International Journal of Engineering Technology Science and Research
IJETSR
www.ijetsr.com
ISSN 2394 – 3386
Volume 4, Issue 7
July 2017

Optimum Design for a Composite Hollow Helical Spring By Particle Swarm Optimization

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ABSTRACT
Nowadays strength and weight optimization are increasingly becoming an important factors for manufacturing and mechanical design. This paper aims at maximization of stiffness of hollow helical spring used in light commercial vehicles subjected to certain constraints. Helical springs are long and twisted wire attached to the frame of a trailer that rest above or below the trailer's axle. A formulation and solution technique using Particle swarm optimization (PSO) for design optimization of composite hollow helical spring is presented in this paper. The dimensions of an existing conventional Helical spring of a light commercial vehicle are used to design mono composite carbon epoxy spring which is of great interest to the transportation industry. The design parameters are mean diameter of coil, external diameter of wire, internal diameter of wire and modulus of rigidity. Compared to the steel spring, the composite spring has stresses and deflection that are much lower. It is observed that the composite hollow helical spring is stiffer, lighter and more economical than the conventional steel spring with similar design specifications for given load.

KEYWORDS: Composites, Hollow helical spring, Particle swarm optimization, Steel Spring.

I. INTRODUCTION

The continued integration of stiffer and light weight composites into automotive and transportation industry reduces the weight of vehicle in recent years. [1] Reduction of the weight reduces the amount of fuel it needs and increases the speed it can reach. [2] The suspension Helical spring is one of the crucial suspension elements for weight reduction in automobiles as it accounts for 10-20% of the un-sprung weight. The elements whose weight is not transmitted to the suspension spring are called un-sprung elements of the automobiles. These include wheel assembly, axles and part of the weight of suspension spring and shock absorbers. The introduction of glass fiber reinforced composites made it possible to reduce the weight of suspension helical spring. Some papers are discussed here, with emphasis on those papers that involve composite helical springs. Since, the composite materials have maximum strength, minimum modulus of elasticity and low mass density as compared to those of steel, steel springs are being replaced by helical composite springs.[3] Excellent strength-to-weight ratio can be achieved by using composite materials which offer opportunities for significant weight saving. The resulting weight reduction realized by using composite materials translate into considerable cost savings in terms of fuel. Composite materials also have excellent fatigue resistance and durability. So in this research paper, design of helical composite spring having maximum stiffness is presented.

This paper presents PSO for design optimization of hollow helical spring. Particle swarm optimization is a population based stochastic optimization technique inspired by social behavior of bird flocking and fish schooling. PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). The system is initialized with a population of random solutions and searches for optima by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation.

In PSO, the potential solutions, called particles, fly through the problem space by following the current optimum particles. In the present work, a steel helical spring used in vehicles is replaced with a composite hollow helical spring made of E- Glass epoxy composites. The dimensions and the number of turns for composite helical spring are same as that of steel spring. Our primary objective here is to achieve maximum stiffness by using Particle swarm optimization.

II. LITERATURE REVIEW

Spaggiari et al. [4] contributed to enhance the performance of actuators by proposing a new helical spring with a hollow section. The hollow spring was modeled, then it was constructed, and finally it was tested in compression to compare its performance with those of a spring with a solid cross section of equal strength. Emptied of the inefficient material from the center of the hollow spring featured a lower mass (37% less). Dighewar [5] in his work presented design optimization of spring using genetic algorithm. Attention was focused on reducing the weight and stresses keeping into consideration the various critical points. The spring was designed to operate with tension load, so the spring stretched as the load was applied to it. The aim of the work was to design the extension spring for various materials like steel, stainless steel, music wire (High carbon steel), oil tempered (High carbon steel) for same loading condition, since each material had different compositions and properties. On applying the GA, the optimum parameters of the spring was obtained, which contributed towards achieving the minimum weight. Stoicescu [6] presented the optimal design method of the helical spring of the automobile suspensions according to the criterion of the minimum mass. The coefficients that were necessary to calculate certain helical spring stresses of an automobile suspension were analytically expressed. A nonlinear programming model with constraints was used for the optimal design of an automobile spring suspension for the minimum mass. The spring mass reduced by 16%. P Patel et al. [7] presented optimization of helical spring for minimum weight by using harmony search algorithm. An Artificial phenomenon, musical harmony was used for developing harmony search algorithm. In music the process of searching better harmony was the base of the algorithm. Bakhshesh et al.[8] studied steel helical spring related to light vehicle suspension system under the effect of a uniform loading. Finite element analysis was compared with analytical solution. Afterwards, steel spring was replaced by three different composite helical springs including E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy. Spring weight, maximum stress and deflection were compared with that of steel helical spring and factors of safety under the effect of applied load was calculated. It was found that the change in material of spring caused reduction of spring weight and maximum stress considerably.

