OPTIMIZATION OF THE ROBOTIC JOINT EQUIPPED WITH EPICYLOIDAL GEAR AND DIRECT DRIVE FOR SPACE APPLICATIONS

Karol Seweryn [(1)], Kamil Grassmann[(1)], Monika Ciesielska [(1)], Tomasz Rybus [(1)], Michał Turek [(1)]

[(1)] Space Research Centre PAS, ul. Bartycka 18a, Warszawa 00-716, Poland, Email: kserweryn@cbk.waw.pl

ABSTRACT

One of the most critical element in the orbital manipulators are kinematic joints. Joints must be adapted to work in tough conditions of space environment and must ensure the greatest efficiency and work without backlash. At the Space Mechatronics and Robotics Laboratory (LMRS) of the Space Research Centre, PAS our team designed and built a lightweight kinematic pair based on a new concept. The new concept is based on the epicycloid two-stage gearbox with torque motor. In this paper we have focused on optimization of the joint design for space application. The optimization was focused on the minimization of the mass and backlash effects and on maximizing the joint efficiency.

1. INTRODUCTION

Nowadays, increasing the interest in application of a robotic system include satellite with the robotic arm. One of them is connected with increasing the satellite lifetime which is often significantly shortened by various malfunctions (e.g., failures of attitude control systems, failures of deployment mechanisms [1]). Possible solution is to use a spacecraft equipped with the robotic arm performing the on-orbiting repair. Servicing satellite capable of making repairs or replacing failed subsystems may restore normal operations of malfunctioned satellite and prolonging operational period of satellites (e.g., [2], [3], [4]). Several new mission developing the on orbit services are currently planned: Deutsche Orbitale Servicing Mission (DEOS) and ESA in-orbit demonstration mission (IOD). The other possible application of space robots is capturing the non-cooperative targets which can give an opportunity to remove large space debris from the orbit (e.g. [5] [6]). However the accurate positioning of the manipulator arm is complicated task due to its nonhonomical nature [7], [8]. The various method of the control of such systems are prepared [9]

The robotic arm in kinematics point of view is a structure build with links and a joint. The main function of this mechanism is to ensure the movement of the end effector with respective velocities which need to apply torques in very precise way. In terms of control system the joint should be characterized no backlash and high efficiency. These two elements can be obtain by using direct drive combined with epicycloial gear. The mentioned cycloid gear common used in the robotic arm on the Earth [10]. The direct drive motor is BLDC actuator which is able to generate the high torque with low speed what is desired in manipulators [11].

The paper is focused on examination the possibility to use robotic joint composed on specially developed direct motor and epicycloid gear as a potential solution for space manipulators. This process was performed through optimization of the existing solution for specific constraints induced by space environment - especially zero gravity. Furthermore the joint was developed and the tests has been done.

The paper consists of seven sections. Following introduction, the requirements and its basic parameters are presented. Next section presents the prepared FEM and dynamic model of the cycloid gear. The results from the simulations are showing in section 4. The detailed CAD design of the two stage cycloid reducer and joint is presented in section 5. Next section contains the description of the conducted test on the gearbox using dedicated test bed. Second to last part of this article presents the discussion about correlation results from the test with simulations. The last section contains plans connected with development of the technology and knowledge about cycloid gear.

2. JOINT REQUIREMENTS AND ITS BASIC PARAMETERS

The presented joint is dedicated to use in 7-DOF manipulator (LEMUR) designed in LMRS. The primary objective of this project is to study the different control algorithm applicable for space robots.

The main requirements are summarized below:

a) **functional and performance requirements**
   - angular position accuracy 0.1 deg.,
   - force- torque capability of 10N and 15Nm,
   - possibility to free configuration with links,
   - speed accuracy 0.1rad/s,
   - possibility to rotate 720 deg.,

b) **physical characteristics**
   - mass of 1600g,

'15th European Space Mechanisms & Tribology Symposium – ESMATS 2013'
Noordwijk, The Netherlands, 25–27 September 2013

- dimensions less or equal than 120x120x 150mm,
- central located hole for lead the wires with diameter of about 30mm,
- maximal angular speed 15 rad/s,

c) operational requirements:

- capability of performing 1-g operations with using special off-loading device.

