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FEM ANALYSIS OF THE MODULES BODIES FOR BUILDING OF THE ROBOTS TECHNOLOGICAL HEADS

Abstract

As a part the project it was necessary to design and implement accurate reducers and actuators in various kinematic solutions of modules. These modules will be possible to stack them into desired shapes, allowing them to be deployed in production machines and robotic equipment according to the specific customer requirements, e.g. technological heads. The article deals with designing and especially FEM analysis modules – technological heads for 2 and 3 axis handling and robotic systems. Designed modules – technological heads will allow correcting inaccuracies motion manipulator or less precise robot. Solving of these modules is based on the use of smart actuators consisting of engine, precise gearbox and appropriate sensing technique. Control of the motion will be implemented on the basis of information obtained from sensors placed directly in drives the positioning module and the sensors working environment according to specific requirements for each application.

1. INTRODUCTION

The analysis of specific solutions can be concluded that technological heads are customized to the needs customer (a very small percentage of the products produced as a catalog) [1-2]. It follows that the solution of the necessary motion functions the technological head are used either catalog motion module; resp. motion axes are original solution throughout the project technological heads. This leads to the need to design appropriate dimensional series, which would be

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applicable for creating mutually compatible modules enable create a complete units. These units allow to create the final shape of the module – the technological head according to different needs, such are intelligent modules – grippers for mounting rotating, non-rotating components to manipulate objects and the like. In the case of proposal heads is important for specific application, what will technological head used, such as grinding, drilling, threading and milling. On the figure 1 is shown 3-axis technological head consisting of the modules RPM 110-70-50 [3].

Rotary axis of positioning and handling unit or rotary positioning module is autonomous, functional and construction module for rotary positioning axes. It has integration function with intelligence for mechanic and driving ability to connect with other modules into one higher function machinery systems. Rotary positioning module is node of device, which must perform driving rotary movement with required to speed and precision of positioning [4,5].
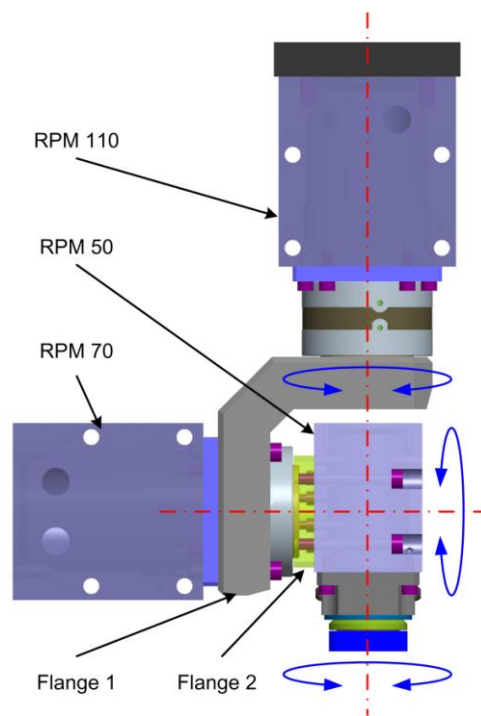

Fig. 1. Technological head (3 – axis) [source: own study]

Rotary positioning module (next **RPM)** in figure 2 is electro servomechanism for drive position (rotary angle or linear displacement) of machine. It consists from gearbox, servomotor and sensors in one construction and function compact [6].
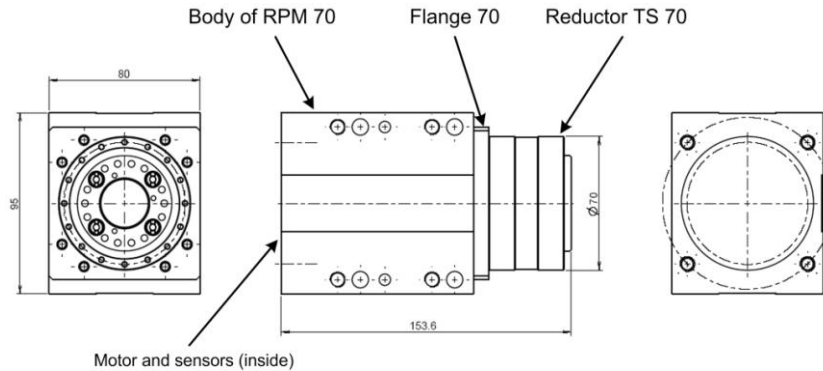
Fig. 2. Module RPM 70 [source: own study]

