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Performance Evaluation of Differential Evolution and Particle Swarm Optimization Algorithms for the Optimal Design of Closed Coil Helical Spring

P.Sabarinath[1], N.B.Karthik Babu[2] M.R.Thansekhar[3], R.Saravanan[3]

K.L.N.College of Engineering, Tamil Nadu , India [1]

K.L.N.College of Engineering, Tamil Nadu, India [2]

K.L.N.College of Engineering, Tamil Nadu, India [3]

Sri Krishna College of Technology, Tamil Nadu, India [4]

ABSTRACT: We consider the design optimization of a closed coil helical spring where the objective is to minimize the weight of the spring. The present situation in the design of machine elements includes the minimization of weight of the individual components in order to reduce the overall weight of the machine elements. It saves both energy and cost involved. The design of mechanical devices imposes the dimensioning of number of common components like shaft, gear, cams etc. Helical compression springs are one among those common components in use for manufacturing of machines. In the present study, minimization of weight of a closed coil helical spring has been investigated. There is a scope for efficient algorithms for the design optimization of machine elements. In recent years, much attention is given to heuristics and search techniques. To solve this problem, we propose Differential Evolution Algorithm (DEA) and Particle Swarm Optimization (PSO) to evolve best values of design variables in order to reduce the weight of the spring. The proposed methods are tested and the performances are evaluated. The computational results show that the proposed algorithms are very competitive for the optimal design of a closed coil helical spring.

KEYWORDS: Optimal design, Helical Spring, Differential Evolution, Particle swarm Optimization.

I. INTRODUCTION

The most important problem that confronts practical engineers is the mechanical design, a field of creativity. The selection of materials and geometry, which satisfies the specified and implied functional requirements while remaining within the confines of inherently unavoidable limitations, is essential. A spring is an elastic body, whose function is to distort when loaded and to recover its original shape when the load is removed. A spring is a mechanical device which is used for efficient storage and release of energy. Generally springs are made up of stainless steel, high carbon steel and alloy spring steels of various grades.

Optimization is a method of finding the best result under the given circumstances. It plays a major role in machine design because the mechanical components are to be designed in an optimal manner. While designing machine elements, optimization helps in a number of ways to reduce material cost, to ensure better service of components, to increase production rate, and many such other parameters. Thus, optimization techniques can effectively be used to ensure both optimal production cost and optimum production rate. Design optimization is the process of finding the maximum or minimum of some parameter, which may be called the objective function and it must also satisfy a certain set of specified requirements called constraints. Many methods have been developed and are in use for design optimization. All of these methods use mathematical programming. One of the most powerful algorithms of evolutionary computation is differential evolution (DE) because of its excellent convergence characteristics and a few control parameters. Only a few parameters are required to be set by the users. Differential evolution is a simple and efficient heuristic originally proposed and shown effective for finding global optima for numerous unconstrained test functions by Storn and Price [1]. Differential evolution is considered one type of evolutionary computational algorithms, which involves the evolution of a population of solutions with size NP using operators such as mutation, crossover, and selection. Particle swarm optimization (PSO) is an evolutionary computation technique developed by Kennedy and Eberhart [2]. The underlying motivation for the development of PSO algorithm was social behavior of animals such as bird flocking, fish schooling, and swarm theory. In this paper, we address the optimal design of closed coil helical spring problem with the objective of minimizing the volume without compromising specified strength. Differential Evolution Algorithm and Particle Swarm Optimization, which are emerging as prominent meta-heuristics, have not been attempted in the past to the design optimization of closed coil helical spring problem. On this concern, this paper proposes DE and PSO algorithms to evolve best values of design variables so as to minimize the weight. The performances of the proposed algorithms are analyzed and also compared with results by other algorithms like GA and published in open literature.

