COMETa 2018
4th INTERNATIONAL SCIENTIFIC CONFERENCE
27th - 30th November 2018
Jahorina, Republic of Srpska, B&H
University of East Sarajevo
Faculty of Mechanical Engineering
Conference on Mechanical Engineering Technologies and Applications

SINGLE-STAGE CYCLOID REDUCER DYNAMIC ANALYSES USING PLM SOFTWARE

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Abstract: The new possibilities of modern PLM software contribute to a higher quality and more productive development of new products. Thanks to these software, engineers can respond to very complex market demands in an appropriate timeframe. Especially interesting are the modules for creating much various simulations and dynamic analyzes of the most complex machine assemblies in conditions that are very close to the real conditions of exploitation. In this paper, using the Autodesk Inventor and SolidWorks software, a dynamic analysis of single-stage cycloid reducer was performed. The forces calculation that occurs on the elements of this reducer is conducted. Also, these values are compared with the analytically obtained results. The results obtained largely correspond to the analytical calculated values so that the application of PLM software for different types of calculations and analysis in the product development phase is welcome.

Key words: dynamic analyses, simulation, cycloid reducer, normal force, output force

1 INTRODUCTION

The cycloid reducer is a very complex mechanical gearbox. Designing a cycloid reducer is, in every aspect, an extremely demanding process. The loads calculation process is particularly complex. The analytical model for the force calculation on the elements of the cycloid reducer was first defined by *Kudrijavcev*, [1]. The model was further developed by other researchers [2,3]. Today's modern PLM software (*Autodesk Inventor, Solidworks, Catia*, ...) provides dynamic analysis of the most complex machine systems. The kinematic analysis of the cycloid reducer using the PLM software was presented in [4], while the analysis of the stress-deformation state of the elements of the cycloid reducer as well as the modal analysis was described in the papers [5,6,7,8,9]. On the loads distribution in the cycloid reducer, the stiffness of certain elements, the friction, and the clearance size are also greatly influenced by [10,11,12,13,14,15].

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In this paper, the *Autodesk Inventor* and *SolidWorks* software calculates the normal and output forces of the rotary angle for a single one-stage cycloid reducer. Then the obtained results were compared with the analytically obtained values [16], as well as with each other.

2 SINGLE-STAGE CYCLOID REDUCER

Dynamic analysis was performed for a specific single-stage cycloid reducer as shown in Figure 1.

Figure 1. *Single stage cycloid reducer*

The basic parameters of the analyzed cycloid reducer, used in the calculation and generation of the CAD model, are given in Table 1.

Table 1. *Basic parameters of single-stage cycloid reducer*

Parameter	*Value*	*Unit*
Input torque	*51,24*	*Nm*
Output torque	*731,00*	*Nm*
Input rpm	*1450*	min^{-1}
Gear transmission ratio	*15*	*/*
Efficiency	*0,95*	*/*
Number of cycloid discs teeth	*15*	*/*
Number of ring gear rollers	*16*	*/*
Eccentricity	*4,5*	*mm*
Ring gear pitch radius	*90*	*mm*
Radius of ring gear rollers	*7,2*	*mm*
Radius of output rollers	*7*	*mm*

In order to simplify the simulation process, the following assumptions have been introduced:

1. The input shaft, the eccentric and the needle bearing are considered as one sub-assembly,
2. A central gear together with the axles, as well as the output shaft with the output axles are considered as one sub-assembly,
3. Only the theoretical case of meshing is analyzed, when all the cycloid gear tooth are meshing with central gear rollers and half of them carries the load.

The numerical designations of the central and output rollers is shown in Figure 2.

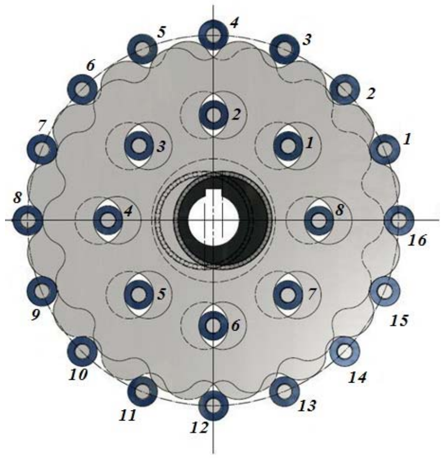

Figure 2. *Central and output rollers designation*

As it shown in Figure 2, a single-stage cycloid reducer is analyzed, with two cycloid gears relatively turned to each other for an angle of 180 ° to balance the dynamic loads and forces.