The proposed concept of the joint is based on the connection of the torque motor and backlash free epicycloid gear. The proposed type of the motor is justified for the following reasons. First of all, this motor could work in space environment considering the electronic commutation (the same as in the BLDC). Torque motors, have the ability to generate high torque at very low speed. The exemplary characteristic of the torque in attitude of angular speed is presented in Fig. 1. In terms of design the motor have a central placed hole with a large diameter which is able to place the slip ring inside the joint. The selection of the type of gear was made on the basis of comparison of the proposed solution with the harmonic gear. One of the key advantages of the epicycloid gear is that the transmission occurs only through rolling friction which is preferable solution from tribological point of view [12].

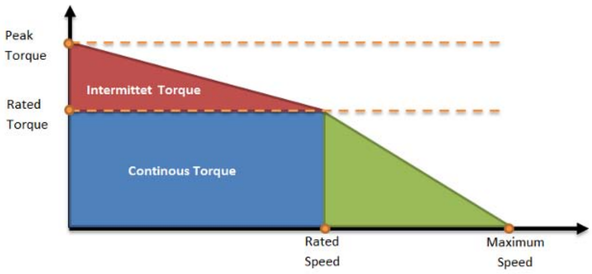

Figure 1. Exemplary torque characteristic via angular speed of the direct drive motor.

Figure 2. Rotor and stator in the housing of the direct drive motor.

Another advantage of the epicycloid gear is the possibility to make a centrally located bore with large diameter to lead the cables. Moreover the cycloid disc with the cycloid shaped tooth allows achieving a high gear ratio of about 171:1 in one stage [13].

The process of defining reference parameters of the mechanism was divided into few steps.

In the first phase, the evaluation criteria were defined as follows: minimum mass, maximum efficiency and possibility to operate in space environment. Next the variables and constraints were defined.

In the next phase the simple mathematical model of the cycloidal gear were defined. It consists four main components (Fig. 3): an input and output shaft, cycloid disc and housing with internal pins. The input shafts has eccentric surface on which the cycloid disc is mounted. This eccentricity causes the centre of the disc to rotate in the housing. There are less wheels teeth are less than housing's pins, causing the reverse orbit rotation within the housing. The rotary motion is converted via the disc rolling over within the housing, which accommodates the rollers. The reduces rotation is transmitted to the output shaft LSS via pins that engage with holes contained within the cycloid disc. All of the mentioned interactions are based only on rolling one elements wrt. others which eliminates the sliding friction problem as well as elasticity of the structural element of the gear which can have an important impact on tribological aspects.

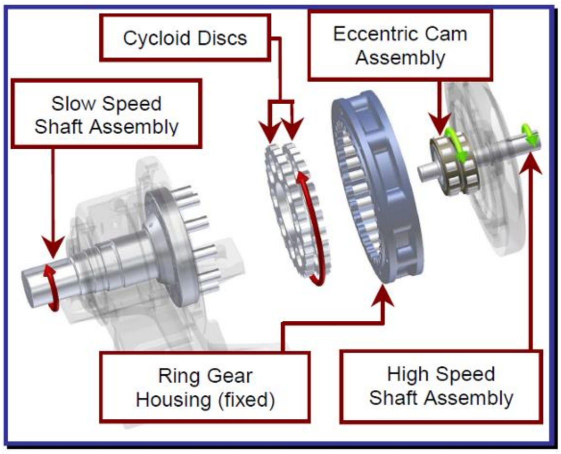

Figure 3. Components of the cycloid gear.

The cycloidal speed reducers are significant different from other speed reducers based on involute gearing. The cycloidal reducer combines the two following mechanism:

i) planetary gear : the cycloidal disc is a planet which is rotating about fixed sun gear.
ii) constant speed internal gearing mechanism.

Mentioned cycloidal disc has cycloidal- shape teeth which is cooperating with circular type teeth of the sun gear. Mostly in the cycloidal reducers the planet wheel has shape of equidistant of shortened epicycloid. The geometrical description of the one stage epicycloid gear is presented on Fig. 4.

