Advanced Design Optimization Procedures for Worm Gear Drives

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Abstract. Concerning the optimization design of worm drives, it is especially important to achieve maximum output power of the gear set, which depends particularly intensively on the efficiency coefficient of the worm gear meshing. The purpose of the study presented is to create advanced design optimization procedures concerning the output power of the worm gear, taking into account nine design variable parameters and several significant mechanical constraints. The variable parameters selected are: number of starts for the worm, number of teeth of the worm gear, center distance, sliding speed and friction coefficient for the meshing, lead and tooth friction angles, permissible contact stresses for the pair of worm and worm gear materials, appropriate values of the safety factors. The research methodology applied includes four different stages, which are briefly described. The research results obtained are analyzed. The conclusions and recommendations deduced are related and focused to the objectives of future research work of the author's team.

Keywords: Worm Gear Drive · Design Optimization procedures · Significant Mechanical constraints

1 Introduction

Solving significant practical problems in the area of mechanical engineering can be considered as a real challenge in terms of evaluating the effectiveness of new algorithms and approaches aiming to find the best possible solution. The optimal design of machine elements plays a vital role in reducing the cost of manufacturing machine parts. Many optimization algorithms have been suggested, applied and presented in scientific literature sources, but there are still opportunities for creating new and/or improved algorithms for design optimization of machine components.

The main objective of mechanical engineers and scientists is to create and describe procedures for designing machine elements in such a way that the pursuit of formulating the best balance between geometric parameters, strength criteria, economic and technological indicators to be a leading goal.

Optimization procedures for designing a mechanical gear drive include the selection of a certain number of variable parameters that determine the geometry boundaries of the existence of a mechanical gear trains and the additional constraints considering kinematic, strength and tribological parameters.

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Over the last three decades, various new and improved algorithmic methods have been developed, containing mathematical programming. These methods aim at solving problems in various engineering and industrial complex problems and applications. Most of these approaches always require a parameter knowledge and selection for the objective function and the definition of various constraints.

Gear drives are the most common components of technical systems and the problem of designing them considering the criteria of minimum weight or minimum volume has been a research objective of several studies. By integrating the configuration design process and the dimensioning process, Chong et al. [1] suggest a new summarized algorithm for designing multistage drives. The objective function this authors' team considers is to minimize the geometry volume of the gear set. Swantner and Campbell describe a similar method for automating the design of gear drives consisting of bevel and worm gear sets [2].

In a study done by S. Golabi et al. [3], the objective function and the constraints for gear set volume and weight are defined in general terms. The Matlab potentials have been used and as a result of the optimization procedures the volume and weight of the gear sets have been minimized.

2 Significant Advanced Methods for Worm Gear Optimization Research

Worm gear drives are used extremely often in a great number of many engineering applications, as they are characterized by large gear ratios and compact overall dimensions. The power loss in worm gears is characterized by relatively great values. The reason for this disadvantage is the sliding friction with its significant values [4, 5]. Optimization studies of worm gear trains have been conducted using various techniques by numerous research teams.

In order to reduce the power loss, the authors Mogal and Wakchaure in [6] implemented a study based on genetic algorithm considering the criterion: maximum power output. Within this research work, the optimization procedures are relatively complex due to the special modified profile of the worm gear. The first paragraphs that follows a table, figure, equation etc. does not have an indent, either.

Chandrasekaran et al. [7] solve a combined objective function for a worm gear set. The authors strive to achieve maximum power and efficiency, as well as minimum total weight and center distance applying the method: Swarm intelligence optimization of worm and worm gear design. Sabarinath et al. [8] optimize worm gear drives according to the "power loss" criterion by using the following two algorithms: Differential Evolution and Particle Swarm Optimization algorithms. The results obtained are compared with the outputs of: genetic algorithm and analytical method.

Rai et al. [9] apply the Simulated Annealing (SA) method, which is aiming to minimize the power loss of worm gear drives within preliminary selected constraints. The results obtained are compared and validated with the results reported in previous research studies. The authors assert that SA is more efficient in achieving optimal design values for worm gears with reduced power loss.

Theoretical studies of existing methods for calculating power losses in worm gears are presented in the following publications of the author's team, which analyzed and cited significant achievements of a large number of scientific publications of famous scientists in this area: [10–12].