3 CALCULATION OF NORMAL AND OUTPUT FORCES

The values of the normal forces can be calculated analytically by using the equation:

$$F_{\mathrm{Ni}} = \left(c \cdot \Delta\beta\right) \cdot r_{\mathrm{i}} \cdot \sin\psi_{\mathrm{i}} \tag{1}$$

The values of the output forces are calculated analytically according to the equation:

$$F_{\mathrm{Kj}} = \left(c_{\mathrm{K}} \cdot \Delta\beta\right) \cdot r_{\mathrm{Kj}} \cdot \sin\psi_{\mathrm{Kj}} \tag{2}$$

A more detailed force calculation method is given in the references [1,2]. Calculated analytical values of normal and output forces are given in Tables 2 and 3.

Table 2. *Normal forces calculation – analytical method*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Normal force, N	1	0	0	0	0	0	0	0
	2	0	1177,2	0	0	0	0	0
	3	0	1398,2	802,9	0	0	0	0
	4	0	1321,3	1413,1	0	0	0	0
	5	0	1158,8	1385,7	1376,5	0	0	0
	6	0	942,4	1243,5	1434,5	1177,2	0	0
	7	313,5	686,1	1039,3	1318,5	1398,2	802,9	0
	8	0	401,9	790,3	1129,8	1321,3	1413,2	0
	9	0	101,6	508,8	890,7	1158,9	1385,8	1376,5

Table 2. *Normal forces values – analytical calculation method (continuation)*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
	10	0	0	206,7	614,5	942,4	1243,6	1434,5
	11	0	0	0	313,6	686,1	1039,4	1318,6
	12	0	0	0	0	401,9	790,3	1129,8
	13	0	0	0	0	101,6	508,8	890,7
	14	0	0	0	0	0	206,7	614,5
	15	0	0	0	0	0	0	313,6
	16	0	0	0	0	0	0	0

Table 3. *Output forces values – analytical calculation method*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Output forces, N	1	2775,7	883,0	0	0	0	0	0
	2	3925,4	3328,9	1720,8	0	0	0	0
	3	2775,7	3824,8	3711,5	2470,3	478,4	0	0
	4	0	2080,2	3528,1	3903,9	3093,7	1342,6	0
	5	0	0	1278,0	3050,6	3896,1	3557,6	2137,9
	6	0	0	0	410,3	2416,7	3688,7	3839,6
	7	0	0	0	0	0	1658,9	3292,1
	8	0	0	0	0	0	0	816,1

After that, *SolidWorks* and *Autodesk Inventor* software packages (in their specific environments) also are used determine the values of these forces. Tables 4 and 5 show the values of the normal and the output forces defined in the *SolidWorks* software, while tables 6 and 7 show the values of these forces specified in the *Autodesk Inventor* software.

Table 4. *Normal forces values – SolidWorks*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Normal force, N	1	120,7	348,3	0	0	0	0	0
	2	194,4	1364	0	0	0	0	0
	3	94,3	1662,7	1142,7	0	0	0	0
	4	55,0	1596,7	1648,7	790,4	0	0	0
	5	20,6	1300,9	1664,7	1482,1	347,9	0	0
	6	0	971,9	1398,1	1670,7	1355	0	0
	7	0	598,0	1054,2	1559,1	1659,3	1171,1	0
	8	0	248,8	694,8	1208,1	1601,0	1659,9	786,9
	9	0	8,5	370,2	813,3	1286,4	1676,9	1480,7
	10	0	0	94,9	463,2	948,7	1413,6	1654,6
	11	0	0	0	176,5	574,8	1047,3	1523,6
	12	0	0	0	0	244,8	703,0	1213,7
	13	0	0	0	0	17,3	370,7	793,2
	14	0	0	0	0	0	91,3	465,6
	15	0	0	0	0	0	0	185,6
	16	20,2	0	0	0	0	0	0

Table 5. *Output forces values – SolidWorks*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Output force, N	1	1911,7	560,7	0	0	0	0	0
	2	3344,5	2752,1	1192,1	0	0	0	0
	3	2595,1	3354,7	3153,5	1952,6	329,1	0	0
	4	480,0	1697,7	2996,3	3407,1	2560,8	899,4	0
	5	0	0	1006,9	2533,4	3364,0	2999,0	1502,5
	6	0	0	0	464,6	1979,1	3202,7	3302,1
	7	0	0	0	0	0	1323,4	2813,7
	8	0	0	0	0	0	0	697,1