The external dimensions of the entire reducer depend on the radius of arrangement the rollers in the sun ring. In the constant speed mechanism the radius of arrangement holes in the cycloid disc have to be the same as the radius of placement pins in the low speed shaft. Together, the diameter of the bore in the cycloid disc minus the diameter of the pins in the low speed shaft should be equal to twice eccentric ‘e’ value in the input shaft.

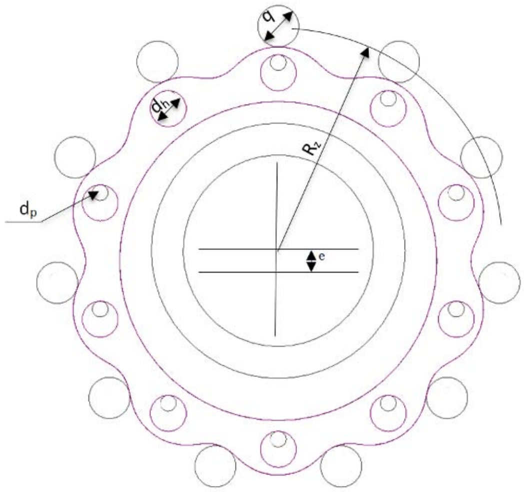

Figure 4. Geometric parameters in the epicycloid one stage gear.

Generally, the shape of the cycloid disc is described as curve cycloid by outer or inner rolling method. In this paper only cycloid curve with one teeth difference between cycloid disc and sun ring is considered. The general equation describes the epicycloid curve in Cartesian is presented in Eq. 1.

$$x(\theta) = R_z \cos(\theta) + e\cos(N\theta) - q\cos\left(\theta + a\tan\left(\frac{\sin(z\theta)}{\frac{1}{\lambda} + \cos(z\theta)}\right)\right) \quad (1)$$

$$y(\theta) = R_z \sin(\theta) + e\sin(N\theta) - q\sin\left(\theta + a\tan\left(\frac{\sin(z\theta)}{\frac{1}{\lambda} + \cos(z\theta)}\right)\right) \quad (2)$$

where,

R_z –radius of the arrangement rollers in the sun ring,

q- coefficient of shortened cycloid (radius of the rollers in the sun gear),

λ- attitude tooth head to the base,

i- gear ratio,

θ- angle of the cycloid in a curve.

Taking into account the curve equation of the cycloid disc and the sun ring geometry, the six independent parameters of the cycloid gear R_z, q, r_p, λ, I and d_p are defined (Fig. 5).

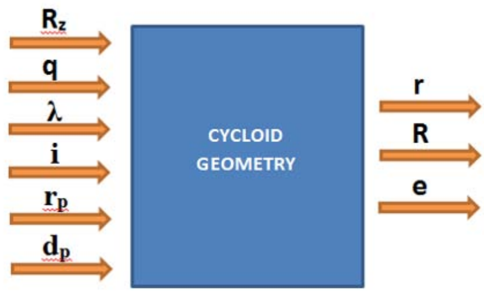

Figure 5. Schematic model of the cycloid gear with marked input and output parameters. Rz –radius of the arrangement rollers in the sun ring, q- coefficient of shortened cycloid (radius of the rollers in the sun gear), λ- attitude tooth head to the base, i- gear ratio, rp-radius of the arrangement holes and pins in the low speed mechanism, dp - diameter of the pins in low speed mechanism.

In the third phase of the optimization process, the verification tool is used. During this part, the dynamic and FEM simulations will be prepared. Based on the results from simulation, the best variation of the parameters will be chosen.

2. DYNAMIC AND FEM SIMULATIONS

During the development of the gear, the dynamic simulations were made. Those simulations allow analyzing the forces between the working teeth. The dynamic simulation is used prior to the FEM analysis to investigate the time instance at which the cycloidal disc experiences the highest load in an operating cycle.

