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APPLICATION OF FIREFLY ALGORITHM FOR OPTIMIZING BEVEL GEAR DESIGN PROBLEMS IN NON LUBRICATED CONDITION

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ABSTRACT

Efficient and reliable power transmission between the intersecting shafts is necessary to meet both the lossless power transmission and to satisfy the current demand of lesser weight gears for computerized machines without lubrication. Also by considering the environmental concerns about the noise generation and pollution due to lubrication, application specific economical bevel gears should be designed. Economical design in less time by satisfying the design, manufacturing and operational constraints can be achieved by computational algorithms. In order to deal with the optimization of these conflicting constraints, that is, minimization of size and weight of the bevel gear pair without affecting the performance and safety can be achieved through meta-heuristic algorithms. This research describes a solution to this problem using a nature-inspired algorithm, called firefly algorithm. The algorithm is described along with case studies by a combined objective function. The results are compared with the traditional design values, to show that it is capable of identifying better optimal solutions with proper selection of firefly control parameters.

KEYWORDS
gear design problems, computerized machines, power transmission, economical design.

1. INTRODUCTION

Recently, Zoology inspired meta-heuristic algorithms have proved to be an efficient way to deal with many NP-hard combinatorial and non-linear conflicting constrained optimization problems. Because by nature, animals are having specific strategy to identify best path and solution to survive in the world by avoiding predators and obstacles [Blum and Sampels, 2004]. These successful mechanisms of a biological phenomenon are mimicked computationally to build the meta-heuristic algorithms to solve the complex optimization problems i.e. identifying the better solution from the available solutions [RAO, 2009]. The mechanism of identifying the shortest path from the nest to the food by the ants is used in Ant colony algorithm [Dorigo and Gambardella, 1997], the breeding of chickens with best properties is used in selective breeding, finding of an optimal solution based on the foraging and storing the maximum amount of flowers' nectar is applied as honey bee's algorithm, identification of its mating pair from the light intensity is utilized in firefly algorithm [Yang, 2010], and so on.

Firefly algorithm is one of the emerging nature inspired algorithms, which is based on the flashing light of fireflies. Fireflies are capable of producing the light from its body and can control the intensities based on the requirement through a complex biochemical process. The light emitted from the fireflies is to find it's mating pair, protecting themselves from their predators and attracting their potential prey [Yang, 2009]. In the firefly algorithm, objective function of the optimization problem is directly mapped with its flashing light brightness or intensity. As the fireflies are move towards the brighter and more attractive locations, the fitness function also move towards the more optimal solution location in the search space [Lukasik and Zak, 2009].

In this research paper, the firefly algorithm is applied to the bevel gear design problem to identify the optimal gear parameters by satisfying the constraints and in non-lubricated conditions. The application specific gear design optimization problem constitutes one of the key problems in the manufacturing sector and planning in which a direct solution cannot be found. This optimization problem deals with reduction in the size and weight of the gears, improves the efficiency and power transmitting capability of the gear pairs. So the objective function used in the research is called as combined objective function. There are numerous variations of this problem exists and different ways to represent the constraints. Moreover, this research is to implement firefly algorithm with suitable control parameters to identify the best value for the combined objective function by satisfying the constraints and thereby to prove the effectiveness of the firefly algorithm. For the effectiveness and validation of this algorithm, sample bevel gear design problem for different application have been tested.

The remainder of this paper is organized as follows: Section 2 gives a brief description of the multi-objective optimization and problem formulation methodology. In Section 3, briefly describes the firefly algorithm in general and the characteristics of the firefly considered in this research. Section 4 presents the experimental implementation and the control parameter for Matlab simulation. Finally, Section 5 provides some conclusions concerning the solutions obtained by the firefly algorithm and some suggestions and ideas for further research.

2. PROBLEM FORMULATION

In most of the real world problems, multiple conflicting objectives arise naturally and those problems are called as multi-objective combinatorial optimization problems, like bin packing, job shop scheduling, gear design, etc [Kumar et al, 2008]. To solve these problems, researchers developed and proposed several principles and methodologies for over a decade. In the multi-objective optimization problems, as the name implies, the objective function having more than one objective or combination of multiple objectives. The objective may conflict or many not conflict with each other and depend on the applications. The aim of the research is to find a vector of decision variables that satisfies constraints in design, manufacturing and operational functions by optimizing the combined objective function. The combined objective function (COF) developed is a linear combination of the normalized conflicting multiple objective functions and is given in the Equation 1.

$$COF = [f(\eta) + f(\hat{W}) + f(Ş)I] / 3 \quad (1)$$

COF is the normalized function and its value ranges from 0 to 1. The primary goal is to maximize the value of the COF i.e. higher the COF value, better the result and vice-versa. In this research, penalty function has also been used and sometimes COF may results with negative value to indicate the infeasible solution. The first function is the efficiency function and the goal is to maximize the efficiency of the power transmission between the gears. The equation for calculating the efficiency is given in the Equation 2 [Townsend, 1992].

