Visualization and analysis of worm gear drives efficiency and load capacity

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Abstract: *Scientific methodologies have been created and applied during the analysis upon worm gear drives. Important parameters have been selected in order to make significant investigations in the area of worm gear efficiency and load capacity. The efficiency coefficient and maximal torque values have been studied for several combinations of modules, ratios, center distances, etc. The results have been presented and analysed through three-dimensional graphics. Conclusions are made.*
Keywords*: WORM GEAR DRIVES, GEAR EFFICIENCY, LOAD CAPACITY, SCIENTIFIC METHODOLOGIES, EFFICIENCY COEFFICIENT, MAXIMAL TORQUE, SOFTWARE SYSTEMS, COMPUTER-AIDED MATHEMATICS, THREE-DIMENSIONAL GRAPHICS.*

1. Introduction

A worm drive is a power transmission device in which a worm meshes with a worm gear to transmit power between two non-intersecting shafts that are oriented at a right angle. Worm gear drives are quite suitable for transmitting large gear ratios in one stage.

Some important features of worm gears are:

- ⇨ A probability to achieve self-locking when reversing the direction of the power flow;
- ⇨ Quiet operation capacity;
- ⇨ Suitable when the space is limited;
- ⇨ Absorption of shock loading;
- ⇨ Minimum maintenance.

Small changes in parameters of worm gear drives can lead to the significant savings which is not the case in other drives [8]. This makes the selection of parameters of these drives to be a very important topic, which product development engineers are often not aware.

The main criterion for worm gear load capacity is the output torque of the worm gear shaft, which is directly connected to the driven machine. Output torque values could be limited certain conditions during transmission operation. Some significant boundary conditions are [1, 2, 3, 14]:

- ⇨ pitting, which can appear on the active flanks of the worm gear teeth;
- ⇨ wear, which usually on the flanks of the bronze worm gear;
- ⇨ heating of transmission and scuffing, which depends on the load and sliding velocity values.

The friction coefficient in the meshing represents a complex characteristic regarding the quality of the worm gear train. Several different approaches and models have been presented in previous research by the authors' team. The German standard DIN 3996: 2012-09 describes a short and clear approach [12]. On the other hand, the approach described in [16] and [17] presents a more complex and detailed method.

Besides, the investigations described in [16] and [17] treat other important problems for worm gear drives. The authors of these publications analyze the temperature and temperature variations in the contact meshing area. They emphasize that these variations could have relative great influence upon the wear of the worm gears. In other previous publications of the authors' team, the calculations for various parameters of worm gears have been analyzed. Some main calculation approaches are standardized in [10, 9, 11, 13].

The authors' team and other scientists from the ***University of Ruse*** have successfully completed some investigation tasks in the field of energy efficiency of drive systems and transmissions. The results of these studies are presented in detail in the following publications: [1-7].

2. A historical overview of this research

In [14], a new methodology was been created including several stages. The methodology involves the application of the scientific approach described in [15].

The new methodology from [14], starts with calculating the tangential frequency, the sliding speed, the efficiency coefficient, and the important tribology parameters. The calculations are carried out for a worm made of case-hardened steel 16 MnCr5 and for a worm made of GZ-CuSn12Ni. The necessary parameters are defined, trough which it becomes possible to determine the maximal actual contact stresses. Upon these calculations, the maximal output torque T_2 is determined. A database is generated and a graphical presentation is created.

Also, an optimization procedure has been created aiming to improve the load capacity parameters of worm gear trains [14]. Different functional parameters and certain geometry parameters have been taken into account such as rotating frequency of the worm shaft, gear ratio, module and geometry dimensions of the worm gear set.

Based upon the methodology described, in [14, 15] a substantial investigation has been carried out. The object of analysis and discussion of the paper presented will be the results concerning the center distance a = 50 mm. The calculation results for the efficiency coefficients ηz and maximal output torques T_2 in Nm depending on gear ratios i and modules m (in mm) at center distance a = 50 mm and n_1 = 1500 min^{-1} are summarized in Table 1 [14]. The calculations are carried out with 9 different values of the gear ratios i and 3 different values of the module m.