An important step in building simulations is to establish relative motions amongst the interacting parts in the gear. The used software allows adding the joints between the parts in the CAD model of the gear to define the mechanism. In the dynamic model of the current gear, two types of the joint were used: revolute constrain and 3D contact. These joints allow adding a degree of freedom to the components. For instance, the revolution joint creating relation between cylindrical faces and cylindrical axes of two components and allowing the angular degree of freedom between the components. The 3D contact force joints and the revolute joint are used in few places in model (ex. Between input shaft and the ground or between rollers in the sun ring and the pins). Table 1 contains the components and the joints which are applied. Additionally, the joints permit to establish the initial positions and apply the kinematic or dynamic loads. Those simulations were prepared in the Inventor Autodesk software, used toolbox for dynamic simulations. It allows to add the material parameters for each element (for example: the cycloid disc, input and output shafts are made from Aluminum 7075 and the rollers and its shafts made from Steel) which gave the opportunity to perform fully elastic dynamic simulation.

Table 1. Table contains the type of the joints used in simplified model prepared for dynamic simulation .

No.	First element	Second component	Type of the joint	Additional parameter
1	Ground	Input shaft	Revolute	Angular velocity
2	Input shaft	Cycloid disc	Revolute	N/A
3-14	Cycloid disc	Rollers in the sun ring	Contact 3D	Coefficient of friction
15-25	Cycloid disc	Pins low speed shaft	Contact 3D	Coefficient of friction
26	Low speed shaft	Ground	Revolute	Load torque
27-37	Outputs Rollers	Pins in low speed shaft	Revolute	N/A
38-49	Rollers in the sun ring	Ground	Revolute	N/A

In the simulation, the boundary conditions are applied on revolute joints. To the input shaft of the gear the constant angular velocity equal 360 deg/s was applied. To the low speed shaft the load torque equal the 900Nmm was applied. The time of the simulation was set to 1 second with 100 inter steps. In this period, the input shaft circles one complete rotation within the sun ring gear.

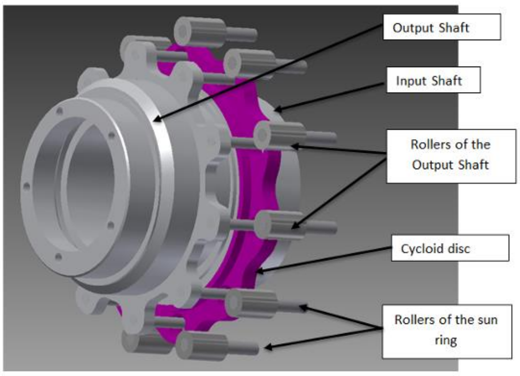

Figure 5. CAD model of the gear used in dynamic simulations.

The typical dynamic parameters like: position, velocity (angular velocity), torque and force were automatically gemnerated by the software. In addition, the 3D force contact joint provides the numerical values of the contact force and values of the penetration between contacting elements. Both of them were used through subsequent analysis and Fine Element Analysis method to generate the von Misses stresses.

3. RESULTS FROM SIMULATIONS

The exemplary results from the initial model of the gear are presented in Fig. 6, Fig. 7. and Fig. 8.

Fig. 6 presents the values of the input and the output torque. According to geometric parameters, the designed gear has gear ratio equal to 1:10. The average gear ratio as attitude the velocity output shaft to the low speed shaft is 1:9,5 what presents the Fig. 8.

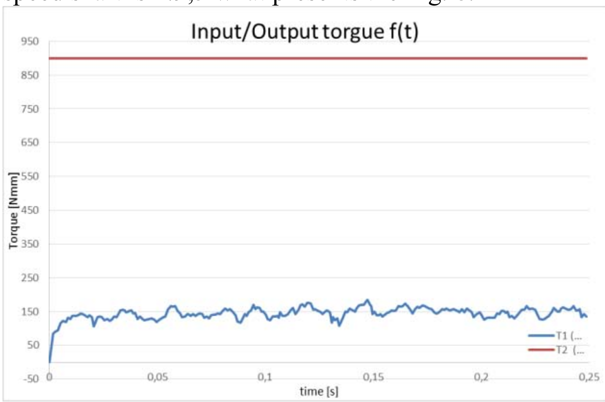

Figure 6. The input and output torque.