$$\eta = 100 - P_L \quad (2)$$

where, 'P_L' = Power loss between the gear pair and is given in the Equation 3.

$$P_L = \frac{50f}{\cos\Phi} \times \frac{(H_s^2 + H_t^2)}{(H_s + H_t)} \quad (3)$$

'H_s' = Specific sliding velocity at start of approach action
'H_t' = Specific sliding velocity at end of recess action
'f' = Coefficient of friction
'Φ' = Pressure angle in degrees
'H_s' and 'H_t' are calculated by the Equations 4 & 5 respectively.

$$H_t = \frac{(i+1)}{i} \times \sqrt{\left(\left[\frac{r_0}{r}\right]^2 - cos^2\Phi\right)} - \sin\Phi \qquad (4)$$

$$H_s = (i+1) \times \sqrt{\left(\left[\frac{R_0}{R}\right]^2 - cos^2\Phi\right)} - \sin\Phi \qquad (5)$$

Whereas, 'R' & 'R_o' = Pitch and Outside circle radius of gear in mm.
'r' & 'r_o' = Pitch and Outside circle radius of pinion in mm
R_0 = R + one addendum
The outside radius of the bevel gear is calculated using the Equation 6 and 7.

$$r_o = r + m = \frac{d_1}{2} + m \qquad (6)$$

$$R_o = R + m = \frac{d_2}{2} + m \qquad (7)$$

The second term in the COF is the weight function. Due to digital controlled machines, the researchers are trying to reduce the weight of the machine parts and in turn the weight of the gears used without compromising the performance [Thompson et al, 2000]. So the weight function is a minimization function and the minimization function for weight, total weight of the gear should be as minimum as possible [Lin et al, 2009]. The formula for calculating the weight of the gear is given in the Equation 8.

$$\hat{W} = \{[\frac{\pi}{4} \times d_1^2 \times b \times \rho] + [\frac{\pi}{4} \times d_2^2 \times b \times \rho]\} \qquad (8)$$

Where, 'd_1' & 'd_2' = Pitch circle diameter of pinion and gear in mm
'b' & 'ρ' = Thickness and Density of the material in kg/mm^3
The third term in the COF is the size function. Normally the machine tools required smaller sized parts, so the third function is to reduce the size of the gear pair without compromising the performance of the power transmission and safety [Huang et al, 2005]. The minimization function for size is to reduce the cone distance between the gears and thereby the size of the gears can be reduced. The equation for calculating the cone distance is given in Equation 9.

$$Ş = \frac{(d_1 + d_2)}{2} = \frac{m}{2}(Z_1 + Z_2) \qquad (9)$$

Where, 'Z_1', and 'Z_2' are the number of teeth in pinion and gear respectively.
The set of bevel gear parameter which produces the higher value for the COF will yield best parameters for the bevel gear pair. But the same set of parameters needs to be satisfied by the constraints involved in the design, manufacturing and operations [Abersek et al, 1996]. Because, obtained solution should be a feasible solution, so that the bevel gear pair can be manufactured and used in the machine tools with less maintenance. This type of multi-objective optimization problem is sometimes called vector minimization problem [Tudose et al, 2010]. In order to identify the optimal solution for the COF, in this research, the emerging meta-heuristic algorithm called firefly algorithm is used.

3. THE FIREFLY ALGORITHM

Firefly Algorithm (FFA) is a meta-heuristic optimization algorithm, inspired by the natural flashing behavior of fireflies for attracting the other fireflies in the summer sky in the tropical temperature regions [Yang, 2008; Lukasik and Zak, 2009; Yang, 2009; Yang, 2010]. The concept of firefly optimization is introduced by Dr. Xin-She Yang at Cambridge University in 2007 [Yang, 2008], and the base for the algorithm is the swarm behavior of the animals such as fish, insects, or bird. Firefly algorithm also has many similarities with other naturally inspired algorithms like Genetic algorithm [Renner and Ekart, 2003], Particle Swarm Optimization [Bauer et al, 1999], Ant colony Algorithm [Bullnheime et al, 1999], Artificial Bee Colony optimization, etc. [Lukasik and Zak, 2009]. Furthermore, firefly algorithm is very simple and easy for implementation and more efficient algorithm which can outperform other evolutionary algorithms, such as genetic algorithm. In order to explore more search space, the algorithm uses real random numbers for convergence it uses global communication among fireflies. The assumptions to be made in the firefly algorithm are as follows.