2. THE BASIC STRUCTURE OF RPM

Systemic *RPM* model describe conception of engine solution (drive and transform mechanism for change of kinematic motion parameters – speed of movement) and it describe internal structure of RPM module (block structure). Basic internal structure is shown on figure 3. Module marked like *IRPM* – intelligent rotary positioning module contains all components like RPM module, but it has one difference. This means that drive and control block have the intelligence which consists from adaptive drive. It allows answer to changes from working activity in real time. Changes are monitored on information base from sensors (for example sensor of revolutions, temperature, speed, acceleration, torque, forces). Quantity and kind of sensors is dependent on currently application [1,3,6].
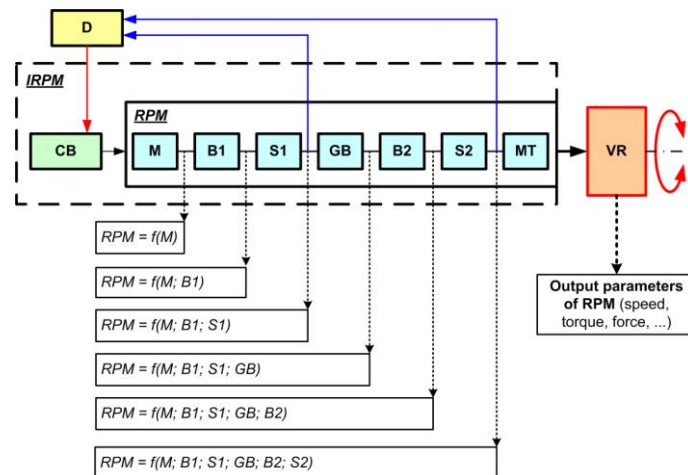

Fig. 3. Systemic RPM model – block structure [source: own study]

Legend of figure 3 Systemic RPM model:
- **D** – *drive* (primary energy, output of drive system),
- **CB** – *control block* (device for editing drive signals),
- **M** – *motor* (rotary servomotor; sensoring function for angular rotation, safety brake), *technical variants*: M_1 without brake, **M – B1** with safety brake integrated,
- **GB** – *gearbox block* (reduction speed of motor **M**, higher torque on module output, physical transfer of rotary motion(ρ_M) from motor **M** out-put to rotary motion of module **VR** (ρ_2); have function for conversion of motor **M** parameters (n_M – revolutions per minute, f_M – motion frequency, P_M – performance, φ_M – path of movement/angle) to module output V_R (ρ_j).

Technical variants: GB1 gear block with classic shaft output, *GB2* – gear block with hollow shaft output, *GB3* – gear block with flange output),
- **MT** – *mount* (motion ensuring for direct path (circle) with one degree of freedom; system of guideways contact between moving and non-moving part of module),
- **S1** – *sensor* (sensor for output parameters of motor *M* (speed, revolutions per minute, position),
- **S2** – *sensor* (sensor for output parameters of module **RPM** (position)),
- **B1** – *safety brake* (non will brake for motor output *M1*),
- **B2** – *positioning brake* (positioning brake for output of module **VR**, fix ending rotary position of module **RPM**),

VR – *output element* (mechanical element / interface for connection **RPM** as higher functional unit).

Totally (theoretical) model of structure RPM consists from: M-B1-S1-GB-B2-S2-MT-VR.

3. BASIC DATA OF INDIVIDUAL MODULES

In conformity with the concept of solutions and objectives of the project development new series RPM to the performance and focus on parametric type series RPM module size range 50, 70 and 110. Basic data on the individual RPM modules are shown in table 1.