Nomenclature

C Ratio of mean coil dia to wire dia

C_1 Cognitive parameter

C_2 Social parameter

C_f Stress factor

C_R Crossover Constant

d Dia of spring wire, cm

d_{min} Minimum wire dia, cm

D Mean coil dia of spring, cm

D_{max} Maximum outside dia of spring, cm

E Young's modulus, kgf/cm2

F_{max} Maximum Working load, kgf

F_p Pre-load compressive force, kgf

g_{best} Global best

G Shear Modulus, kgf / cm2

K Spring stiffness, kgf / cm

l_f Free length of spring, cm

l_{max} Maximum free length, cm

N_c Number of active coils

N_P Population size

p_{best} Personal best

rand1 Random Number between 0 and 1

rand2 Random Number between 0 and 1

S Allowable shear stress, kgf / cm2

U Volume of spring wire, cm3

v Particle velocity

w Inertia weight

δ_p Deflection under pre-load, cm

δ_t Deflection under maximum working load, cm

δ_{pm} Maximum Deflection under Pre-load, cm

δ_w Deflection from pre-load to maximum load, cm

II. LITERATURE REVIEW

The importance and application of various traditional optimization techniques to solve many real world design optimization problems taken from wide range of industries have been discussed in [3]. The procedure and the necessary steps to design various mechanical elements and transmission elements with design calculations are dealt in [4]. The theory and applications of traditional optimization techniques such as linear and nonlinear programming, dynamic programming, integer programming and stochastic programming along with recently developed techniques such as Genetic Algorithm, Simulated annealing and neural network based fuzzy optimization techniques to solve design optimization problems have been discussed in [5]. Minimization of the fabrication cost of a pressure vessel and weight minimization of helical compression spring having real, integer and discrete variables is attempted using ACO Algorithm in [6]. The problem of optimizing the gear ratio of a gear train and minimizing the fabrication cost of a welded beam subjected to geometric and behaviour constraints is solved using real integer coded PSO Algorithm in [7]. Minimizing power loss associated with hydrodynamic thrust bearing involving four design variables and seven constraints is solved using improved PSO Algorithm in [8]. Since many high-performance power transmission applications (e.g., automotive, aerospace, machine tools, etc.) require low weight, Rao et al [9] solved weight minimization of spur gear drive using PSO and SA Algorithms. Weight minimization of the speed reducer subject to constraints on bending stress of the gear teeth and surface stress is attempted using ABC Algorithm in [10]. It is evident that lot of attempts has been made for single objective design optimization (i.e. Weight minimization) of basic machine elements such as bearings, pressure vessel, gear drives, welded joints, belt drives etc using non-traditional optimization techniques. But very few attempts have been carried out to optimize the design of springs, one of the important and basic machine elements. So in this work, volume minimization of closed coil helical spring is solved. The objective function of minimizing the volume of the spring is taken from [11] in which siddall used some traditional techniques under some constraints to solve the optimal design of closed coil helical spring. The same problem is solved by using a non-traditional optimization technique namely Genetic Algorithm (GA) for getting the solution in [12]. The detailed procedure for the implementation of DE algorithm is presented in [1] and that of for PSO algorithm is presented in [2]. In this research paper, DE and PSO algorithms are used for solving the volume minimization of closed coil helical spring problem.

III. PROBLEM FORMULATION

The helical spring is made up of a wire coiled in the form of a helix which is primarily intended for compressive and tensile load. The cross section of the wire from which the spring is made, may be circular, square or rectangular. Two forms of helical springs are used, namely, compression helical spring and tensile helical spring. The helical springs are said to be closed coiled when the spring wire is coiled so close that the plane containing each turn is nearly at right angles to the axis of the helix and the wire is subjected to torsion. Shear stress is produced in the helical spring due to twisting. The load applied is parallel to or along the axis of the spring.

IV. OBJECTIVE FUNCTION

The optimization criterion is to minimize the volume of a closed coil helical spring as shown in Fig.1 under several constraints.

The volume of spring (U) can be minimized as under subjected to the constraints discussed below

$$U = \frac{\pi^2}{4}(N_c + 2)Dd^2 \tag{1}$$

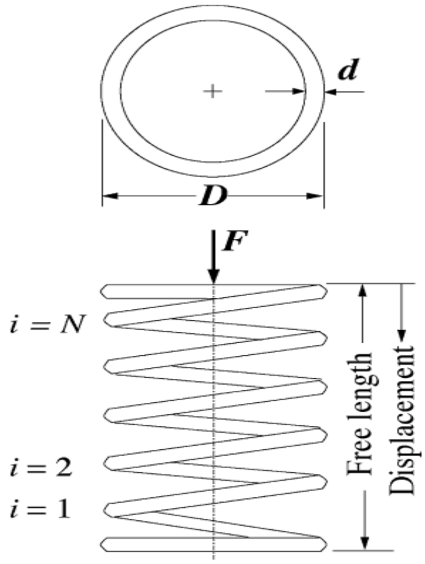

Fig. 1. The closed coil helical spring configuration

V. STRESS CONSTRAINT

The shear stress must be less than the specified value and can be represented as

$$S - 8C_f F_{max} \frac{D}{\pi d^3} \geq 0 \tag{2}$$

Where

$$C_f = \frac{4C-1}{4C-4} + \frac{0.615}{C} \tag{3}$$

$$C = \frac{D}{d} \tag{4}$$

Here the maximum working load F_{max} and allowable shear stress are set to be 453.6 kg and 13288.02 Kgf / cm^2 respectively.

VI. CONFIGURATION CONSTRAINT

The free length of the spring must be less than the maximum specified value.