III. PROBLEM DEFINITION

A helical spring is a simple form of spring commonly used for the suspension in wheeled vehicles. A helical spring takes the form of a slender arc-shaped. The material used for helical springs is usually a plain carbon steel having 0.90 to 1.0% carbon. Since, the composite materials have maximum strength, minimum modulus of elasticity and low mass density as compared with those of steel, helical steel springs are being replaced by composite springs. Here we are taking three materials Glass Epoxy, Kevlar Epoxy and carbon epoxy respectively. Table 1 and Table 2 shows the various spring materials and their properties and various design parameters for designing helical spring.

Table 1. The composite spring materials used and their Mechanical properties (9,10,11).

Material	Modulus of Elasticity Gpa (E)	Shear Modulus Gpa (G)	Ultimate Strength Mpa (S_{ut})	Yield Torsional Strength Mpa (S_y)	Endurance Torsional Strength Mpa (S_e)
Glass Epoxy	37.63	20	880	352	176
Kevlar Epoxy	70.83	17.5	1175	470	235
Carbon Epoxy	111.67	35	1058	423	212

Table 2. The Various design parameters for designing the helical spring.

Parameters	Range
Mean coil diameter	80mm-120mm
Outer diameter of spring wire	15mm
Inner diameter of spring wire	5mm-8mm
Maximum design load F_{max}(N)	4000
Minimum designed load F_{min}(N)	3000
Number of turns	8-12

IV. OBJECTIVE FUNCTION

The objective of this paper is to arrive at the maximization of stiffness of the hollow helical spring. The objective, identified for the study is given as shown in Equation 1.

Spring stiffness : $K = \frac{G(d_o^4 - d_i^4)}{8ND^3}$ (1)

Where G is the modulus of rigidity of composite material, D is the mean diameter, N is the number of turns, d_o is the outer diameter of the wire, d_i is the inner diameter of the wire.

V. DESIGN CONSTRAINTS

To design the spring, certain constraints are being put on this model.

1) Stresses in Spring

In some applications, spring is used for millions number of cycles such as in automotive engine, cam and follower etc. so spring is subjected to variable stresses and there is large chances of fatigue failure and we must check for fatigue and variable stresses, if F_{max} and F_{min} are respectively the maximum force and minimum force applied on spring then equations 2-6 are used for design of spring [9].

$$F_a = \frac{F_m \quad - F_m}{2} \quad (2)$$

$$F_m = \frac{F_m \quad + F_m}{2} \quad (3)$$

$$\tau_a = K_w \times \frac{8F_a D}{\pi d^3} \quad (4)$$

$$\tau_m = K_s \times \frac{8F_m D}{\pi d^3} \quad (5)$$

$$K_w = \frac{4C-1}{4C-4} + \frac{.6 \quad D}{D} \quad (6)$$

$$Whe \quad K_s = 1 + \frac{1}{2C}$$

Where F_m is mean force, F_a is force amplitude, K_s is shear correction factor and K_w is Wahl correction factor.

τ_a and τ_m are stresses produced for Fa and Fm respectively. Factor of safety for helical spring should be greater than and equal to 1.5 and is given by Equation.7

$$\frac{S_y S_e}{\tau_m S_e + \tau_a S_y} \leq f \quad (7)$$

2) Condition of Coil Gap

In helical spring, when the force is applied on the spring then spring compresses but the coil must not touch under maximum load condition so different length of spring according to end condition and number of end coils are given by Table 3.

Table 3. Different lengths of spring according to end condition and number of end coils.