The research work presented in [13, 14] delivers additional results in the field of worm gear investigation. These publications present essential studies of worm gear sets as components of driving systems. Possible solutions for increasing the energy efficiency and functional capability of worm gear drives are described. Based upon the analysis of some significant publications mentioned, the following conclusions can be made: the main characteristics of different methods for optimization research have been indicated; the advantages of the most innovative possible solutions for increasing the energy efficiency of worm gears have been deduced.

The main conclusion based upon literature survey is that it is still possible to achieve a significant improvement of the energy efficiency of worm gear drives and of their maximum load capacity with optimal selection of geometry parameters and other significant mechanical constraints.

3 Research Methodology

The methodology used includes the following sequence of stages within the study:

The first stage aims to determine important kinematic parameters of the worm gear such as: peripheral speed of the worm and sliding speed in the meshing of the worm gear set.

The second stage of the methodology focuses on determining the tribology parameters in the meshing. According to the author's team, the most appropriate approach for determining the coefficient of friction in gearing is the application of an approach applied by [15], which recommends relationships for estimating the friction coefficient in the meshing engagement for a hardened steel worm (58 HRC minimum) and a bronze worm gear. The authors of [16] developed further this approach by graphically representing the friction coefficient as a function of the sliding speed for a steel worm and a bronze worm gear, using different analytical equations for sliding speeds higher or respectively lower than 0.051 m/s.

Within the third stage of this methodology, the efficiency coefficients in the worm gear meshing engagement are determined in accordance with [17]. Databases are created, which significantly expand the information presented in [18].

During the fourth stage, the maximum possible output torque for the worm gear set is calculated based upon the preliminary determined permissible contact stresses according to the Niemann methodology, [19]. This stage includes also several advanced design optimization procedures concerning the output power of the worm gear, taking into account nine design variable parameters and several significant mechanical constraints. The variable parameters selected are: number of starts for the worm, number of teeth of the worm gear, center distance, sliding speed and friction coefficient for the meshing, lead and tooth friction angles, permissible contact stresses for the pair of worm and worm gear materials, appropriate values of the safety factors.

The fourth stage includes also graphical presentation and analysis of the results obtained.

Table 1. Research results.

a = 80 mm			a = 63 mm		
i	η_z	T_2, Nm	i	η_z	T_2, Nm
5	0,9456	61,5	4,83	0,9397	30,01523
7,5	0,9343	101,8	7,25	0,9209	49,71331
10	0,9209	128,9	9,75	0,9107	61,19244
13,25	0,9107	155,6	12,75	0,9019	76,04179
15	0,8763	239,9	14,5	0.8617	117,1633
20	0,8614	302,8	19,5	0.8478	143,7961
26,5	0,8458	364,2	25,5	0.8289	178,0894
30	0,7852	560,4	29	0.7622	273,8751
40	0,7622	703,8	39	0.7444	334,3952
53	0,7444	841,3	51	0.7132	411,764

4 Results and Discussion

Optimization design procedures have been performed for different center distances of worm gear sets according to the methodology described.

The results obtained for a center distance a = 80 mm and rotational speed of the worm shaft $n_1 = 1500\ \text{min}^{-1}$ are shown in Table. The efficiency coefficient is considering only the power losses in the meshing of the worm gear set (Table 1).

The graphical results are displayed on Fig. 1. The variations of the efficiency in the meshing and the maximum possible output torque for the worm gear at a center distance a = 80 mm and worm shaft speed $n_1 = 1500\ \text{min}^{-1}$ for gear ratios in the range 5 to 53 are shown.

The study has been carried out for different values of the module of the worm gear set. For the case regarded, the values of the module are: m = 4; 3.15 and 2.15 mm. It is to be observed that when gear ratio increases, the efficiency coefficient of the meshing gear decreases.

The opposite trend is observed concerning the variations of the maximal output torque. When the gear ratio increases, the maximum permissible values of the output torque for the worm gear shaft increase as well.

The most rapid enlargement is to be observed at m = 2.5 mm. Taking into account the two criteria: maximum efficiency in meshing and maximum output torque for the worm gear, it becomes clear that the most advantageous range of gear ratios for all three modules considered is the range from i = 13.25 to i = 30 (Fig. 2).