The spring constant (K) can be determined using the following expression.

$$K = \frac{Gd^4}{8N_c D^3} \tag{5}$$

where shear modulus G is equal to 808543.6 kgf / cm^2.
The deflection under maximum working load is given by

$$\delta_t = \frac{F_{max}}{K} \tag{6}$$

It is assumed that the spring length under F_{max} is 1.05 times the solid length. Thus the free length is given by the expression

$$l_f = \delta_t + 1.05(N_c + 2)d \tag{7}$$

Thus, the constraint is given by

$$l_{max} - l_f \geq 0 \quad (8)$$

Where l_{max} is set equal to 35.56 cm.
The wire dia must exceed the specified minimum value and it should satisfy the following condition

$$d - d_{min} \geq 0 \quad (9)$$

where d_{min} = 0.508 cm.
The outside dia of the coil must be less than the maximum specified and it is

$$D_{max} - (D + d) \geq 0 \quad (10)$$

where D_{max} = 7.62 cm.
The mean coil dia must be at least three times the wire dia to ensure that the spring is not too tightly wound and it is represented as

$$C - 3 \geq 0 \quad (11)$$

The deflection under preload must be less than the maximum specified. The deflection under preload is expressed as

$$\delta_p = \frac{F_p}{K} \quad (12)$$

where F_p = 136.08 kgf.
The constraint is given by the expression

$$\delta_{pm} - \delta_p \geq 0 \quad (13)$$

Where $\delta_{pm} = 15.24 cm$

The combined deflection must be consistent with the length and the same can be represented as

$$l_f - \delta_p - \frac{F_{max} - F_p}{K} - 1.05(N_c + 2)d \geq 0 \quad (14)$$

Truly speaking, this constraint should be equality. It is intuitively clear that at convergence, the constraint function will always be zero.

The deflection from preload to maximum load must be equal to the specified value. These two made an inequality constraint since it should always converge to zero. It can be represented as

$$\frac{F_{max} - F_p}{K} - \delta_w \geq 0 \quad (15)$$

Where $\delta_w = 3.175 cm$

During optimization, the ranges for different variables are kept as follows

$$0.508 \leq d \leq 1.016,$$
$$1.270 \leq D \leq 7.620,$$
$$15 \leq N_c \leq 25$$

Therefore, the above mentioned problem is a constrained optimization problem with a single objective function subjected to eight constraints.

4. Differential Evolution Algorithm

Differential evolution, a stochastic, simple yet powerful evolutionary algorithm, not merely possesses the advantage of a quite few control variables but also performs well in convergence was introduced to solve the global optimization by Storn and Price [1]. DE creates new candidate solutions by perturbing the parent individual with the weighted difference of several other randomly chosen individuals of the same population. A candidate replaces the parent only if it is better than its parent. Thereafter, DE guides the population towards the vicinity of the global optimum through repeated cycles of mutation, crossover and selection.

VII. PSO ALGORITHM

PSO is initialized with a group of random particles (solutions) and then searches for optima by updating generations. In every iteration, each particle is updated by following two “best” values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another “best” value that is tracked by the particle swarm optimizer is the best value, which is the best value obtained so far by any particle in the population. This best value is a global best and called gbest. After finding the two best values, the particle updates its velocity and positions. Eberhart and Shi [13] have introduced an inertia weight factor that dynamically adjust the velocity over time, gradually focusing the PSO into a local search, the particle updates its velocity and positions with the following equations:

v[]=w*v[]+C1*rand()*(pbest[]−present[])+
C2*rand()*(gbest[]−present[]) (16)
present[]=present[]+v[] (17)

Where v[] is the particle velocity, present[ ] is the current particle (solution), pbest[ ] is the Particle’s best, gbest[ ] is the global best, rand ( ) is a random number between (0,1), and C1, C2 are learning factors, and usually, C1= C2 = 2.

VIII. RESULTS AND DISCUSSION

The weight minimization of closed coil helical spring problem is solved by both DE and PSO algorithms. Both the algorithms are implemented using MATLAB 2009 to run on a PC compatible with Pentium IV, a 3.2 GHz processor and 2 GB of RAM (Random Access Memory). In this experiment, to start DE Algorithm, the population size is set to 10, the crossover constant is set to 0.8 and scaling mutation factor is set to 1. To start PSO approach, the population size is set to 20 particles, learning factors are set to 2 and inertia weight w is set based on a gradual decreasing from 0.9 to 0.4 with a linear decreasing rate. Static penalty method is applied for handling the constraints in both the algorithms. A total of 4000 and 2000 fitness function evaluations are made in each run for DE algorithm and PSO algorithm respectively. The programs are executed 20 times to see the convergence characteristics of both DE and PSO algorithms. The convergence of the results obtained by DE algorithm is shown in Fig.2 and that for PSO algorithm is shown in fig.3. The results obtained by the implementation of both the algorithms have been compared with the published results in Table 1. From Table 1, it is evident that the result converges to 45.938589 cm3 after 400 generations for DE algorithm and 45.807305cm3 after 150 generations for PSO algorithm and the best value obtained for both the algorithms is better than the published result of 46.665343 cm3 obtained using GA and slightly better than the published result in open literature i.e., 46.539262 cm3.