Term	Plain	Plain and Ground	Square and Closed	Square and Ground
End Coils	0	1	2	2
Total Coils, N_t	N	N+1	N+2	N+2
Solid Length, L_s	$D_o(N_t+1)$	$D_o(N_t)$	$d_o(N_t+1)$	$d_o(N_t)$
Free Length, L_f	$L_s+\delta_{max}+\delta_{allowance}$	$L_s+\delta_{max}+\delta_{allowance}$	$L_s+\delta_{max}+\delta_{allowance}$	$L_s+\delta_{max}+\delta_{allowance}$

In the above nomenclature for the spring, N is the number of the active coils, i.e., only these coils that take part in the spring action. However, few other coils may be present due to manufacturing consideration, thus total number of coils, N_t may vary from total number of active coils.

Solid length, L_s is that length of the spring, when compressed , all the spring coils will clash with each other and will appear as a solid cylindrical body.

Free length L_f , is the spring length under no load condition is the free length of a spring.

Maximum amount of compression the spring can have is denoted as δ_{max} , which is calculated from the design requirement. The addition of solid length and the δ_{max} should be sufficient to get the free length of a spring. However, designers consider an additional length given as $\delta_{allowance}$. This allowance is provided to avoid clash between two consecutive spring coils. As a guideline, the value of $\delta_{allowance}$ is generally taken as 15% of δ_{max}.

$$L - L_s \leq \delta_{max}. \quad (8)$$

3) Condition of Buckling

Buckling is also a problem, it depends on ratio of free length of spring to coil diameter of spring and if we increase the length of spring and uses as a compressive spring then there will be high chances of buckling so ratio must be maintained and given by Equation 9.

$$L - \frac{\pi}{\alpha} \times \sqrt{\frac{2(E-G)}{2G+E}} \leq 0 \quad (9)$$

Where α, E, G are End condition constant, Young's modulus and Modulus of rigidity respectively.

VI. PENALTY FUNTIONS

Constraints can be handled by Penalty function method. In the penalty function method, the constrained optimization problem is solved as unconstrained optimization method by incorporating the constraints into the objective function thus transforming it into an unconstrained problem.

Penalty function techniques are usually used in evolutionary algorithms for constrained optimization problem. The penalty function combines the constraints with the objective function by adding the penalty value to the infeasible solution.

PROPOSED CONSTRAINT HANDLING METHOD

The proposed method belongs to both second and third categories of constraint handling methods described by Michalewicz and Schoenauer [12]. Although a penalty term is added to the objective function to penalize infeasible solutions, the method differs from the way the penalty term is defined in conventional methods.

In this method the following criteria[13] are enforced:

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www.ijetsr.com
ISSN 2394 – 3386
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(1) Any feasible solution is preferred to any infeasible solution,

(2) Among two feasible solutions, the one having better objective function value is preferred,

(3) Among two infeasible solutions, the one having smaller constraint violation is preferred.

Although there exist a number of other implementations [14,15,16] where criteria similar to the above are imposed in their constraint handling approaches, all of these implementations used different measures of constraint violations which still needed a penalty parameter for each constraint.

Penalty parameters are needed to make the constraint violation values of the same order as the objective function value. In the proposed method, penalty parameters are not needed because in any of the above three scenarios, solutions are never compared in terms of both objective function and constraint violation information. Of the three cases mentioned above, in the first case, neither objective function value nor the constraint violation information is used, simply the feasible solution is preferred. In the second case, solutions are compared in terms of objective function values alone and in the third case, solutions are compared in terms of the constraint violation information alone. Moreover, the idea of comparing infeasible solutions only in terms of constraint violation has a practical implication. In order to evaluate any solution, it is a usual practice to first check the feasibility of the solution. If the solution is infeasible (that is, at least one constraint is violated), the designer will never bother to compute its objective function value. It does not make sense to compute the objective function value of an infeasible solution, because the solution simply cannot be implemented in practice.

Motivated by these arguments, fitness function is given by Equation 10 where infeasible solutions are compared based on only their constraint violation:

$$F(x) = \begin{cases} f(x) & i\ \left(g_j(x)\right) \leq 0 \forall j = 1,2,\ldots\ldots\ldots..,m \\ f_m \ - \sum_{j=0}^{m} a \ \ (g_j(x)), & o\ he \end{cases} \quad (10)$$

The fitness function F(x) is defined as the sum of the objective function f(x) and a penalty term which depends on the constraint violation $a \ \ (g_j(x))$, where abs denote the absolute value of the operand, if the operand is negative and returns a value zero.

