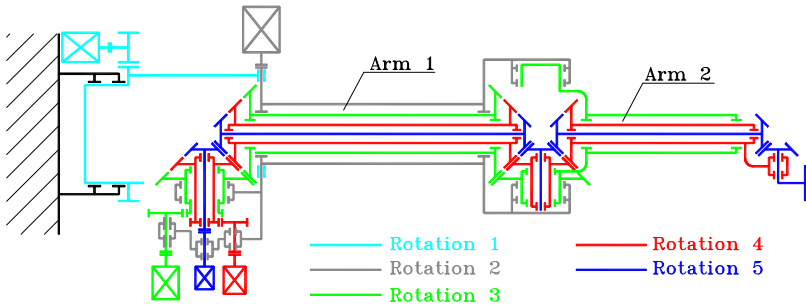
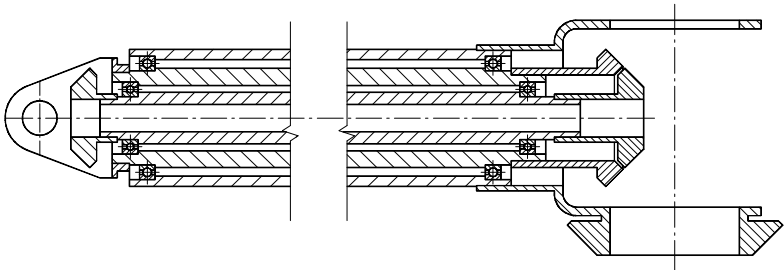Figure 1 – Kinematics scheme of manipulation subsystem

Figure 2 – Design scheme of arm 2

In the figure 3, *a* the simplest model of a bearing is displayed, created only by the ring, whose dimensions are given by the bearing mating dimensions. This model is formed only by one part. In the following figure 3, *b* is the assembly model of a bearing, which is formed by the outer and inner ring and further by the inlaying flexible ring that supplies here the rim of bullets. The last model of the bearing, the figure 3, *c* represents practically the authentic picture of real bearing. These individual models of the bearings are used for creating the simple types of the shaft support subassemblies, the figure 4.

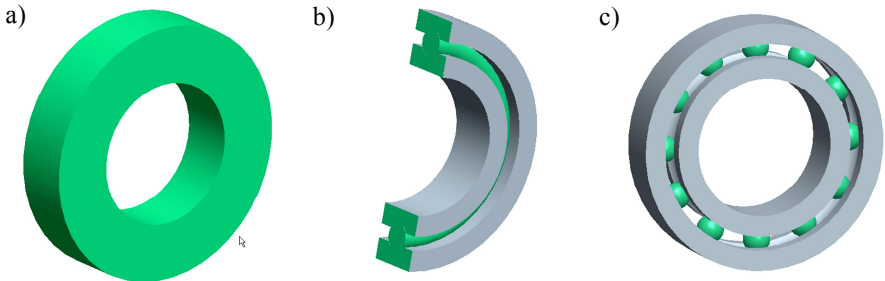a)   b)   c)

Figure 3 – Models of Bearing: *a* – Ring, *b* – Inlaying flexible ring, *c* – Bullets
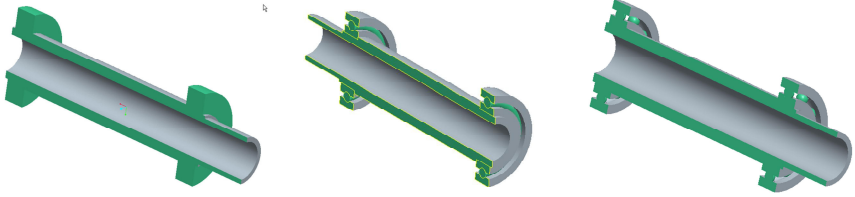
Figure 4 – Models of the shaft support

3 Replacement of rolling elements by springs

For the analysis of the shafts assembly the CAD system Pro/MECHANICA STRUCTURE will be used. Springs can be used as a substitution of the flexible rolling elements, in this case bullets. System Pro/MECHANIKA enables to create idealized components of *"Spring″* type, to which can be assigned stiffness with respect to the choice of coordinated system. For definition of the computational model of the bearing it is the advantage to define system of springs only in bearing subassembly. All information and settings are transferred to the main assembly of the shaft support.