1. All fireflies are unisex and any firefly can move towards any other brighter ones regardless their sex.
2. The firefly attractiveness is proportional to its brightness or the light intensity and will decreases with increase in distance. Also the attractiveness decreases with increase in absorption coefficient.
3. Either, if there is not a brighter firefly or all the fireflies having similar brightness, than movement can be at random path.
4. For optimization, the brightness is proportional to the objective function of a given problem.

Thus the major firefly control parameters are the attractiveness, distance between the fireflies and the movement of the fireflies.

3.1 ATTRACTIVENESS

The fireflies are having glowing light in the bodies to attract other fireflies. The attractiveness of the firefly can be evaluated by the Equation 10.

$$\beta = \beta_0 e^{-\gamma r2} \qquad (10)$$

where, r is the distance between i^{th} and j^{th} firefly. β_0 is the initial attractiveness of the fireflies at distance r = 0 and γ is an absorption coefficient which controls the decrease of the light intensity and vary based on the surrounding environment. The attractiveness will vary from distance between the fireflies.

3.2 DISTANCE

The distance between the fireflies is inversely proportional to the intensity of the light. The distance between i^{th} and j^{th} fireflies at x_i and x_j positions and its movement is given in the Equation 11.

$$X_i = X_i + \beta_0 e^{-\gamma r2} (X_j - X_i) + \alpha\varepsilon^i \qquad (11)$$

The existing distance is updated based on the firefly attractiveness and to explore more search space, randomization parameter α is also included and the value should be in the range of 0 and 1. However, this attractiveness is the deciding factor for the movement of fireflies and inversely proportional to the distance between fireflies.

3.3 CONVERGENCE BEHAVIOR

The primary objective of most of the optimization and evolutionary algorithms are to converge the results at global optimal points instead of local optimal points. In order to identify the global optimization points, algorithm should have two properties. The first property is exploring the search space with all possible solutions and the second property is to search the entire search space. In this research, the major parameters which influencing the bevel gear design are considered and the interval selected will be very least, thereby increasing the search space. The convergence of the algorithm at global optimal point is achieved with large number of fireflies and in every trial, 10% of the fireflies will be allowed to move in the random path. Especially in firefly algorithm, the concept of exploration and exploitation will help largely in attaining the global optimal point by avoiding the stagnation at the local optimal points. Also the initial locations of 'n' fireflies are distributed uniformly and randomly in the search space. However, many researchers are trying to bring a formal proof of the convergence of the evolutionary algorithms and assume that the algorithms will attain global optima when $n \rightarrow \infty$.

The experimental results proved that the firefly algorithm converges very quickly in 90 iterations and with 10 fireflies per iteration. Indeed, the appropriate choice of firefly algorithm parameters such as number of iterations, number of fireflies, γ, β, α, and n parameters are highly influencing the convergence and depends on the nature of the given optimization problem. In this research, these parameters are set by conducting the sensitivity analysis, as the parameters vary from application to application and as there is no hard relations exist between them in finding both local and global optima. The computational time and the search are inversely proportional constraints and need to be compromised. As the search space and the number of fireflies increases will lead to better solution and proportionally computational time increases and vice versa. Larger population size becomes the greater the computational time.

3.4 SENSITIVITY ANALYSIS

As the performance of the firefly algorithm depends on the parameters and those should be fixed by conducting sensitivity analysis. The minimum and maximum range of the absorption coefficient 'γ' is between $\gamma \rightarrow 0$ and $\gamma \rightarrow \infty$. When $\gamma \rightarrow 0$, the sky is assumed to be clear and the attractiveness coefficient 'β' is constant. The light intensity does not decrease or increase with respect to the distance 'r' between fireflies. Therefore, light from any firefly can be seen anywhere and the local or global optimum can be easily reached. On the other hand, when $\gamma \rightarrow \infty$, denotes the foggy sky and the attractiveness coefficient uses Dirac delta function. The attractiveness became almost zero in the foggy surrounding as the light intensity is absorbed by the fog. Thus the fireflies cannot see each other, and movement will be completely randomly in a foggy place. Therefore, it improves the search on the entire space for better solution. Thus there exist a tradeoff between them and will be varied from application to application. Similarly most of the firefly parameters are having conflicting ranges and will be decided by conducting sensitivity analysis.

4. EXPERIMENTAL IMPLEMENTATION

Optimization problem having more than one objective functions will have more than a solution and one solution may dominate over the other will be best solution. Bevel gear design problem is a multi-objective optimization problem with conflicting constraints. So the dominating solution should also satisfy the constraints involved. The set of solution which satisfies the constraints are the feasible solution and the best among the feasible solution is the optimal solution for the given problem or the set having no other feasible solution 'Y' and the condition is given in the Equation 12.

f(y) ≤ f(x) for all i _ 1, 2, . . . , k. and f(x)ε C. (12)

which means that the solution f(x) is no worse than f(y) in all objective functions and constraint satisfaction. As it is very difficult to effectively handle with all the conflicting objective functions and constraints, in this research, objective function had been converted to linear function and several trials with different firefly parameters had done to attain the goal. In the former, the objective function is normalized between 0 and 1 and thereby making the multi-objective problem into single objective problem. The gear data set which violates the constraints will be provided with a negative penalty value to the objective function and eliminate them from the search space. The addition of the penalty value to the objective function will convert the constraints into linear function. In this method, the problem is transformed into a single-objective function problem with penalty value. i.e. the multi objective function and the constraints are converted to a linear problem and that can be solved easily using firefly algorithm. Thus the overall utility function of the problem is defined as in the Equation (13).

