

Volume optimization of the worm gear using SSO algorithm

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ABSTRACT

Machine design is a field of research where the process of designing a mechanical element is optimized, having certain goals and limitations in mind. In this paper, the Sperm Swarm Optimization algorithm (SSO for short) was used to optimize volume of worm gear with constant number of variables. By applying the SSO algorithm, we obtained optimal or near-optimal results. By further development of this algorithm, this method can be modified and improved in order to obtain better results.

KEYWORDS

Optimization, Worm Gear, Sperm Swarm Optimization.

1. INTRODUCTION

Optimization techniques play a significant role in modern mechanical engineering design, where the primary objective is often to improve performance while reducing material consumption, manufacturing cost, and overall system dimensions. In power transmission systems, worm gears are widely used because of their compact structure, high transmission ratio, smooth operation, and ability to provide significant speed reduction in a single stage. However, despite their advantages, worm gears are frequently associated with challenges related to efficiency, heat generation, wear, and geometric constraints. These challenges can be formulated as an optimization function, therefore making them a candidate for solving them using metaheuristics.

A worm gear is a gear consisting of a shaft with a spiral thread that engages with and drives a toothed wheel. Worm gears are an old style of gear and a version of one of the six simple machines. Basically, a worm gear is a screw butted up against what looks like a standard spur gear with slightly angled and curved teeth[8].

Finding the solution to worm gear problems in machine design is very complex and a time consuming process. Many design variables, constraints, different graphs and tables, empirical formulas are involved. As the literature reveals, not much research has been undertaken on worm gear drive optimization. Besides this certain challenging industry relevant constraints, namely, gear strength capacity, wear capacity, thermal capacity, dynamic load and face width are also not considered in the literature.

In recent decades, metaheuristic optimization algorithms inspired by natural phenomena and biological systems have become increasingly popular in solving complex engineering optimization problems. Algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Differential Evolution (DE) [1,2,3,4,5], and many others have demonstrated strong capabilities in handling nonlinear, constrained, and multimodal optimization problems. These algorithms are particularly suitable for mechanical design optimization because they can handle constraints and explore large search spaces in an efficient manner.

Classification of optimization algorithms are shown in Figure 1.