Table 1: *Results for center distance* a *= 50 mm and* n_1 *= 1500 min*$^{-1}$

	i	***m***	***ni***	***T2***
1	4.83	2.5	0.9314	14.97
2	7.25	2.5	0,9120	24,79
3	9,5	2	0,8994	30,91
4	14,5	2,5	0,8478	58,43
5	19	2	0,8289	72,67
6	29	2,5	0,7445	136,61

On this stage of the research, a question haw to present and analyze the data obtained raising.

In [1, 2, 14, 15] this is solved with the help of the software system ***MS Excel***. A plain 2-D graphs are created to visualize the relations obtained.

In [18] is analyzed an idea to use the flexibility and power of the contemporary computer-aided mathematics software systems.

For example, Fig. 1 and Fig. 2 [14] shows the variation of coefficient of efficiency and output torque in a graphical way depending on the values of the gear ratio and the module.

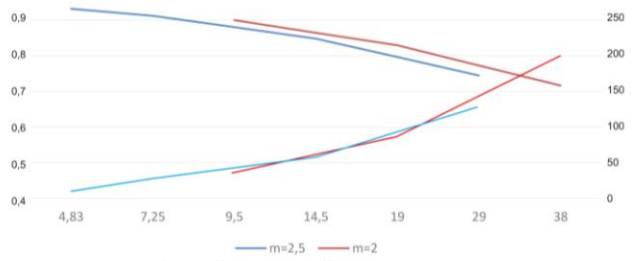

***Fig. 1**. Variation of the efficiency coefficients and maximal output torques for a center distance a = 50 mm and rotation speed of worm gear shaft n_1 = 1500 min^{-1}.*

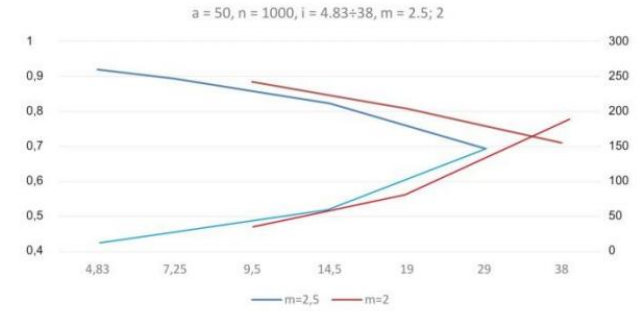

***Fig. 2**. Variation of the efficiency coefficients and maximal output torques for a center distance a = 50 mm and rotation speed of worm gear shaft n_1 = 1000 min^{-1}.*

In [14], a conclusion has been made that the area of maximal values of efficiency efficient and output torques is located in the gear ratio interval between 20 and 29 with modulus equal to 2 mm and 2.5 mm.

3. A new methodology – data interpolation and three-dimensional visualisation

The contemporaly growth of software systems provides powerfull new opportunities in all areas of engineering and science. This also applies to the field of mathematics. The systems ***MATLAB, Wolfram Mathematica*** and ***Maple*** can be cited as leading systems for computer-aided mathematics [18].

With the help of software system ***MATLAB***, the calculated in [14, 15] data has been interpolated and visualized [18]. This gives two new abilities, as follows:

- ⇨ An ability to directly signify the relations between three parameters (or even between four parameters, if the color in set as independent indicator);
- ⇨ An ability to render relations in uninterrupted three-dimensional space (or even in four-dimensional space, if the color in set as independent indicator).

It follows some three-dimensional visualisation created and the conclusions obtained from them.

3.1. Efficiency coefficient in relation from ratio and module

Colored three-dimensional graphs are created for the all combinations of:

- ⇨ **center distances:** a = 50 mm, a = 63 mm, a = 80 mm, and a = 125 mm

and

- ⇨ **input rotation speeds**: n_1 = 750 min^{-1}, n_1 = 1000 min^{-1}, n_1 = 1500 min^{-1}.