Tab. 1 Technical characteristic RPM 50, 70 a 110

	RPM module		**Units**	**RPM 50**	**RPM 70**	**RPM 110**
1.	Max. dimension RPM Module	b x b	[mm]	58x66	80x95	112x135
2.	Max. dimension body of reducer	ØA (a x a)	[mm]	55 x 55	Φ 70	Φ 110
3.	Length of RPM	L	[mm]	111	153,6	202
4.	Reduction ratio	**i**	--	63	57	67
5.	Rated output torque	T_R	[Nm]	18	50	122
6.	Acceleration and braking torque	T_{max}	[Nm]	36	100	244
7.	Rated input speed	n_R	[rpm]	2000	2000	2000
8.	Cycle effective speed	n_{ef}	[rpm]	3000	2500	2000
9.	Max. allowable input speed	n_{max}	[rpm]	5000	5000	4500
10.	Lost motion	**LM**	[arcmin]	<1,5	<1,5	<1,0
11.	Average angular transmission error	**ATE**	[arcsec]	+/- 36	+/- 36	+/- 20
12.	Hysteresis	**H**	[arcmin]	<1,5	<1,5	<1,0
13.	Input inertia	**I**	[10^{-4} kgm^2]	0,006	0,061	0,16
14.	Torsional stiffness	k_t	[Nm/arcmin]	2,5	7	22
15.	Tilting stiffness	M_t	[Nm/arcmin]	4	35	150
16.	Max. tilting moment (a2=0)	$M_{c\ max}$	[Nm]	44	142	740
17.	Max. axial force	$F_{a\ max}$	[kN]	1,9	3,7	13,1
18.	Rated radial force	$F_{R\ max}$	[kN]	1,44	2,6	9,3

4. FEM ANALYSIS OF BODIES RPM MODULES

FEM analysis focuses on static analysis, result of a determination of the appropriateness of the proposed use of the material for the carrier body of module RPM. Load carrier body of the module is at the maximum torque values and burdensome forces acting on exactly reducers used in the construction of modules. Based on the above structure, three were selected sized series the modules that are most to deployed for the handling and robotic applications. With regards to the modules RPM 50, 70 and 110.

FEM analysis was carried out on all three type - size series the modules RPM. In the next part of the article we focus on the medium size range of the module RPM 70. Module the RPM 70 is formed in a 3D CAD program ProEngineer 5.0/Creo and FEM analysis is the solution in module Pro/Mechanica. The material of the module body was compared according to standard EN AW 2017, which is characterized by good machinability and good strength properties. Material parameters are shown in table 2.

Tab. 2 Characteristic EN AW 2017 (AlCu4MgSi)

Material / EN	State	Rm (min.) [MPa]	Rm (max.) [MPa]	Rp 0,2 [MPa]	Ductility [%] (A 50 mm)
AlCu4MgSi EN AW 2017	O/H111		250	Max. 135	10
	T3	400		250	8
	T4	500		240	8

The proposed module body 70 RPM (2D model – sketch), figure 4 is also fitted with the connecting holes in which they is possible the install flange through bolts.

Connection holes on the body module are located on the back and bottom side of the module. Therefore, it is necessary for analysis of stress taken into account way and direction of the load as shown in figure 5.

The resulting value of the tilting moment depends on the load RPM module from constituents radial and axial forces. The formula is as follows:

$$M_C = F_R.a + F_A.b \qquad (1)$$

where: M_C – tilting moment [Nm],
          F_R – radial force [N],
          F_A – axial force [N],
          a – arm radial forces [m],
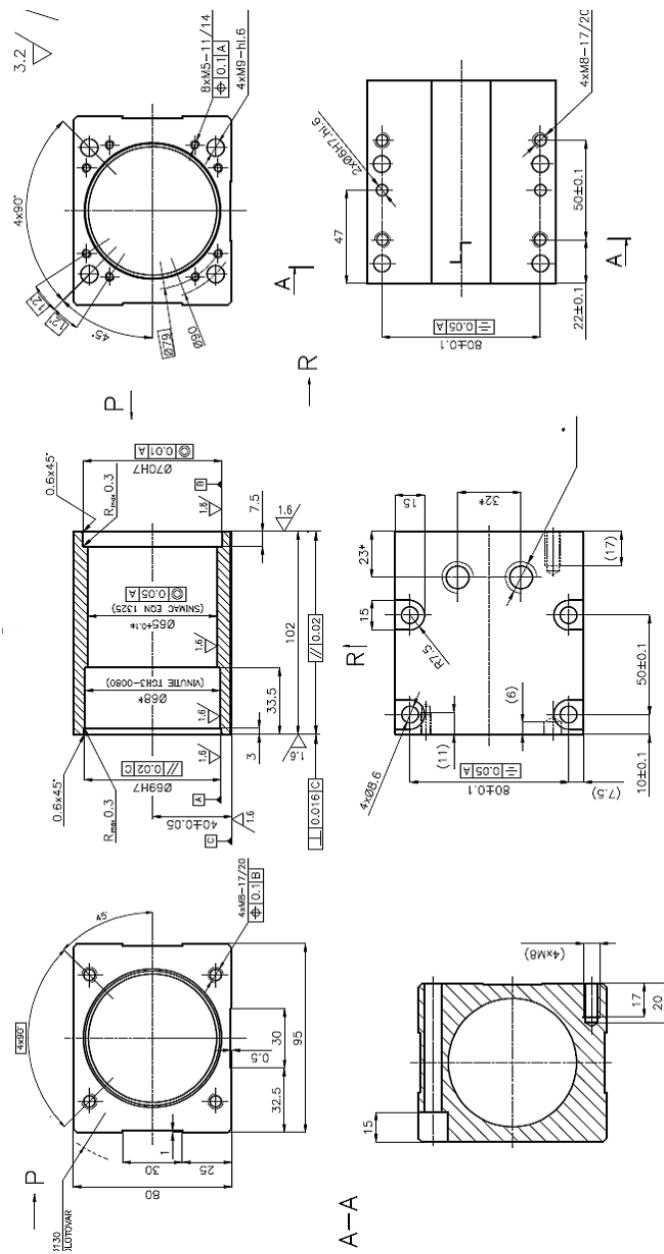 b – arm axial forces [m].

Fig. 4. Sketch of the module body RPM 70
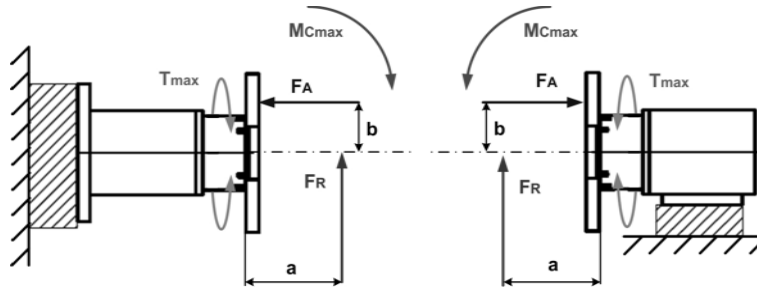
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Fig. 5. Location of forces and moments

Creating of different configurations 2- and 3-axial technological head is dependent on the action of applied forces and character of the proposed application use of the heads. It was therefore necessary to determine the maximum value of burdensome moments and forces applied to the output flange technological heads. By maximum torque and forces acting on each RPM modules are defined their structure and composition. Specific the value of maximum loads to module RPM 110, 70 and 50 are shown in table 3, focusing on the module RPM 70.