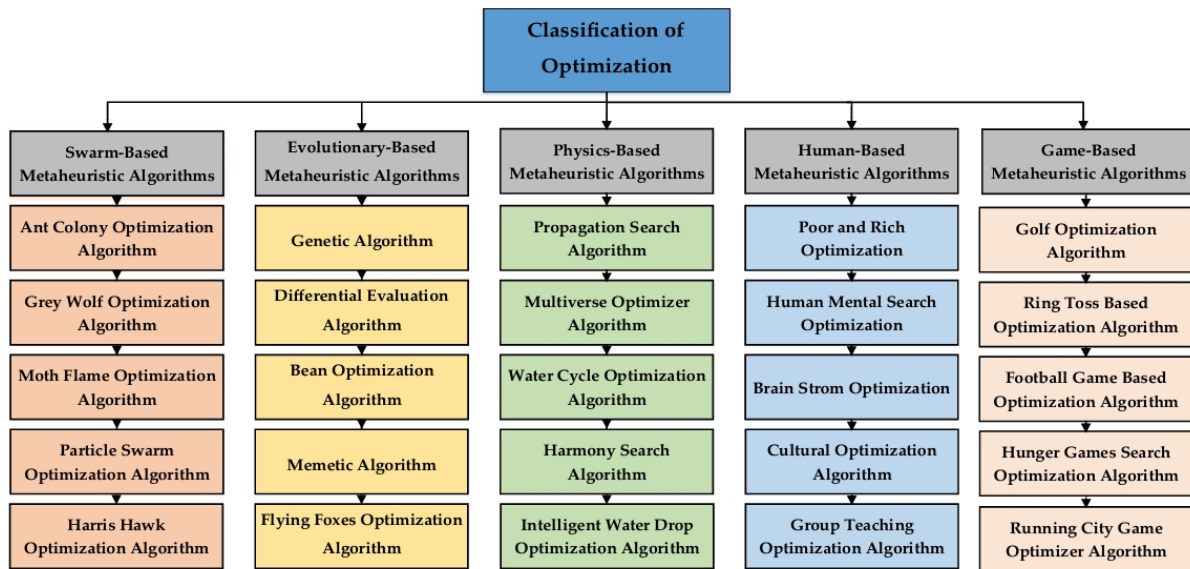


Figure 1: Classification of Optimization

The remainder of this paper is organized as follows. Section 2 presents an overview of the Sperm Swarm Optimization algorithm and its mathematical formulation. Section 3 describes the worm gear design optimization problem, including the objective function, design variables, and imposed constraints. Section 4 discusses the obtained optimization results and evaluates the effectiveness of the proposed approach. Finally, conclusions and potential future research directions are provided.

2. SPERM SWARM OPTIMIZATION

Sperm Swarm Optimization algorithm (SSO) represents a bio-inspired population-based metaheuristic algorithm, whose inspiration stems from the fertilization procedure, where a fertilized egg is surrounded by sperm cells (search agents), which compete to fertilize the egg (Figure 2). Two key biological mechanisms additionally inspire this algorithm: sperm cell's head acting as a temperature sensor, helping it locate the egg, and the female reproductive system having a differing pH value, which may be more or less harmful to the sperm cells. The algorithm goes through an initialization phase, where all search agents are initialized, and update phase, where search agents move through the search space, in order to find the best solution [6,7].

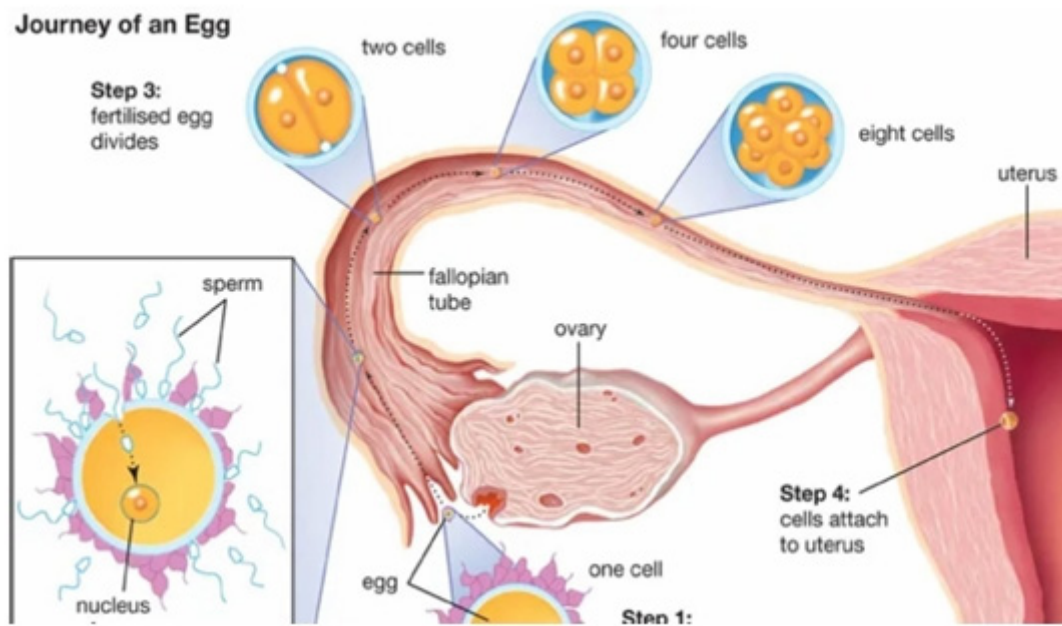


Figure 2: Mechanism of fertilization

The position of the search agents is updated by:

$$x_i(t+1) = x_i(t) + v_i(t) \quad (1)$$

Where $x_i(t+1)$ is the position of the search agent in the next iteration, $x_i(t)$ is the position of the search agent in the current iteration, and $v_i(t)$ is the velocity of the search agent in the current iteration. The search agent's velocity is calculated as follows:

$$v_i(t) = \text{Initial Velocity} + \text{Current Best} + \text{Global Best} \quad (2)$$