The parameter f_{min} is the objective function value of the worst feasible solution in the population. Thus the fitness of an infeasible solution not only depends on the amount of constraint violation, but also on the population of solution at hand.

However, the fitness of a feasible solution is always fixed and is equal to its objective function value.

VII. DESIGN VARIABLES

The design variables chosen for the present problem are:

(1) mean diameter of the coil, D

The value of stiffness will increase as the value of D increases.

(2) inner diameter of the spring wire, d_i

(3) number of turns, N

VIII. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization (PSO) proposed by Dr. Eberhart and Dr. Kennedy [17] is based on global optimization evolutionary algorithm. Particle swarm optimization (PSO) is a social-psychological model of social influence and social learning, inspired by the social behavior of bird flocking or fish schooling. A PSO algorithm maintains a swarm of particles, where each particle represents a potential solution. In analogy with evolutionary paradigms, a swarm is similar to a population, while a particle is similar to an individual. In simple terms, the particles are flown through a multidimensional search space, where the position of each particle is adjusted according to its own experience and that of its neighbors.

After finding the two best values, the particle updates its velocity and positions as given by Equations 11 and 12:

$$V_{new}=w\times V_{old}+C_1\times(rand_1)\times(p_{best}-x_{old})+C_2\times(rand_2)\times(g_{best}-x_{old}) \quad (11)$$

$$x_{new}=x_{old} + V_{new} \quad (12)$$

where

w - Inertia weight

V_{new} - New velocity calculated for each particle

V_{old} - Velocity of the particle from the previous iteration

x_{new} - New position calculated for each particle

x_{old} - Position of the particle from the previous iteration

C_1&C_2 - Cognitive and social acceleration constants

rand - Generates random value in the range [0 1]

p_{best} - Personal best position stored.

g_{best} - Best position of particle in the population.

IX. RESULTS AND DISCUSSION

The design problem here is to design a hollow composite spring with maximum stiffness. The design parameters such as number of turns of spring and load are same as that of the conventional steel helical spring. A computer program using MATLAB is developed to perform the optimization process, and to obtain the best possible design. Table 4. shows the input parameters for composite spring used by us. Particle swarm optimization (PSO) technique is used to determine the best combination of our design variables.

Table 4: Design parameter of helical spring

Parameters	Range
Mean coil diameter	80mm-120mm
Outer diameter of spring wire	15mm
Inner diameter of spring wire	5mm-8mm
Number of turns	8-12

By the stiffness formula it is clearly seen that stiffness of the spring mainly depends upon the mean coil diameter, outer diameter of the coil, inner diameter of the coil, modulus of rigidity etc. Range is constituted of lower bound and upper bound. Hence the optimized value would come within this range and these values are given in the Table 5.

Table 5: Parameters obtained by PSO

Material	Iteration	D	Turns(n_o)	d_i	K
Glass Epoxy	5000	*80*	12	8mm	18.93 N/mm
Kevlar Epoxy	5000	*99.035*	12	8mm	8.732 N/mm
Carbon Epoxy	5000	*82.532*	8	5mm	48.645 N/mm

From the Table 5 it is seen that the value of stiffness of the spring is least for the Kevlar Epoxy and maximum for the Carbon epoxy composites. Hence from the stiffness values it is clear that the Carbon epoxy composite materials have better stiffness compare to Glass Epoxy and Kevlar Epoxy.

Figure 6.1, Figure 6.2 and Figure 6.3 shows the value of fitness function v/s number of iteration for Glass Epoxy, Kevlar Epoxy and Carbon Epoxy.