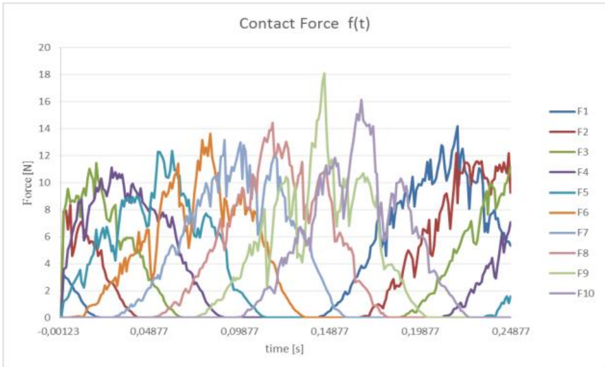

Figure 7. The contact force in the cycloid gear.

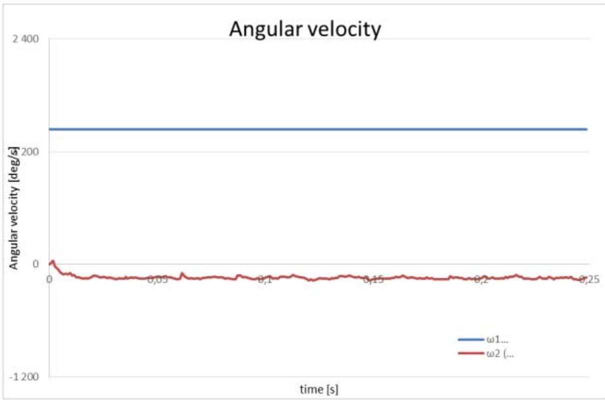

Figure 8. Angular velocity of the components in the cycloid gear.

Fig. 7 presents the values of the contact force between rollers on the sun ring and cycloid disc in terms of input shaft position. This plot also presents the main advantages of the cycloid shape gear regard to involute gear. In each moment of the gear work the load from output shaft is transmitted by few teeth (the maximum number of working tooth is half of the tooth teeth in the cycloid disc).

In the next steps the dynamic simulations were conducted for various values of the cycloid curve parameters. Exemplary results of the contact force in function of parameter λ are presented in Tab. 2.

Tab 2. Table presents the results from simulations in the variation of parameter λ.

λ values	E [mm]	F_{tooth_max} [N]	Weight [g]
0.45	1.375	10	9
0.5	1.6	14	12
0.6	1.87	5.2	15
0.7	2.23	8	20
0.8	2.56	5.5	22

4. CAD PROJECT

Based on the results of the FEM and dynamic simulations the CAD model of the joint (direct drive and epicycloidal gear) was created. Fig. 9 and Fig. 10 present the accordingly two stages epicycloid gear and joint assembly.

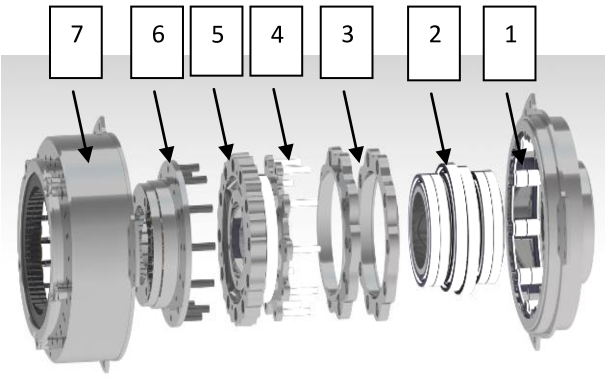

Figure 9. Cycloid gear decomposition. 1- sun ring in first stage, 2- input shaft, 3- cycloid disc in the first stage, 4- low speed shaft in the first stage, 5-cycloid disc in the second stage, 6- low speed shaft in the second stage, 7- sun ring in the second stage.

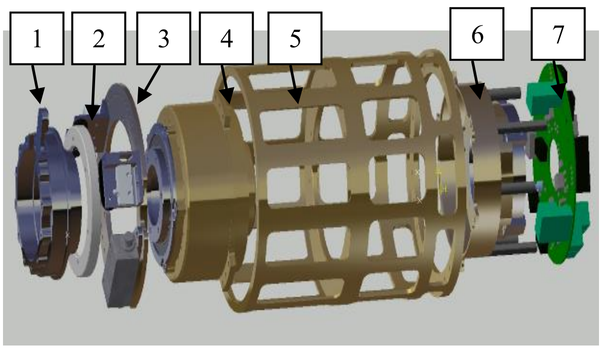

Figure 10.Joint decomposition. 1- output shaft, 2- absolute encoder, 3- end sensor assembly,4- cycloid gear, 5- housing of the joint,6- torque motor assembly, 7-control unit .