The search agent's initial velocity is calculated as follows:

$$\text{Initial Velocity} = D \log_{10}(PHRand) v_i \quad (3)$$

where D is the damping factor (a random number between 0 and 1), $PHRand$ is a random number between 7 and 14, and v_i is a velocity vector (randomized between 0 and maximum values of the search space).

The current best term of the velocity is calculated as follows:

$$\text{Current Best} = \log_{10}(PHRand) \log_{10}(TempRand) (x_{best_i} - x_i(t)) \quad (4)$$

where $TempRand$ is a random number between 35.1 and 38.5, and x_{best_i} is the current best solution for the search agent.

The global best term of the velocity is calculated as follows:

$$\text{Global Best} = \log_{10}(PHRand1) \log_{10}(TempRand2) (x_{gbest_i} - x_i(t)) \quad (5)$$

where x_{gbest_i} is the global best solution for the current iteration.

3. WORM GEAR DRIVE OPTIMUM DESIGN

The objective is to minimize volume of worm and worm wheel assembly. The volume equation from is:

$$f(x) = 14.310926 \cdot \frac{x_4 \cdot x_3^2}{x_1} + 455.5309 x_2 x_4 + 0.8382 \left(\frac{256x_4^2 + x_1^2 x_2^2}{x_1 x_4} \right)^2 + 104634.67 \quad (6)$$

The design variables are: Gear ratio (i), Face width (b), Pitch circle diameter of worm (D_1) and Pitch circle diameter of worm wheel (D_2). The function for design variables of the worm drive can be written as $F(x) = F(i, b, D_1, D_2) = F(x_1, x_2, x_3, x_4)$

Upper and lower bounds of design variables are: $40 \leq i \leq 70, 100 \leq b \leq 200, 150 \leq D_1 \leq 280, 1000 \leq D_2 \leq 1500$.

The face width of a gear is the length of teeth in an axial plane. The face width of the gear should not exceed half the worm outside diameter.

$$g_1(x) = x_1 - 0.5(x_3 + 48) \leq 0 \quad (7)$$

Mathematically, the tangent of the helix angle of the worm gear is less than the coefficient of friction between the worm and the gear. This condition is referred to as self locking of worm gears.

$$g_2(x) = \frac{22.5}{x_3} - 0.099 \leq 0 \quad (8)$$

For better performance, dynamic load must be greater than strength and wear capacity.

$$g_3(x) = 6430.01 - 754.56x_2 \leq 0 \quad (9)$$

$$g_4(x) = 6430.01 - 0.552x_2x_4 \leq 0 \quad (10)$$

Amount of power lost in friction is converted into heat. To prevent overheating, heat generated should not exceed the rate of heat transfer.

$$g_5(x) = 120 - 406(0.785x_4^2 + 0.075408x_3) \leq 0 \quad (11)$$

To achieve compact design of gear pairs, the centre distance of optimized gear pair should be less than that of actual gear pair.

$$g_6(x) = \frac{\frac{x_1 x_2}{\sqrt{65x_3 + 1}} + x_3}{2} - 901 \leq 0 \quad (12)$$

The condition for maximum power transmission capacity is constraint g_7 and constraint g_8 .

$$g_7(x) = \frac{\left(\frac{x_1 x_2}{\sqrt{\frac{65x_3}{x_4} + 1}} + x_3 \right)^{0.875}}{3} - x_3 \leq 0 \quad (13)$$

$$g_8(x) = x_3 - \frac{\left(\frac{x_1 x_2}{\sqrt{\frac{65x_3}{x_4} + 1}} + x_3 \right)^{0.875}}{1.7} \leq 0 \quad (14)$$