In this paper are presented some of the characteristic plots. On Fig 3 is shown a graph composed of two planes. The second plane is located in the left down corner on Fig. 3a, but for this to be visible, the graph must be rotated as it is shown on Fig. 3b. The black straight line is the border between the planes.

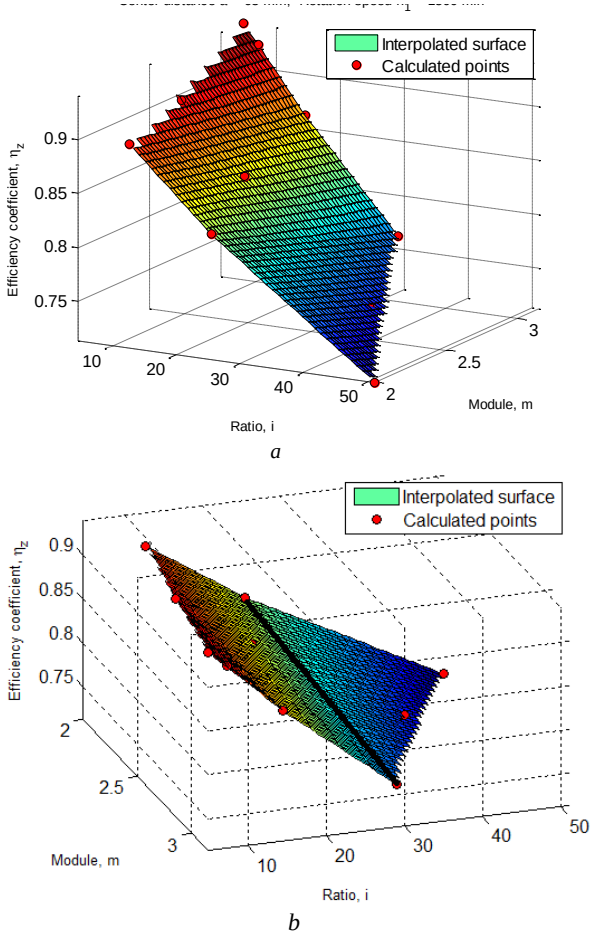

***Fig. 3**. Efficiency coefficient in relation from ratio and module for center distance a = 63 mm and rotation speed n_1 = 1500 min^{-1}.*

From Fig. 3, it can be observed that the efficiency coefficient increases with the increase of the module and the decrease of the ratio.

On Fig 4 is presented an analogical case, i.e., a surface that interpolates data points, one of which is higher than others. The relations of the efficiency coefficient from the ratio and module remains the same as on Fig 3.

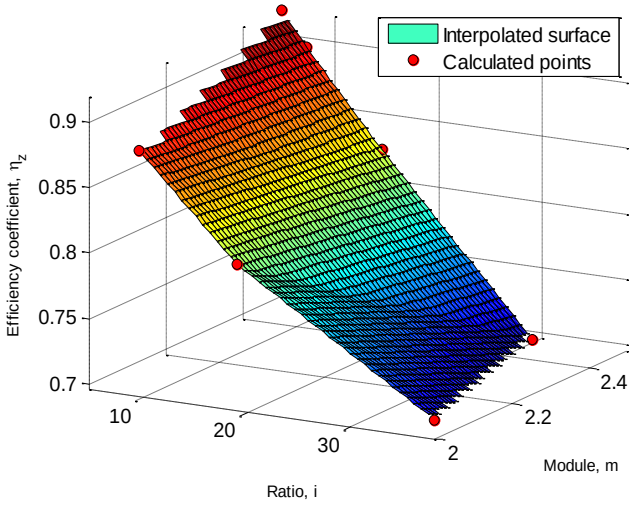

***Fig. 4**. Efficiency coefficient in relation from ratio and module for center distance a = 50 mm and rotation n_1 = speed 1000 min^{-1}.*

The next plot is example for two data points located about the middle of the interpolated surface, which are out of the plane – Fig. 5. It can be observed that in these points the efficiency coefficient has a higher value, than in the other points of the interpolated plane surface.