The joint contains four main assemblies: control unit, torque motor, cycloid gear and the end sensor product. The PCB with electronic components is placed in the rear part of the joint. The placement of the control unit on the back joint simplify the access to the programing socket. Behind the PCB is mounting the stator of the torque motor with its housing. From the other side of the joint housing the cycloid gear with end sensors assemblies are mounted. To lead the signals between moving parts of the robotic arm inside the joint the slip ring is placed.

The mass of the reducer equals 500g, but the 20% of this mass is the weight of the cross roller bearing on the output shaft. The total weight of the joint equal 1500 g. The developed joint and the cycloid gear is presented on Fig. 11. The surface on cycloid disc is expose hard anodizing to increase the durability. This treatment of the surface in future allow to moisten e.g. molybdenum disulphide to improve the tribology parameters in vacuum conditions.

Figure 11. On the left first prototype of the lightweight joint. Picture on the right presents one stage of the cycloid gear.

5. TESTS

To verify the gear parameters, the geometrical, kinematic and dynamic tests were conducted. The first one were done on standard coordinate control measuring machine which allow to measure the epicycloid shape. The rest of tests were performed on specially developed test-bed system. The system was equipped with two optic absolute sensors with 26 bits resolution connected with PC via BISS protocol. The input torque to the gear is applying by direct drive motor. Considering the need to measure the efficiency of the gear the test bed was equipped with force sensors which ensure the opportunity to measure the input and output torque coming to the gear. The first force sensor measures the reaction torque between motor stator and the test bed The second one, measures the reaction force between gear housing and test bed. The gear housing and the stator housing have opportunity to rotate regard to test bed. The measuring data is collecting using program created in LabView Software.

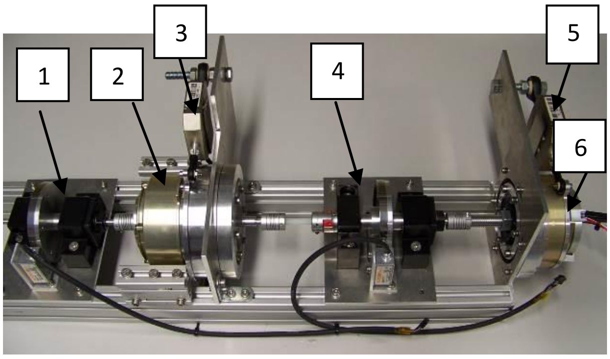

Figure 12. Test bed for dynamic and kinematic characteristic of the cycloid gears. 1- encoder on the output shaft, 2- testing gear, 3- reaction force sensor of the cycloid housing reducer, 4- encoder on the input shaft, 5- reaction sensor of the direct drive housing, 6- direct drive motor.

Such configuration of the test-bed system allowed to measure the efficiency of the system and the backlash which is important especially for space robots.
To examine the efficiency the different lubricants were used. The Fig. 13 presents the efficiency of the gear in terms of angular velocity of the input shaft and type of the lubricant. During the test the output shaft was load 4 Nm torque. The highest value of the efficiency in the one stage cycloid reducer is equal 0.7 with the PTFE lubricant. The tests were done in air conditions.

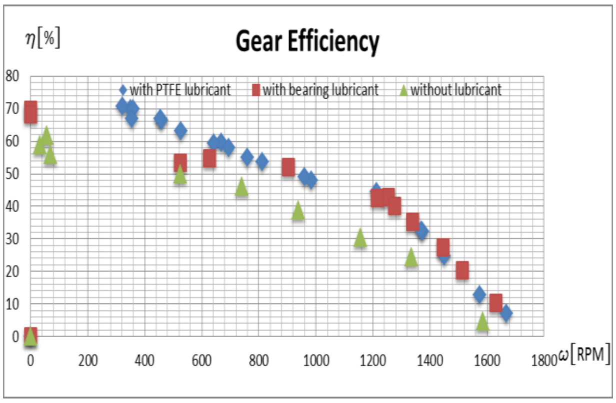

Figure 13. Efficiency via velocity of the input shaft.