Table 6. *Normal forces values – Autodesk Inventor*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Normal force, N	1	89,7	386,5	0	0	0	0	0
	2	206,9	1326,3	0	0	0	0	0
	3	97,4	1662,7	1149,4	0	0	0	0
	4	78,0	1587,9	1631,7	802,1	0	0	0
	5	34,9	1325,8	1658,2	1496,3	284,4	0	0
	6	0	968,5	1404,5	1682,7	1328,0	0	0
	7	0	602,3	1071,8	1571,2	1643,3	1136,5	0
	8	0	250,8	703,0	1194,3	1612,4	1639,9	737,8
	9	0	11,8	362,2	823,6	1292,4	1678,9	1464,7
	10	0	0	97,8	436,5	923,7	1401,6	1643,1
	11	0	0	0	182,5	601,5	1054,7	1513,5
	12	0	0	0	0	252,8	715,4	1221,2
	13	0	0	0	0	20,6	374,46	806,6
	14	0	0	0	0	0	101,3	472,3
	15	0	0	0	0	0	0	203,4
	16	16,4	0	0	0	0	0	0

Table 7. *Output forces values – Autodesk Inventor*

	Roll. No.	Driving angle β, °						
		0	30	60	90	120	150	180
Output force, N	1	2106,8	589,4	0	0	0	0	0
	2	3379,5	2818,5	1192,4	0	0	0	0
	3	2590,2	3332,8	3127,9	1964,2	318,9	0	0
	4	492,2	1705,2	2990,1	3396,1	2542,8	925,4	0
	5	0	0	1028,8	2499,9	3363,8	3012,1	1514,8
	6	0	0	0	473,3	2010,1	3251,4	3326,7
	7	0	0	0	0	0	1418,2	2837,4
	8	0	0	0	0	0	0	702,4

4 RESULTS ANALYSES

After the analytical calculation of the normal and the output forces, and after the obtained values of the same forces in the *SolidWorks* and *Autodesk Inventor* software, the obtained results were compared. Table 8 shows the percentage deviations of the maximum values of the normal forces. The deviations were determined for both software, and for the analytical values, the obtained gain values were taken. Table 9 shows the percentage deviations of the maximum values of the output forces.

Table 8. *Percentage deviations of maximum values of normal forces related to analytical calculated values*

Roll. No.	*Deviation, %*	
	Autodesk Inventor	*Solidworks*
1	*22,90*	*21,49*
2	*16,10*	*15,93*
3	*18,07*	*17,75*
4	*19,80*	*19,31*
5	*18,81*	*18,22*
6	*17,30*	*16,46*
7	*16,99*	*16,05*
8	*19,43*	*19,12*
9	*18,52*	*18,38*
10	*11,88*	*16,26*
11	*14,78*	*15,55*
12	*8,09*	*7,43*
13	*9,43*	*10,94*
14	*23,14*	*24,23*
15	*35,11*	*40,79*
16	*/*	*/*
Note: Designation (/) shows that on both calculation analytical and numerical was equal to 0.		

Table 9. *Percentage deviations of maximum values of output forces related to analytical calculated values*

Roll. No.	*Deviation, %*	
	Autodesk Inventor	*Solidworks*
1	*24,09*	*31,13*
2	*13,90*	*14,70*
3	*11,69*	*11,97*
4	*11,57*	*11,92*
5	*12,15*	*12,63*
6	*12,95*	*13,30*
7	*13,81*	*14,53*
8	*13,93*	*14,59*

5 CONCLUSION

This paper is a result of the author's desire to explore the possibilities of dynamic simulations within *SolidWorks* and *Autodesk Inventor*. It has also been shown that using dynamic simulations can significantly contribute to a more quality and faster development of new products. The obtained results lead to the following conclusions:

- Using dynamic simulations, obtained results has a very small deviations related to results obtained by analytical methods.
- The deviation of the maximum values of the normal and output force obtained in the *SolidWorks* and *Autodesk Inventor* software from the analytically obtained values is not negligible. That means the dynamic model of the analyzed cycloid reducer should be further developed. In addition, it is needed to explore the possibilities of dynamic simulations that are not used in these analyses.
- The results obtained in these two software packages differ very little from one another, which is a very valuable conclusion.

ACKNOWLEDGMENT

This paper is a result of research on project TR33015 of Technological Development of Republic of Serbia. This project is titled “Investigation and development of Serbian zero-net energy house”. We would like to thank to the Ministry of Education, Science and Technological Development of Republic of Serbia for their financial support during these project investigations.

NOMENCLATURE

Variables:

c stifeness of central gear rollers, N/m

c_K stifeness of output rollers, N/m

F_{ni} normal force on gear tooth, N

F_{Kj} output force, N

r_i distance between contact point of i^{th} central gear roller and cycloid gear, and cycloid gear center, mm

r_{Kj} distance between contact point of j^{th} output roller and cycloid gear, and cycloid gear center, mm

Greek symbols

$\Delta\beta$ angular movement of cycloid gear, rad

ψ_i placement angle of normal force, rad

Subscripts and superscripts

N central gear rollers
K output rollers
i number of central gear roller
j number of output roller

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