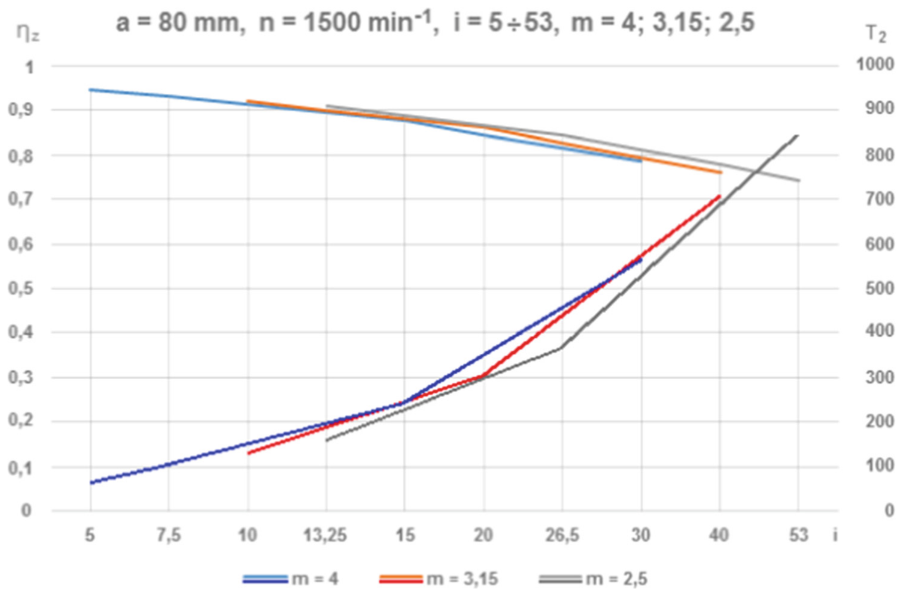

Fig. 1. Research results for center distance a = 80 mm.

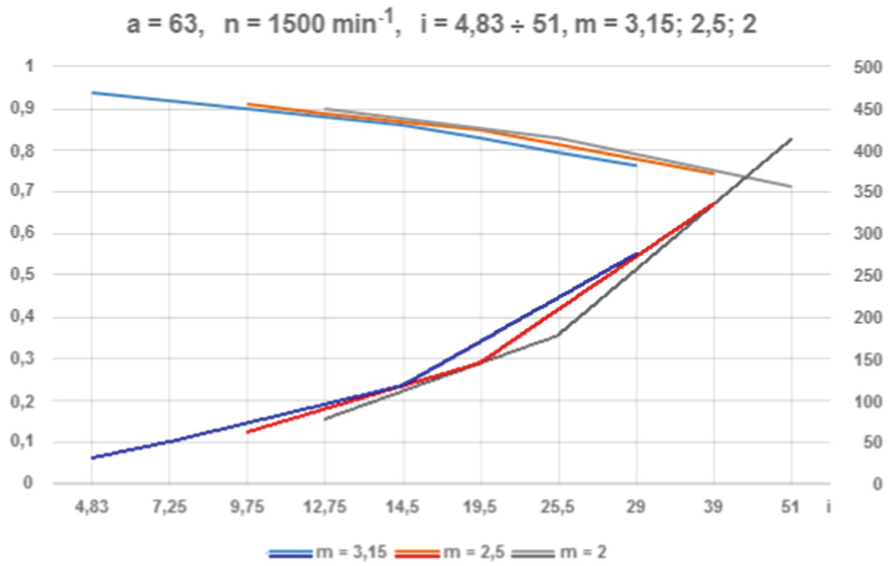

Fig. 2. Research results for center distance a = 63 mm.

Conclusions and Future Work

Advanced design optimization procedures concerning the output power of the worm gear, taking into account nine design variable parameters and several significant mechanical constraints have been created. The variable parameters selected are described in details within the description of the research methodology. The most advantageous areas of application in terms of the most important according to the authors' team optimization criteria have been indicated.

It is envisaged that the results obtained from the design optimization procedures will be linked to future optimization work with a linear interpolation method based on the software system Matlab. This method sets the value of an interpolated point to the value of the nearest data point. It provides the creation of three-dimensional graphs and ensures a better visualization of the recommended areas for different center distances, which will take into account both optimization criteria: maximum efficiency in the meshing and maximum output torque for the worm gear set. This method has already been applied by the authors' team in previous investigations, [14].

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