The next test conducted on the cycloid reducer concerns study of the backlash. In this test to the output shaft of the reducer was applied the torque 0.5 Nm and the shaft performing the cyclic movements with 10 deg. step with change of the direction. The Fig. 14 presents the value of the backlash which is understanding as the delay expressed in degrees between input shaft and the output shaft in moment when the input shaft have been changing the direction of rotations. In other words this backlash contains also the elasticity of the gear. The additional post processing analysis is planned to extract pure backlash.

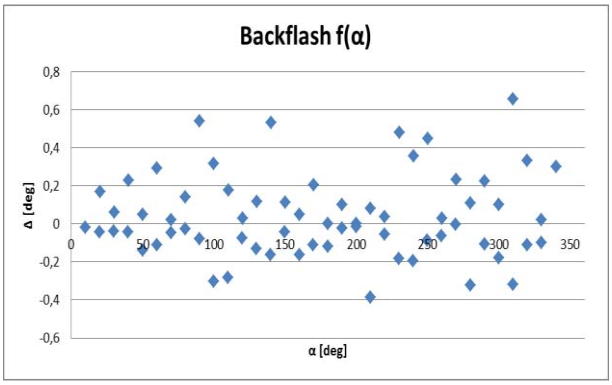

Figure 17. Backlash of the one stage reducer as a function of angular position of the input shaft.

The last parameter of the cycloid gear which was validate during prepared test campaign is the kinematic gear ratio. The Fig. 14 presents the value of the gear ratio of the one stage in a function of the input velocity.

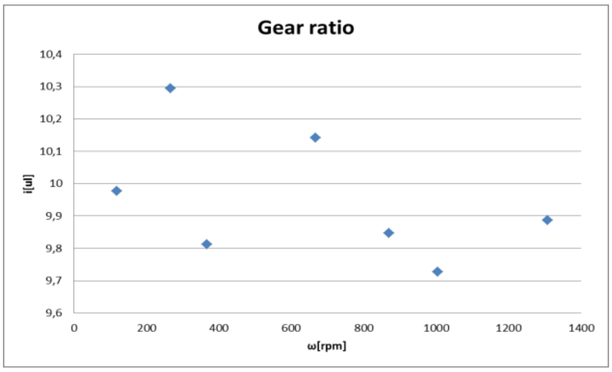

Figure 14. Gear ratio of the one stage reducer as a function of angular speed of the input shaft.

6. RESULTS DISCUSSION

This paper presents the methodology of the developing and optimization of the complex structure of the robotic joint. The dynamic simulations have shown the influence of the parameters to the structural behavior of the cycloid reducer. The exemplary influence of the λ parameter to the e.g. contact force was presented.
Based on the evaluations criteria the best combination of the cycloid curve parameters have been chosen and based on that the cycloid reducer was manufactured and tested.
The tests validate the parameters of the designed reducer. The efficiency of the gear was achieved of about of 0.7 with PTFE lubricant which is expected results. The backlash (0.6 deg) in the gear is surprisingly high in comparison to manufacturing accuracy (15 µm) however it contains also elastic component. In terms of the gear ratio the fluctuation of this parameter is of about 3% which is acceptable. Comparing results from tests with machining accuracy of the components the strength connections was observed.

7. FUTURE STUDY

The study has shown that the backlash is real problem for such type of joints. Especially taking into account that space robots working in zero gravity environment where the load is small comparing to earth application however the sign of the load can change in different position of the joint and different velocity. From that reason the magnetic version of the cycloid gear will be consider. Replaced the contact between gear elements by magnetic force. Such solution should eliminate the backlash but increase the elasticity to the joint. However the influence of the joint elasticity to the control system have been already studied and prospective solutions has been found [10]. In the future the prototype of the designed magnetic gear will be test on the microgravity table to study its influence on the free floating base [15].