Tab. 3 Maximum and rated load RPM modules

Maximum load output flange	Units	RPM 110	RPM 70	RPM 50
Rated output moment - T_{max}	Nm	244	**100**	36
Maximal tilting moment - M_{cmax}	Nm	740	**142**	44
Rated radial force - F_R	kN	9,3	**2,6**	1,44
Maximal axial force - F_A	kN	13,1	**3,7**	1,9

Static analysis of stress and strain in the body of module RPM 70 - load body at a torque value of 100 Nm. The direction of load (torque) and anchorage area - constraints (fixation on the back of the body) is shown in figure 6.

For create of networking the body module RPM 70 was created 6765 elements of type Tetrahedron, figure 7. In a programme ProE / Creo Mechanica module is a most preferred element. Type elements Wedge and Brick were not used. Calculation method has type QuickCheck which do not check convergence calculation. The degree of polynomial was set to value 3.
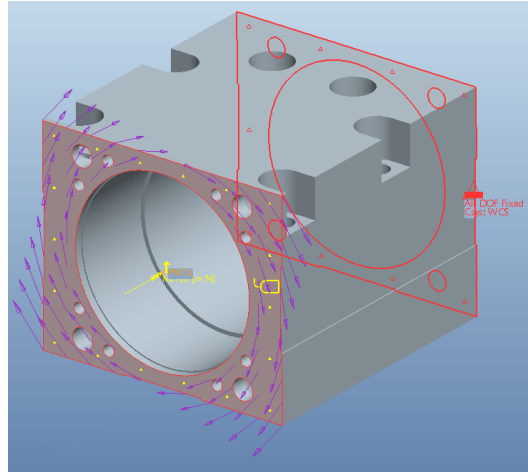
**Fig. 6. Method of load and anchorage – constraints
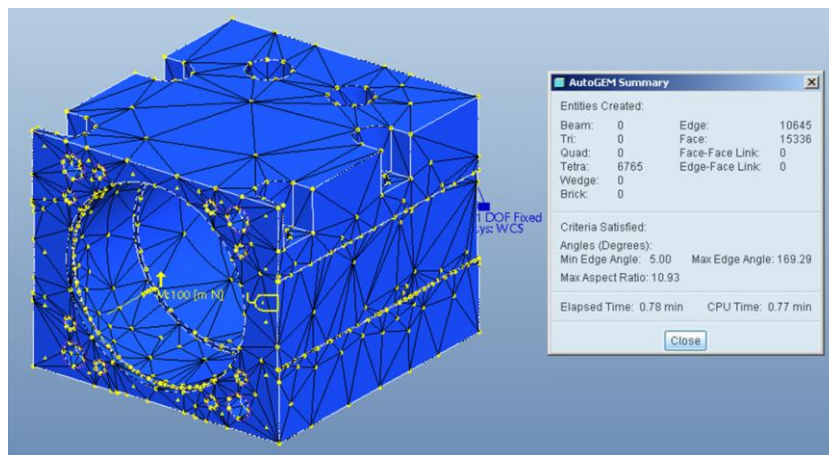of the body for 70 RPM (back of body) [source: own study]**

Fig. 7. Network on the module body RPM 70 [source: own study]

The findings of stress value (fixation on the back of the body) are shown in figure 8, where the value of the measured voltage has a value of 11,4 MPa. The permissible stresses for materials in accordance with EN AW 2017 have a value of 250 MPa. Comparison of the observed and the permissible stress (11.4 ≤ 250 MPa) confirms that the proposed material for a maximum torque of 100 Nm satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the back of the body) for the load of torque Mk 100 nm is 0,0053 mm. The based on expected deployment module for the application robotics and manufacturing techniques, the value of deformation sufficient.
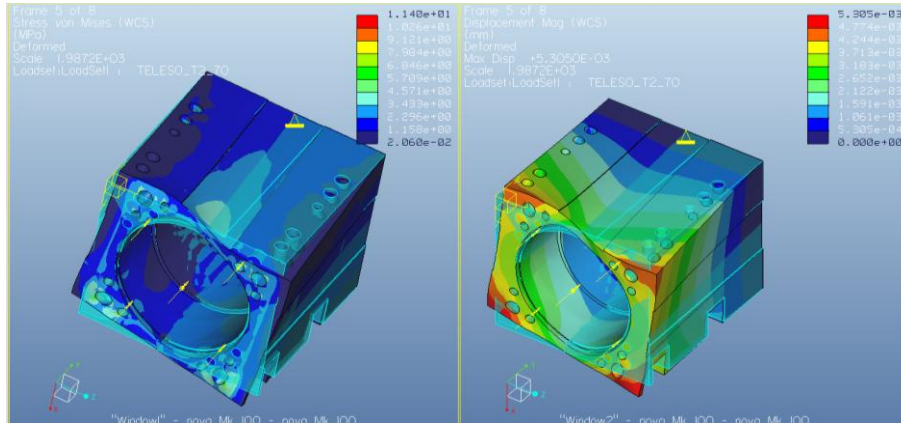
Fig. 8. Value of stress and distortion body the module RPM 70 for M_k 100 Nm (fixation on the back of the body) [source: own study]