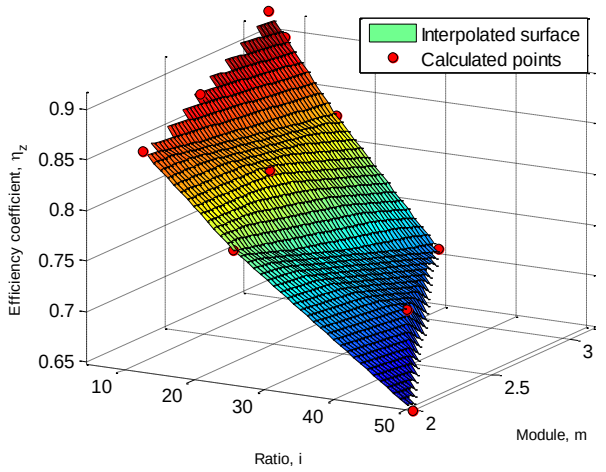

Fig. 5. *Efficiency coefficient in relation from ratio and module for center distance a = 63 mm and rotation speed n_1 = 750 min^{-1}.*

And, as the end of this section, Fig. 6 shows a different picture. There is a data point with lower value of the efficiency coefficient than other points in the plane interpolated surface. That is in the top left corner, i.e., in the area with higher values of the efficiency coefficient.

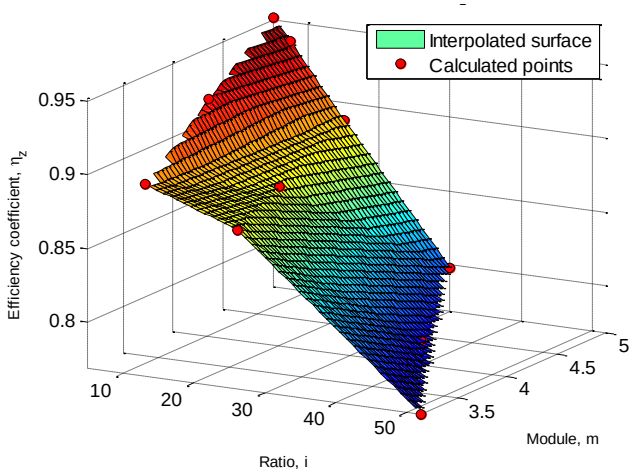

Fig. 6. *Efficiency coefficient in relation from ratio and module for center distance a = 100 mm and rotation speed n_1 = 1500 min^{-1}.*

The trend of the dependence of the efficiency coefficient from the ratio and module permanently becomes unchanged and is confirmed in all four figures from Fig. 3 to Fig. 6.

3.2. Efficiency coefficient in relation from ratio and output torque

On Fig. 7 is shown a relation of the efficiency coefficient from the ratio and the output torque T_2. **It can be concluded that, the efficiency coefficient grows with decreasing the output torque and the ratio.**

The software system ***MATLAB*** gives the ability multiple three-dimensional surfaces to be superimposed. On Fig. 8b are presented two three-dimensional relations together for center distance a = 63 mm and rotation speed n_1 = 1500 min^{-1}, as follows:

- ⇨ the dependence of the efficiency coefficient from the ratio and module;
- ⇨ the dependence of the efficiency coefficient from the ratio and **output torque.**

The relations for efficiency coefficient ant the output torque for other center distances and input rotation speeds are also investigated. Some of them are shown oh Fig. 9, Fig. 10, and Fig. 11. From these graphs, it can be concluded that **the trend of the dependence of the efficiency coefficient from the ratio and the output torque becomes unchanged, i.e., the efficiency coefficient grows with decreasing the output torque and the ratio.**

The presented results can be used for performing an optimization process with ***MATLAB Optimization Toolbox*** [18]. It provides functions for finding parameters that minimize or maximize objectives while satisfying constraints. The toolbox includes solvers for linear programming (LP), mixed-integer linear programming (MILP), quadratic programming (QP), second-order cone programming (SOCP), nonlinear programming (NLP), constrained linear least squares, nonlinear least squares, and nonlinear equations.