REFERENCES

1. Kreisel J., *On-Orbit Servicing of Satellites (OOS): Its potential market & impact*, in Proc. of the 7th ESA Workshop on Advanced Space Technologies for Robotics and Automa-tion 'ASTRA 2002', ESTEC, Noordwijk, The Netherlands, 2002.

2. Yasaka, T. and Ashford, W. (1996). GSV: *An Approach Toward Space System Servicing.* Earth Space Review 5 (2), 9 – 17.

3. Wenfu Xu, Bin Liang, Dai Gao, and Yangsheng Xu (2010*). A Space Robotic System Used for On-Orbit Servicing in the Geostationary Orbit. In Proc*. 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems, Taipei, Taiwan.

4. Visentin, G. and Brown, D.L. (1998*). Robotics for Geostationary Satellite Servicing,* Robotics and Autonomous Systems 23, 45 – 51,

5. Rebele B., Krenn R. and Schäfer B., *Grasping strategies and dynamic aspects in satellite capturing by robotic manipulator*, in Proc. of the 7th ESA Workshop on Advanced Space Technologies for Robotics and Automation 'ASTRA 2002'. ESTEC, Noordwijk, The Netherlands, 2002.

6. Smith, D.A., Martin, C., Kassebom, M., Petersen, H., Shaw, A., Skidmore, B., Smith, D., Stokes, H. and Willig, A. (2004). *A Mission to Preserve the Geostationary Region*. Advances in Space Research 34, 1214 – 1218.

7. Dubowsky, S. and Papadopoulos, E. (1993) *The Kinematics, Dynamics and Control of Free-flying and Free-floating Space Robotic Systems*, IEEE Transactions on Robotics and Automation 9 (5), 531 - 543.

8. Seweryn K., Banaszkiewicz M., Maediger B., Rybus T. and Sommer J., *Dynamics of space robotic arm during interactions with noncooperative objects*,. in Proc. of the 11th ESA Workshop on Advanced Space Technologies for Robotics and Automation ‘ASTRA 2011’, ESTEC, Noordwijk, The Netherlands, 2011.

9. Rybus T., BArciński T., Lisowski J., Seweryn Karol, *Analyses of a free-floating manipulator control scheme based on the fixed-base Jacobian with spacecraft velocity feedback*, Conference on Aerospace Robotics ‘CARO 2013’,Warsaw, Poland, 2013.

10. E.P. Pollitt, Some applications of the cycloid machine design, ASME Journal of Engineering for Industry 82 (1960) 407–414

11. Dragan Kostic, Bram de Jager, Maarten Steinbuch, Ron Hensen, *Modeling and Identification for High-Performance Robot Control: An RRR-Robotic Arm Case Study,* IEEE Transactions on control systems technology Vol. 12. No. 6, November 2004

12. European Space Tribology Laboratory, European Space Agency, *Space Tribology Handbook*, European Space Agency, 1997

13. Chen BingKui, Fang TinTin, Li ChaoJang, Wang ShuYan (2008). *Gear Geometry of cycloid gears*, Science in China press, Springer.

14. Ulrich, S., and Sasiadek, J. Z, *Direct Adaptive Fuzzy Control of a Manipulator with Elastic Joints*, AIAA Journal of Guidance, Control, and Dynamics, 2012.

15. T. Rybus, T. Barciński, J. Lisowski, J. Nicolau-Kukliński, K. Seweryn, M. Ciesielska, K. Grassmann, J. Grygorczuk, M. Karczewski, M. Kowalski, M. Krzewski, T. Kuciński, R. Przybyła, K. Skup, T. Szewczyk, R. Wawrzaszek, *New Planar Air-bearing Microgravity Simulator for Verification of Space Robotics Numerical Simulations and Control Algorithms,* in Proc. 7th ESA 12th Symposium on Advanced Space Technologies in Robotics and Automation ‘ASTRA 2013’, ESTEC, Noordwijk, The Netherlands, 2013.

ACKNOWLEDGMENTS

This paper was partially supported by the National Centre for Research and Development project no. LIDER/10/89/L-2/10/NCBIR/2011.