The findings of stress value (fixation on the upper part of the body), where the value of the measured voltage has a value of 23,8 MPa. The permissible stresses for materials in accordance with EN AW 2017 have a value of 250 MPa. Comparison of the observed and the permissible stress (23,8 ≤ 250 MPa) confirms that the proposed material for a maximum torque of 100 Nm satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the upper part of the body) for the load of torque Mk 100 nm is 0,00687 mm.

Static analysis of stress and strain in the body of module RPM 70 – load body at a axial force value of 37 000 N. The findings of stress value (fixation on the back of the body) are shown in figure 9, where the value of the measured voltage has a value of 26,28 MPa. Comparison of the observed and the permissible stress (26,28 ≤ 250 MPa) confirms that the proposed material for a maximum axis force F_A 3,7 kN satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the back of the body) for the load of axial force F_A 3,7 kN is 0,00612 mm. The based on expected deployment module for the application robotics and manufacturing techniques, the value of deformation sufficient.

The findings of stress value (fixation on the upper part of the body) are shown in figure 9, where the value of the measured voltage has a value of 29,01 MPa. Comparison of the observed and the permissible stress (29,01 ≤ 250 MPa) confirms that the proposed material for a maximum axis force F_A 3,7 kN satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the upper part of the body) for the load of axial force F_A 3,7 kN is 0,009 mm.
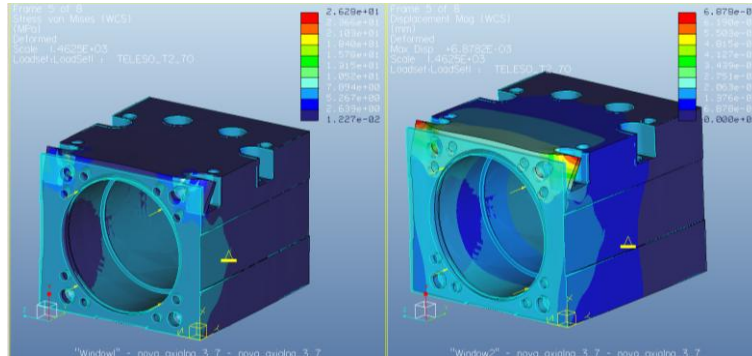
**Fig. 9. Value of stress and distortion body the module RPM 70
for F_A 3,7 kN (fixation on the back of the body) [source: own study]**

Static analysis of stress and strain in the body of module RPM 70 – load body at a radial force value of 26 000 N. The findings of stress value (fixation on the back of the body) are shown in figure 10, where the value of the measured voltage has a value of 14,89 MPa. Comparison of the observed and the permissible stress ($14,89 \leq 250$ MPa) confirms that the proposed material for a maximum radial force F_R 2,6 kN satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the back of the body) for the load of radial force F_R 2,6 kN is 0,01475 mm.