In GA approach [12], the population size is 80 and number of generations is 100. So a total of 8000 fitness function evaluations were made with GA approach in each run whereas both DE and PSO Algorithms, implemented in the present work, use only 4000 and 2000 fitness function evaluations respectively in each run. Also the statistical performance of the results obtained by 20 runs using both the algorithms implemented in this work clearly shows that the standard deviation is very small for both the algorithms in the range of 0.001. It clearly indicates that both DE and PSO algorithms performs well for the closed coil helical spring problem with minimum number of function evaluations and converges quickly to the global best solution than GA and graphical methods. The statistical performance of both PSO and DE algorithms implemented in this work has been presented in Table 2. The number of fitness function evaluations is less for PSO algorithm than DEA. It clearly indicates that PSO algorithm performs well for the spring problem with minimum number of function evaluations than DEA.

Table 1. Result using DE and PSO algorithms for Minimization of Weight of Closed Coil Helical Spring

Method	Coil mean Diameter (D) (cm)	wire diameter (k) (cm)	Number of turns (Nc)	Volume of spring (Ws)(cm^3)
DE Algorithm (present work)	2.391912	0.673198	15.192214	45.938589
PSO Algorithm (present work)	2.404994	0.674120	15.003824	45.807305
GA [12]	2.339787	0.670082	16.002046	46.665343
Published Result [11]	2.311400	0.668020	16.286294	46.539262

Table 2. Statistical performance of DE and PSO Algorithms for Closed Coil Helical Spring

Method	Best	Worst	Mean	Standard Deviation	Evaluations
DE Algorithm	45.938589	49.547895	46.547235	0.012845	80000
PSO Algorithm	45.807305	48.214536	46.135247	0.001431	40000

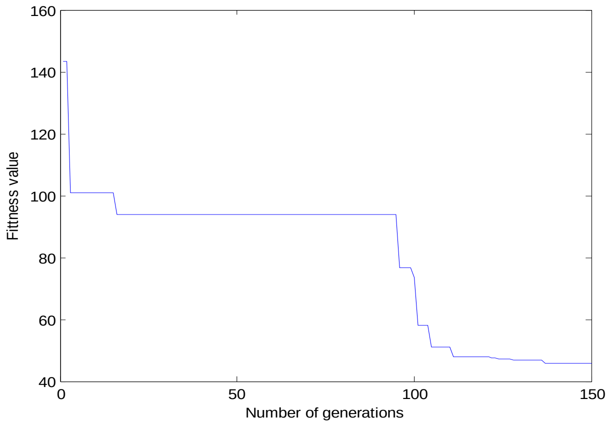

Fig. 2. Evolution of best mean results obtained by PSO algorithm

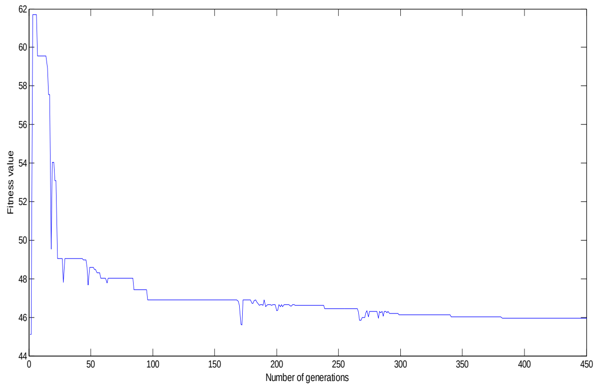

Fig. 3. Evolution of best mean results obtained by DE algorithm

IX. CONCLUSION

In this paper, two heuristic algorithms DE and PSO are proposed and applied to solve engineering design problem i.e., constrained optimization of input parameters to minimize the volume of the closed coil helical spring. The simulation results presented in this paper demonstrate that both the algorithms tested are effective to improve the performance in preventing premature convergence to local minima. Both the proposed algorithms DE and PSO provide better and optimal solution than the results obtained by GA and previously published solutions for this problem. The simulation results show that both the algorithms converge to obtain solutions closer to the good solution and present a small standard deviation. In this work, PSO performs better in terms of accuracy and quicker convergence than DE. Future work will consider improved DE and PSO variants (DEPSO, MODE, QPSO and SADE) and other methods such as ABC, HS, TLBO etc. Furthermore, hill climbing local search can be combined with both DE and PSO algorithms as hybrid technique for constrained problems so that better solutions can be obtained as a future extension of the present work.

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