Maximize U(x) = F(x) + P(x) (13)

The utility function 'U(x)' is to be maximized by maximizing the fitness function value and nullifying the penalty function value. The basic bevel gear parameter used to identify the maximum or optimal value for the fitness function is given in the Equation 14.

B = {Power, Module, Cone distance} (14)

The power transmitting capability of the gear pair should be the maximum, the module determines the size of the gear and should be minimum, and the cone distance determines the size and weight of the gear pair and should be minimum [Madhusudan and Vijayasimha, 1987]. The fitness function 'f(x)' is given in the Equation 1 as combined objective function. To neutralize the penalty value, the identified parameter in the Equation 14 should satisfy the constraints as given in the Equation 15.

*P(x) = {0.3 *D(c), 0.3*M(c), 0.2*Op(c), 0.2*nl(c)}* (15)

Whereas, *D(c), M(c), Op(c) and nl(c)* denotes the design, manufacturing, operational and non-lubrication constraints to be satisfied by the gear pair respectively.

In order to apply the firefly algorithm to the bevel gear design problem, it is necessary to effectively deal with the necessary constraints and the firefly algorithm can directly solve only maximum optimization problems, not minimization problems. So the light intensity or firefly brightness at a particular location can be chosen as analogous or equal to utility function value for the parameters at that location. For this reason, to avoid the violation of constraints, which could cause infeasible solutions, the constrained optimization problem have been converted into an unconstrained problem by penalizing infeasible solutions, instead of repairing them. The solution space constructed is consisting of three stages of input parameters given in the Equation 14 with the interval of 0.001 units. Total number of iterations considered for the search is set to 200 and in each iteration, total number of fireflies allowed to search is 25. In end of every iteration, the best path have been stored and the final iteration will be the search only from the best paths identified by the fireflies, so the search starts to identify the best from the better solutions. The algorithm was developed in Matlab 2008 [On-line Matlab Tutorials] and it can run on a portable computer with an Intel Core2 Duo _1.8GHz_ processor, 2GB RAM memory and MS Windows 7 as an operating system. The firefly control parameters obtained from sensitivity analysis are as follows α = 0.2, γ = 1.0, β0 = 1.0, and n = 25. The main characteristics of the firefly algorithm is the fact that it simulates a parallel independent run strategy, where in every iteration, a swarm of 25 fireflies generated n solutions. Each firefly works almost independently, and as a result the algorithm, will converge very quickly with the fireflies aggregating closely to the optimal solution. The result obtained from the algorithm is at par and the validation also done manually. Thus the performance of the approach found satisfactory both in the computational time and the effectiveness of the result obtained i.e. the algorithm stably converges to the optimal solution very quickly and on average of 100^{th} generation/iteration. This developed algorithm also differs from other approaches in the selection procedure in which each firefly constructs its own solution and 20 % of the fireflies are allowed for the random search to explore more search space apart from initial random search.

From the obtained experimental results, it is observed that the proposed implementation of the firefly algorithm is very fast and predicts accurate results while satisfying conflicting constraints at various levels. It also offers a considerable saving in computer memory and computational time. The algorithm generated the optimal solution in less than 50 seconds. As the best case, the algorithm also identifies the best result in 12 seconds. By comparing the obtained out manually, it is found that the firefly algorithm gives a global optimum in every iteration.

5. CONCLUSIONS AND FUTURE WORK

From the experimental result, it is very clear that the firefly algorithm, developed by Dr. Xin-She Yang, is a very powerful novel population-based method for solving multi-objective constrained optimization problems. As the behavior of fireflies is used to identify the optimal parameters, it is easy to formulate the objective function. In this research, with the focus of identifying the optimal bevel gear parameter values, firefly algorithm had used and the results obtained are satisfactory. The results are obtained in less computational time and the most of the result obtained are the global optimal solution, thus it validates the effectiveness of the algorithm. The algorithm achieved good results in less time with high success rate.

However, from the simulations, it is found that the proper selection of the firefly parameters such as population size, number of generations, absorption coefficient, etc having paramount importance for the convergence. Also these control parameters heavily depends on the nature of the application and vary from problem to problem. So either sensitivity analysis has to be performed or it might be hybridize with other heuristic search methods for better results.

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