The findings of stress value (fixation on the upper part of the body), where the value of the measured voltage has a value of 44,36 MPa. Comparison of the observed and the permissible stress ($44,36 \leq 250$ MPa) confirms that the proposed material for a maximum radial force F_R 2,6 kN satisfies requirements. The maximum value for the deformation body module RPM 70 (fixation on the upper part of the body) for the load of radial force F_R 2,6 kN is 0,0172 mm.
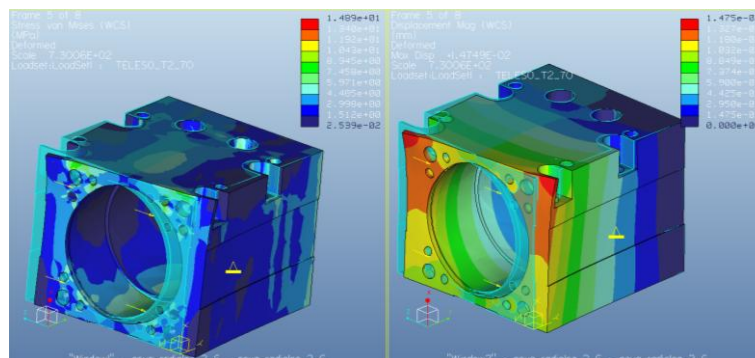

**Fig. 10. Value of stress and distortion body the module RPM 70 for F_R 2,6 kN
(fixation on the back of the body) [source: own study]**

In an analogous way, was the solution FEM analysis on the sized series RPM 50 and 110.

5. CONCLUSION

Development of a new RPM types allows better meet the needs constructors of automatized and robotized workstations. By deploying of precise technological head on end member of the robot can be improved resulting accuracy and repeatability of the robot in space. This leads to the reduction of the resulting rates robotized workplaces, since there is no need make it to deploy of accurate and expensive robot.

FEM analysis of the proposed modules is achieved by confirm the suitability of the use of aluminium alloys in structures RPM module. Deployment of the material was reduced by resulting of module weight while maintaining of sufficient strength and rigidity. This leads to the possibility of deployment of the proposed modules for robots and manipulators with lower load capacity.

REFERENCES

[1] ŚWIĆ A., GOLA A.: *Elements of design of production systems – methodology of machine tool selection in casing-class FMS*. Management and Production Engineering Review, vol. 1, No 2, 2010, pp. 72-80.

[2] GOLA A., ŚWIĆ A.: *Computer Aided FMS Machine Tools Subsystem Selection – Conception of Metodology*. Applied Computer Science, vol. 5, no 1, 2009, pp. 27-39.

[3] HAJDUK M. et al.: *Trends in industrial robotics development*. Applied Mechanics and Materials, vol. 282 (2013), ISSN 1660-9336, pp. 1-6.

[4] YANG G., CHEN I.M.: *Task-based optimization of modular robot configurations: minimized degree-of-freedom approach*. Mechanism and Machine Theory, vol. 35, issue 4 (2000), pp. 517-540.

[5] SEMJON J. et al.: *Procedure selection bearing reducer twinspin for robotic arm*. Applied Mechanics and Materials, vol. 245 (2013), ISSN 1660-9336, pp. 261-266.

[6] SEMJON J. et al.: *Benchmarking analysis of the application of small bearing reducers and actuators in service robotics*. Annals of the University of Oradea: Fascicle of Management and Technological Engineering : 26st – 28st may 2011, Oradea, 2011, vol. 10 (20) (2011), ISSN 1583-069, pp. 5.303-5.306.

[7] WEDLER A. et al.: *DLRs dynamic actuator module for robotic space applications*. Proceedings of the 41st Aerospace Mechanisms Symposium, Jet Propulsion Laboratory, Robotics and Mechatronics Center (RMC), German Aerospace Center (DLR), Wessling, Germany, May 16-18, 2012.

[8] MALINOWSKI T., MIKOLAJCZYK T., OLARU A.: *Control of articulated manipulator model using ATMEGA16*. Applied Mechanics and Materials, vol. 555 (2014), ISSN 1660-9336, pp. 147-154.