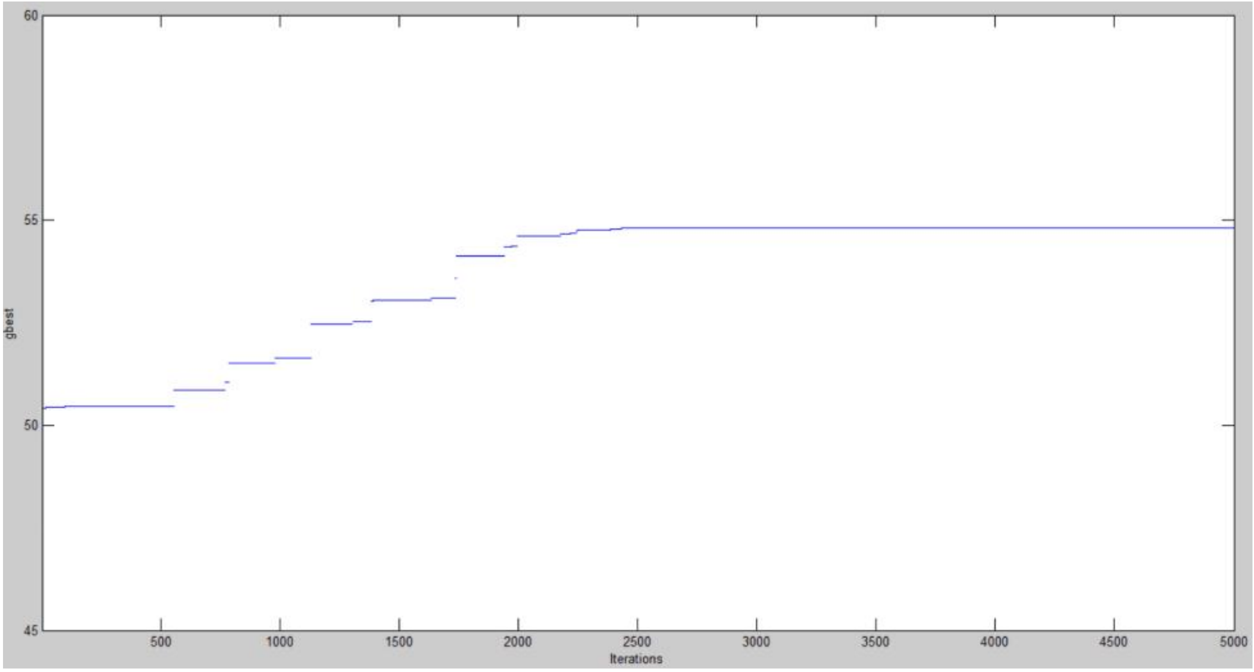

Figure 2: Fitness value v/s number of iteration for Glass Epoxy

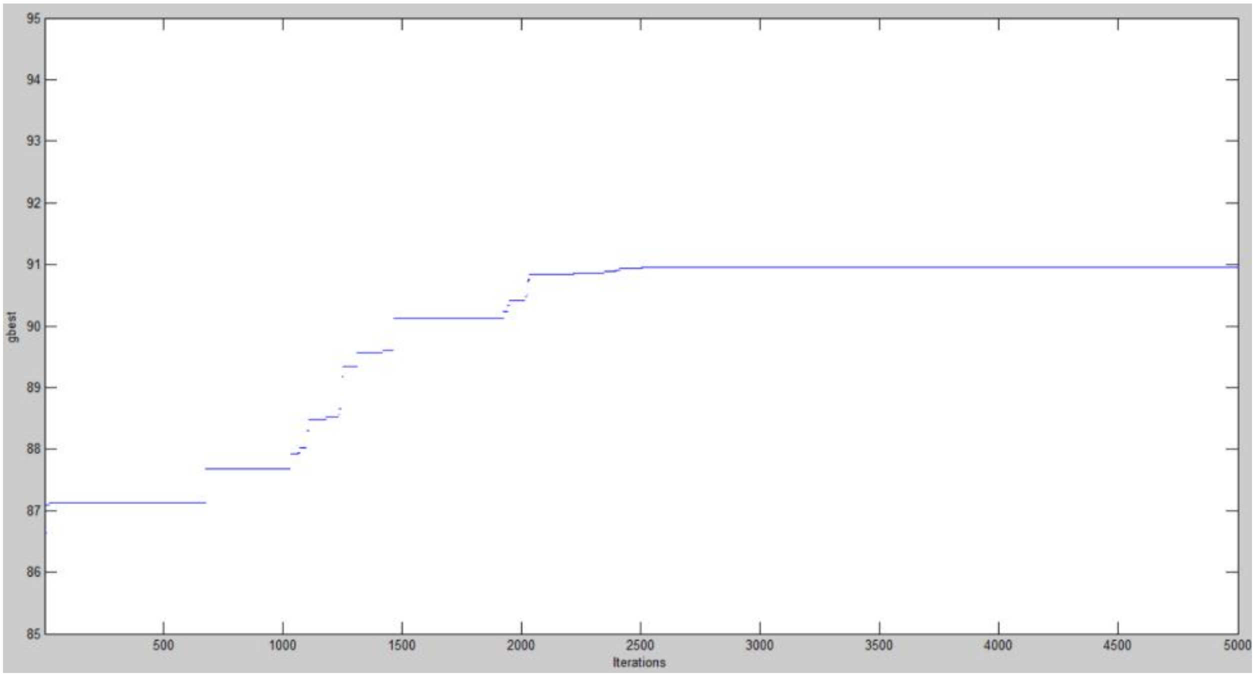

Figure 3: Fitness value v/s number of iteration for Kevlar Epoxy

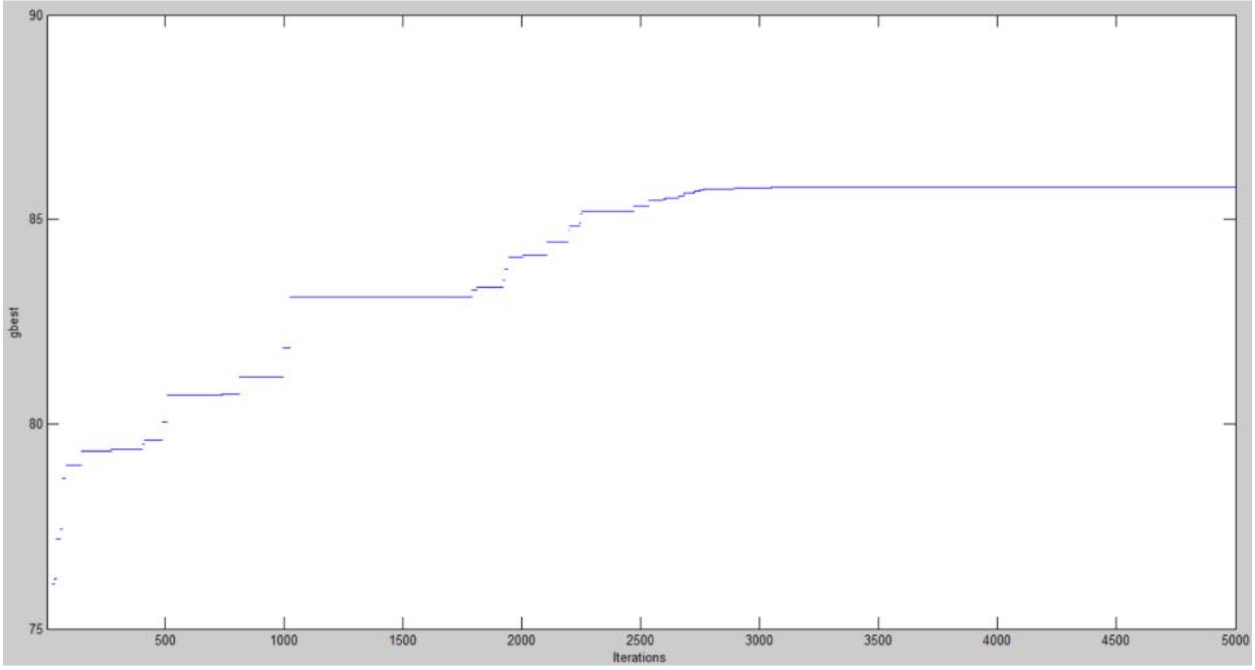

Figure 4: Fitness value v/s number of iteration for Carbon Epoxy

X. CONCLUSION

In spring optimization problem, maximizing the stiffness was our objective. By running the program, following conclusions are made:

1. This algorithm does not require gradient information of the objective function, which makes it very attractive.

2. In PSO, it has been found that introduction of velocity bounding and inertia weight is extremely important to ensure convergent behavior.

3. Particle Swarm optimization is a powerful non-traditional optimization technique used for optimizing the composite helical spring for maximization of stiffness and the value of stiffness comes out to be 48.645 N/mm for the composite carbon epoxy.

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