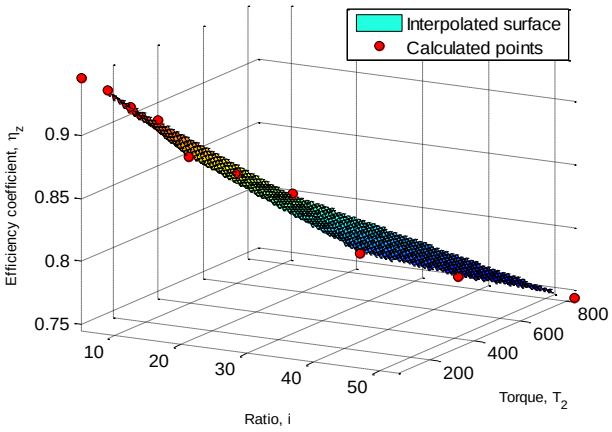

Fig. 7. *Efficiency coefficient for center distance a = 80 mm and rotation speed n_1 = 1500 min^{-1}.*

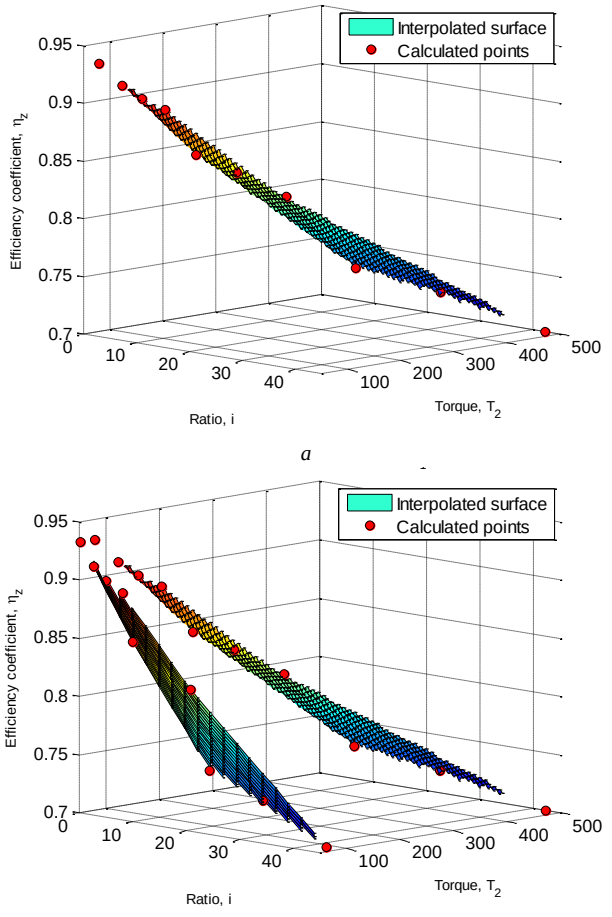

Fig. 8. *Efficiency coefficient for center distance a = 63 mm and rotation speed n_1 = 1500 min^{-1}: a – efficiency coefficient in function of ratio and torque; b – with superimposed surface of efficiency coefficient in function of ratio and module.*

