Design optimization of worm gear drive with reduced power loss

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Abstract. In worm gear mechanism, power loss is one of the critical issues, which requires attention from gear designers and researchers. This is due to power loss; the overall efficiency of worm gear drive gets reduced. In this article, Simulated Annealing (SA) is used to minimize the power loss of worm gear drives within the prescribed set of design constraints. Various design constraints included in the design optimization problem are linear pressure, bending strength and deflection of worm. Gear tooth number, coefficient of friction and helix angle are the design variables considered. Results obtained are compared and validated with the results obtained in previous research work found in the literature. It shows that SA is more efficient in attaining optimal design values for worm gear drive for reducing power loss.

1. Introduction

Worm gear drives are used in transmission system because of their ability to achieve high reduction ratio with compact size. The relative sliding motion between the gear teeth is the reason for poor efficiency of worm gear mechanism. Thus friction is high in these gears leading to high power loss. Very less attention has been paid by the gear researchers and designers on reducing the power loss of worm gears using evolutionary techniques.

There are many literatures available related to design optimization of various gear drives using conventional and non-conventional optimization techniques. Gologlu and Zeyveli [1] demonstrated the use of genetic algorithm for minimization of volume of a two-stage helical gear drive. Genetic algorithm was again used by Mendi and Baskal [2] for reduction of volume of gearbox which includes shaft bearing and gears. Weight of cylindrical parallel gear train has been minimized using GA by Caballero [3]. An approach developed by combining Finite Element Analysis, Artificial Neural Network and Genetic Algorithm was proposed by Su and Peng [4] for achieving optimal design values of a cylindrical worm with helical gear drive. Chong and Lee [5] proposed a technique for utilizing genetic algorithm for optimization of volume of two-stage gear drive and simple planetary gear. To reduce the weight of worm gear pair, modified artificial immune algorithm had been used by Padmabhanan et al. [6]. Stojanovic et al. [7] studied the effect of lubricant viscosity on the worm gear efficiency. Rai and Barman [8] utilized genetic algorithm and simulated annealing for performing design optimization of spur gear set. Yaman et al. [9] used genetic algorithm to minimize the power loss in worm gears and further compared it with analytical results to prove its efficiency. In continuation of this work, differential evolution and particle swarm optimization technique was used for optimizing the worm gear power loss by Sabrinath et al [10].

In the presented article, the problem of power loss of worm gear mechanism has been reported. Simulated annealing, which has not been utilized in the previous studies, has been used to minimize...
the power loss. The efficiency and performance of the algorithm is analysed by comparing it with the results obtained using other optimization algorithms like genetic algorithm (GA), differential evolution (DE), particle swarm optimization (PSO) etc.

2. Problem definition
This work aims at minimizing loss of power in worm gear drive. High friction between the gear teeth while in meshing is the reason for power loss. Therefore, power loss in worm gear drive can be expressed as [10]

\[ \Delta P = P_1 - P_2 \]

where \( P_1 \) is the input power and \( P_2 \) is the output power. In this case, the expression for output power is

\[ P_2 = F_n (\cos \alpha_n \cos \phi_n - \mu \sin \phi_n) \frac{m \omega_1 z_2}{2\mu} \]

where \( F_n \) is the normal force, \( \alpha_n \) is the normal pressure angle, \( \phi_n \) is the helix angle, \( m \) is the axial module, \( z_2 \) is the number of teeth on worm wheel and \( \omega_2 \) is the angular velocity of worm. The schematic diagram for worm gear drive is shown in Fig 1.

![Schematic Diagram of worm gears](image)

Fig 1. Schematic Diagram of worm gears

Here the material of worm and worm wheel is hardened steel and bronze respectively. The angle between the shaft is 90° and worm has three threads. Various input parameters used for performing design optimization of worm gears are shown in Table 1.

**Table 1. Input parameters for worm gear design optimization [9]**

| Input Parameter          | Unit | Value |
|--------------------------|------|-------|
| Input Power              | kW   | 11    |
| Transmission ratio       |      | 15    |
| Number of revolution for worm | rpm | 720   |
| Centre distance of worm gear pair | mm | 200   |
| Distance between of worm shaft bearing | mm | 330   |
| Module                   | mm   | 7     |
| Number of worm teeth     | mm   | 3     |
| Worm diameter            | mm   | 71    |
| Bottom of teeth diameter of worm | mm | 55    |
| Pressure angle           | degree | 22.5 |
Elasticity Modulus | N/mm$^2$ | 21*10$^4$
---|---|---
Inertia | mm$^4$ | 449000

2.1. Objective function
Thus the final expression for the objective function for power loss minimization in worm gear mechanism, is
\[
\Delta P = P_1 - F_n (\cos \alpha_n \cos \phi_n - \mu \sin \phi_n) \frac{m \omega_1 z_2}{2l}
\]