For creating of the springs pattern that replaces bullets, it is first needed to create a pattern of points on the rotational surface of bearing's rings, Figure 5, a. In the following Figure 5, b the computational model of the bearing is displayed. The important step is the setting of the proper values of the individual spring stiffness in the chosen coordinate system. In the Figure 6 the dialog of the stiffness setting of the spring is displayed, in order to be able to simulate tilting of the inner ring caused by the shaft deflection.
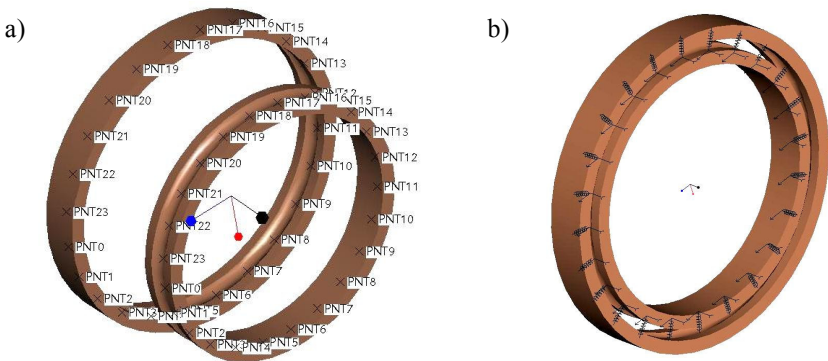
a)

b)

Figure 5 – Simulation of rolling elements:
a – Modified model of bearing, *b* – Computational model of bearing

Figure 6 – Setting dialog of the spring stiffness

The proper setting of the spring stiffness is the question of testing, first it is necessary to measure the deformation of the analyzed shaft placed in joints and then compare it with the same behavior of shaft supported in bearings.

4. Bearing with inlayed flexible ring

The next possibility of the bearing computational model is using the inlaying flexible ring with a different stiffness. In the Figure 7 there is displayed the model of ball bearing support of the shaft end, when balls are replaced by ringlet of circular cross section. To be able to model a tilting of the inner ring, it is important to proper define the elasticity of the inlaying ring.

Figure 7 – Model of shaft support with bearing with ringlet of circular cross-section

One of the possibilities is using a material with different stiffness in the individual axes. Pro/MECHANICA enables definition of the three materials types with the view to the stiffness matrix, Figure 8:

– **Isotropic -** 2 independent elements of the stiffness matrix, identical elastic characteristics in all directions.

– **Orthotropic -** 3 symmetry planes of the materials properties, 9 independent elements of the stiffness matrix.

– **Transversely isotropic -** 3 planes of symmetry of the material properties, in one plane it behaves as isotropic, 5 independent elements of the stiffness matrix.

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix}$$

Figure 8 – Stiffness matrix of the orthotropic material

The orthotropic material is used to reach suitable properties of the bearing's middle ringlet. The setting is evident from the Figure 9. According to these setting it is necessary to modify orientation of directions of materials properties, to correspond to stiffness matrix.

Figure 9 – Definition of the orthotropic material

The setting of the stiffness matrix elements is a question of testing and investigation of the behavior of the bearings and the shaft deflection in the concrete model of the shaft supports.

5 Shaft support by the help of pin joints

From the previous chapters it results, that for the correct setting of the stiffness of elastic parts of the computational model it is necessary to learn about the behavior of the shaft first. If we suppose, that the shaft deflection is given by shaft stiffness with the ends placed in joints with corresponding degrees of freedom, it is necessary to create joints in the area of the bearings. In the Figure 10, a the arm model of the analyzed shaft is displayed. The schemes in the Figure 10, b are displayed boundary conditions of middle shaft model.

In the area of bearings are placed joints with one degree of freedom in axis that is normal to plane in which the load actuates. In the Figure 11 the total deflection of the shaft is displayed in enlarged scale, its value is 0,1 mm. For this deflection value are search bearings stiffness.
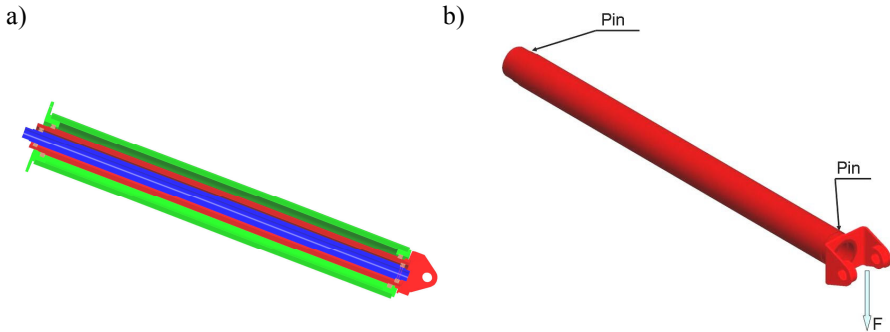
a)   b)

Pin

Pin

F

Figure 10 – Shaft model:
a – Model of arm 2 (cross-section); *b* – Boundary conditions of shaft model
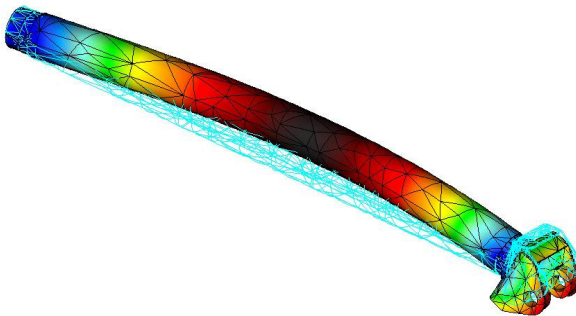

Figure 11 – Total deflection of the shaft

6 Analysis of the shaft support with the elastic ring or springs

For the next analyses there were created computational models of the shaft support in both variants to compare presented methods. In the Figure 12 and 13 the shaft deflection is displayed that corresponds to shaft deformation with the ends placed in the joints. The details in cross-section of the model arm assembly that is displayed in the Figure 14. Here is displayed the total deformation of several supports.