If the worm shaft bends too much, the teeth will not mesh properly. This will result in excessive wear and early failure. To avoid this, the maximum deflection is constraint g_9 given by:

$$g_9(x) = \frac{90.887873 \frac{x_4^4}{x_1}}{\left[x_2^2 - 4 \frac{x_4^2}{x_1^2} \right] \cdot \left[x_3 - 2.4 \frac{x_4}{x_1} \right]^4} - 0.001 \cdot x_3 \leq 0 \quad (15)$$

Beam strength of worm gear tooth is the maximum tangential load the worm gear tooth can take without tooth breakage. Constraint g_{10} based on Lewis equation is:

$$g_{10}(x) = \frac{66116467.3 \cdot x_1}{x_4 \cdot x_2 \cdot x_3} - 83.33333 \leq 0 \quad (16)$$

4. RESULTS AND DISCUSSION

For this algorithm, 30 search agents and 1000 iterations were chosen as input parameters. During the course of the research, it has been noted that increasing search agent and iteration count did not yield better solutions.

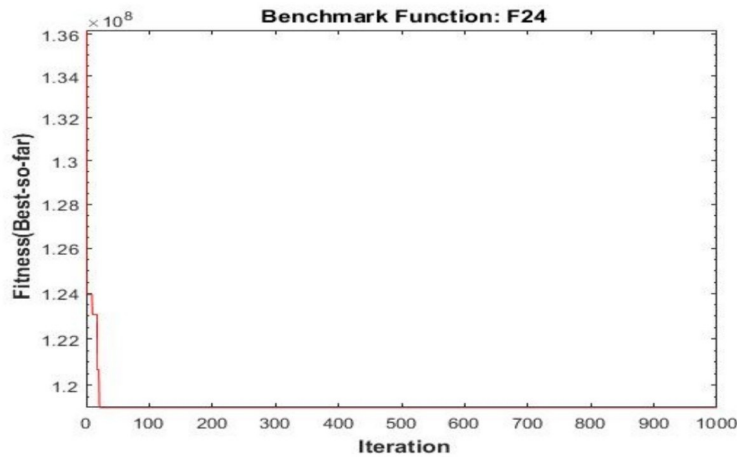


Figure 3: Convergence rate of SSO algorithm respectively for finding the best possible fitness of worm gear

In Figure 3 a convergence diagram for the problem of worm gear optimization is given. As SSO gives best results, it is compared with literature [9] in Table 1.

Table 1: Percentage change in optimal parameter values by SSO of this work (bold values) and literature

Parameters	Literature [9]	SSO	Change in value [%]
Gear ratio	46	45.6	0.87
Face width [mm]	197	130.2	33.91
Pitch circle diameter of worm [mm]	188	280	48.93

Pitch circle diameter of worm wheel [mm]	1000	1000	0
Volume of worm and worm wheel [mm ³]	1.45442 · 10 ⁸	1.1822 · 10⁸	18.72

Percentage change in optimal design parameters values is shown in Table 1. It is observed that a decrease in value of 0.87 % in gear ratio, 33.91% in face width, and an increase of 48.93% in pitch circle diameter of worm. Interestingly, there is no change in value in pitch circle diameter of the worm wheel.

5. CONCLUSION

In this paper, optimum design for a worm gear drive considering industry relevant constraints using Sperm Swarm Optimization (SSO) algorithm is obtained. All constraints are well satisfied. The important findings are:

- There is 18.72 % reduction in volume of worm gear drive as compared to literature. It is worthwhile to mention that this reduction in volume is achieved after including industry relevant constraints.
- There is a decrease in design parameter value of 0.87 % in gear ratio, 33.91% in face width, and an increase of 48.93% in pitch circle diameter of worm. This research also reports the value of thermal capacity, strength capacity and wear capacity of worm gear drive which are not reported in any of the literature.
- This work is readily applicable and suitable for optimization of other similar gear drives employed in industries.

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