2.2. Design variables
Three design variables are considered for performing design optimization of worm gear mechanism. They are gear tooth number, helix angle and coefficient of friction. The ranges for these design variables are given below

\[21 \leq z_2 \leq 80\]
\[0.03 \leq \mu \leq 0.05\]
\[15 \leq \phi_n \leq 25\]

2.3. Design constraints
Bending strength, contact pressure and linear deflection of worm are the design constraints considered while performing optimization for worm gear design problem. They can be expressed as

\[g_1 = \frac{F_{ax}}{b_2 m n} - 30 \leq 0\]
\[g_2 = \frac{F_{rz}}{b_2 m z_2} 2.5 - 3.6 \leq 0\]
\[g_3 = \frac{d_{f_1}}{1000} - \frac{F_{rt} L^3}{48EI} \leq 0\]

Here, $g_1$ is the bending strength of the worm gear tooth, $g_2$ is the linear pressure of worm gear and $g_3$ is the linear deflection of worm shaft. Here $F_{ax}$ and $F_{rt}$ are the axial force on worm gear and total radial force respectively. $b_2$ and $d_{f_1}$ are the face width of worm gear and root diameter for worm gears respectively.

3. Optimization technique
Simulated annealing is a stochastic optimization technique which can solve both constrained and unconstrained optimization problems [11]. This technique is based on the principle of heating of a material and then letting it cool down, thereby minimizing the defects and thus further reducing the system energy. There is random generation of new point at every iteration in simulated annealing. The distance between new and current point can be measured with the help of probability distribution with a scale. This probability distribution is proportional to the temperature. When the value of objective function is lowered, the algorithm accepts candidate point for solution along with those points which raise the value with a certain probability. Thus, the algorithm will not be trapped in local minima and produces a global optimum solution.

4. Results and Discussions
Minimization of power loss of worm gear set problem is solved using simulated annealing algorithm. This algorithm has been run using MATLAB 2016 on PC compatible with Intel(R) Core(TM) i7-3770,
a 3.4 GHz processor and 4 GB of RAM. Various parameters of SA employed while performing the optimization of worm gear mechanism are shown in Table 2.

| Design parameter          | Value  |
|---------------------------|--------|
| Maximum run               | 100    |
| Final stopping temperature | 1e-2   |
| Initial temperature       | 1      |
| Cooling rate              | 0.8    |

The algorithm has been executed 10 times for verifying the convergence of SA. The results obtained using SA are compared with the results obtained in previous works (DE, PSO, GA and analytical method). The value of power loss for worm gear drive obtained is 0.2988 kW which is lower in comparison to power loss obtained using other algorithms as shown in Table 3. The percentage reduction of power loss is also shown in Table 3.

| Optimization Algorithm       | No of teeth on worm gear | Friction coefficient | Helix angle | Power loss (kW) | % reduction in power loss by SA |
|------------------------------|--------------------------|----------------------|-------------|----------------|--------------------------------|
| SA (present article)         | 45                       | 0.0301               | 15.045      | 0.2988         | -                              |
| DE algorithm [10]            | 45                       | 0.0302               | 15.008      | 0.388          | 22.98%                        |
| PSO [10]                     | 45                       | 0.0302               | 15.002      | 0.369          | 19.02%                        |
| Binary GA [9]                | 44                       | 0.0305               | 15.24       | 0.881          | 65.5%                         |
| Analytical method [9]        | 46                       | 0.0390               | 16.280      | 1.362          | 78.02%                        |

The optimum solution obtained using SA converges after 16th iteration. The convergence curve of power loss versus iteration is shown in Fig. 2.

The frictional coefficient value is less which results in better efficiency of worm gear pair. This is because of less heat generation while in mesh. There is no change in gear tooth number obtained using SA, but the value of helix angle is greater compared to other optimization techniques.
5. Conclusions
This study presents the power loss minimization of worm gear mechanism using simulated annealing. The optimal worm gear model obtained is found to be better in comparison to earlier used optimization techniques. The algorithm used in the design optimization of worm gear proves to be effective in avoiding the premature convergence in local minima. Thus, this shows good performance of the algorithm in implementing the design problem. It can be seen that the value of friction coefficient is lower in comparison to other optimization technique used earlier (DE, PSO and GA). Helix angle obtained using SA is greater in comparison with DE, PSO and GA. The percentage reduction of power loss using SA ranges from 78.02% to 22.98%. The optimized gear pair will have better service life. Hence, the attained results show that the performance of SA is better in comparison with other approaches used earlier for power loss minimization of worm gears. Thus, optimum design of worm gear drive has been achieved with reduced power loss. Further, the optimization problem can be formulated as multi-objective optimization problem.

6. References
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