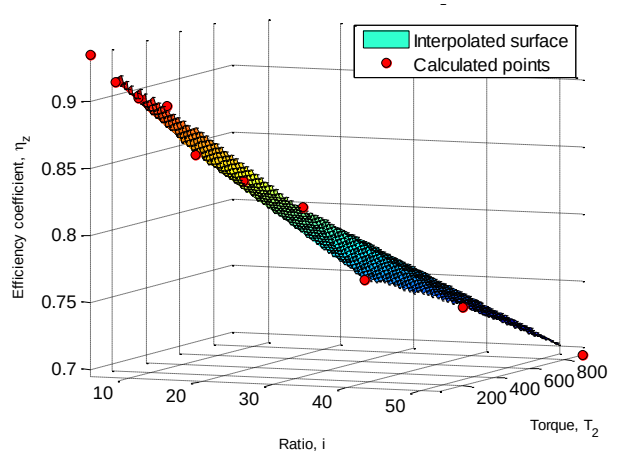

Fig. 9. *Efficiency coefficient and output torque for center distance a = 80 mm and rotation speed n_1 = 1000 min^{-1}.*

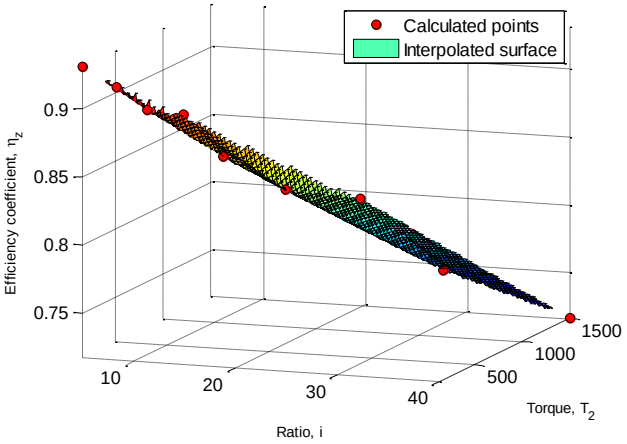

Fig. 10. *Efficiency coefficient and output torque for center distance a = 100 mm and rotation speed n_1 = 750 min^{-1}.*

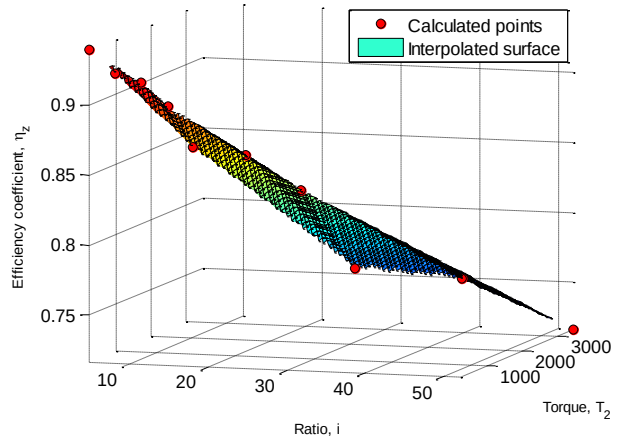

Fig. 11. *Efficiency coefficient and output torque for center distance a = 125 mm and rotation speed n_1 = 750 min^{-1}.*

4. Conclusions

The efficiency coefficient and maximal torque values have been investigated for several combinations of modules, ratios, center distances, etc. The results have been presented and analyzed through three-dimensional graphics. For the aim of this, a new methodology based on data interpolation and three-dimensional visualization are developed and applied.

From the results obtained, it can be concluded that the efficiency coefficient increases with the increase of the module and the decrease of the ratio. This trend remains for all the cases studied. Although this trend, there is some exceptions for local points as it is noted specifically when the graphs were discussed.

It is established that the efficiency coefficient grows with decreasing the output torque and the ratio. This trend is also stable for all cases studied.

MATLAB Optimization Toolbox™ lets design optimization tasks to be conducted. It includes parameter estimation, component selection, and parameter tuning. In combination with computer-aided design software (CAD), this gives an ability the above presented research to be continued with development and investigation of an automatized optimization and design system. This can be done in the integrated working environment of the software systems ***MATLAB*** and ***SolidWorks***.

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