Conclusion. In this article are introduced methods of strength calculations of robots arm assemblies with inserted shafts. Both of presented methods embody roughly identical results concerning deflection of the inserted shafts and deformation and deflection of the bearing rings. The method that use a bearings model with springs can be commonly used in several FEM systems. Using of the elastic ring from the orthotropic material is also suitable, the disadvantage of that method is complicated meshing because of type of geometric elements and therefore it puts higher claims to hardware. This article was compiled as part of projects FT-TA3/014, supported by the Fund for University Development from the Ministry of Industry and Trade, 2008.
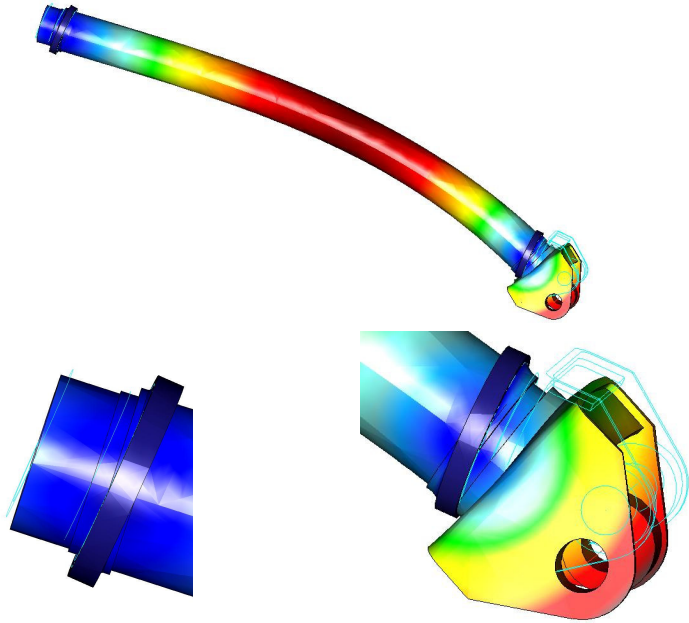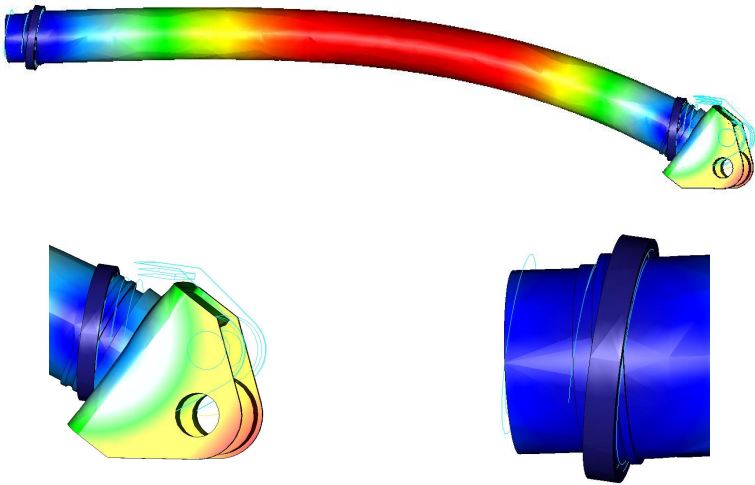
Figure 12 – Shaft deformation with elastic ring

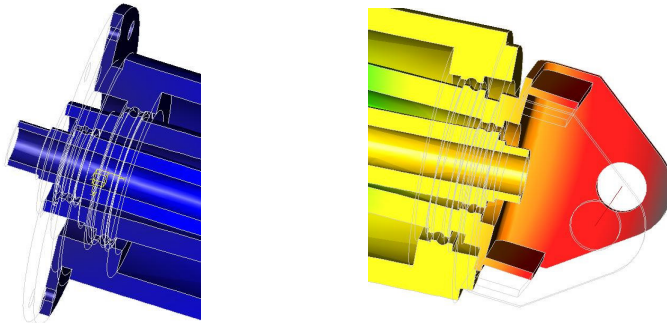Figure 13 – Shaft deformation with springs

Figure 14 – Total deformation of shafts supports

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3. КОНЕЧНЫ
АНАЛИЗ ПОВЕДЕНИЯ РУКИ РОБОТА

Конструирование руки роботов с двигателями, помещенными в корпус, требует использования вставных валов, которые передают вращающий момент отдельным узлам робота. Эти валы поддерживаются шарикоподшипниками нескольких уровней. Поскольку эти конструкции очень сложны, то необходимо выполнить проверку отклонений отдельных валов, чтобы предотвратить нежелательные столкновения. Кроме того следует проверить угол наклона колец подшипника, который не должен быть большим значения, указанного производителем. В статье рассматривается методология создания математических моделей и путей интерпретации результатов вычислений.

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