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Parameter Optimization of Composite Leaf Spring Using TLBO Algorithm

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ABSTRACT

Leaf springs are commonly used in the suspension system of automobiles and are subjected to millions of varying stress cycles leading to fatigue failure. The suspension system in an automobile significantly affects the behaviour of vehicle, i.e. vibrational characteristics including ride comfort, directional stability, etc. If the unsprung weight is reduced then fatigue stress induced in the leaf spring is also reduced. Leaf spring contributes for about 10-20% of unsprung weight. Hence even a small amount of weight reduction in leaf spring will lead to a passenger comfort as well as reduction in vehicle cost. The replacement of steel by composite material along with an optimum design will be a good contribution in the process of weight reduction of leaf spring. Various methods are used design optimization, most of which use mathematical programming techniques. In this paper, we are representing Teaching and Learning Base Optimization (TLBO) as a formulation and solution technique. By applying TLBO, the optimum dimensions of leaf spring have been obtained, which contribute towards achieving the minimum weight with adequate strength and stiffness. A reduction of 77.5% weight is achieved when a multi-leaf spring is replaced by mono-leaf composite spring under identical conditions of design parameters and optimization by TLBO Algorithm.

***Keywords*— Optimization, Teaching and Learning Base Optimization (TLBO), Composite material, Leaf spring, Automobiles, Weight reduction**

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I. INTRODUCTION

In order to conserve natural resources and economize energy, weight reduction has been the main focus of automobile manufacturer in the present scenario. Weight reduction can be achieved primarily by the introduction of better material, better design, by using optimization technique and by using better manufacturing processes. Suspension leaf spring is one of the potential items for weight reduction in automobile as it accounts for ten to twenty percent of the unsprung weight. The elements whose weight is not transmitted to the suspension spring are called the unsprung elements of the automobile. These include wheel assembly, axles, and part of the weight of suspension spring and shock absorbers [1, 2]. As the more numbers of failure are occurring in the leaf spring so there is a need of using a better material than the conventional material and the reduction of unsprung weight so that it will give more strength to weight ratio. This helps in achieving the vehicle with improved riding qualities. It is well known that springs, are designed to absorb and store energy and then release it. Hence, the strain energy of the material becomes a major factor in designing the springs. The relationship of the specific strain energy can be expressed as

$$\mathbf{U} = \frac{\sigma^2}{2\rho E} \quad (1)$$

where, σ is strength, ρ is density and E is Young's modulus of spring material. It can be easily observed that material having lower modulus and density will have a greater specific strain energy capacity. The introduction of composite materials was made it possible to reduce the weight of the leaf spring without any reduction on load carrying capacity and stiffness [1, 3, & 5]. Since; the composite materials have more elastic strain energy storage capacity (1) and high strength-to-weight ratio as compared to those of steel.

By considering the above parameter the composite material is selected for design of leaf spring that is unidirectional Glass Fibre/Epoxy. FRP springs also have excellent fatigue resistance and durability. Fibre-reinforced plastics are best suited for any design problem that demands weight savings, precision engineering, finite tolerances, and the simplification of parts in both production and operation, multi-leaf steel springs are being replaced by mono-leaf FRP springs [2, 4].

I. SELECTION OF OPTIMIZATION ALGORITHM

Some well known meta-heuristic algorithms developed during the last three decades are [6]:
Genetic Algorithm (GA) which works on the principle of the Darwinian theory of the survival of the fittest and the theory of evolution of the living beings [7]; Artificial Immune Algorithm (AIA) which works on the immune system of the human being [8]; Ant Colony Optimization (ACO) which works on the foraging behaviour of the ant for the food [9]; Particle Swarm Optimization (PSO) which works on the foraging behaviour of the swarm of birds [10]; Differential Evolution (DE) which is similar to GA with specialized crossover and selection method [11]; Harmony Search (HS) which works on the principle of music improvisation in a music player [12]; Bacteria Foraging Optimization (BFO) which works on the behaviour of bacteria [13]; Shuffled Frog Leaping (SFL) which works on the principle of communication among the frogs [14], Artificial Bee Colony (ABC) which works on the foraging behaviour of a honey bee [15]; Biogeography-Based Optimization (BBO) which works on the principle of immigration and emigration of the species from one place to the other [16]; Gravitational Search Algorithm (GSA) which works on the principle of gravitational force acting between the bodies [17]; Grenade Explosion Method (GEM) which works on the principle of explosion of a grenade [18].

These algorithms have been applied to many engineering optimization problems and proved effective to solve some specific kind of problems, [6-20]. All the above mentioned algorithms are nature-inspired population based optimization methods, but they have some limitation in one or the other aspect. The main limitation of all the algorithms mentioned above is that different parameters are required for proper working of these algorithms. Proper selection of the parameters is essential for the searching of the optimum solution by these algorithms. A change in the algorithm parameters changes the effectiveness of the algorithm. GA requires crossover probability, mutation rate, and selection method; PSO requires learning factors, variation of weight, and maximum value of velocity; ABC requires number of employed bees, onlooker bees and value of limit; HS requires harmony memory consideration rate, pitch adjusting rate, and number of improvisations: SFL algorithm requires number of memeplexes, iteration per memeplexes; ACO requires exponent parameters, pheromone evaporation rate and reward factor. Therefore, the effort must be continued to develop an optimization technique which is free from the algorithm parameters, i.e. no algorithm parameters are required for the working of the algorithm, by considering this aspect the TLBO algorithm is selected in the present work. The TLBO method has used to solved various complicated problems like continuous non-linear large scale problems [21], constrained mechanical design [6, 22], Parameter Optimization of Machining Processes[23], Design of planar steel frames [24], Parameter optimization of modern (non- Traditional) machining processes [25] and given effective solutions.

II. TEACHING–LEARNING-BASED OPTIMIZATION

An efficient optimization method called “Teaching–Learning-Based Optimization” (TLBO) is propose in this paper for parameter optimization composite leaf spring for finding the global solutions with less computational effort and high consistency. TLBO proposed recently by Dr. R. V. Rao et al. (2011), [6] based on the effect of the influence of a teacher on the output of learners in a class. The TLBO method works on the philosophy of teaching and learning. For TLBO, the population is considered as a group of learners or a class of learners. In optimization algorithms, the population consists of different design variables. In TLBO, different design variables will be analogous to different subjects offered to learners and the learner’s result is analogous to the ‘fitness’ of objective function, as in other population based optimization techniques. The teacher is considered as the best solution obtained so far.

The process of working of TLBO is divided into two parts. The first part consists of ‘Teacher Phase’ and the second part consists of ‘Learner Phase’. The ‘Teacher Phase’ means learning from the teacher and the ‘Learner Phase’ means learning through the interaction between learners.

A. Teacher Phase

As shown in Fig. 1, mean of a class increases from M_A to M_B depending upon a good teacher. A good teacher brings his or her learners up to his or her level in terms of knowledge. But in practice this is not possible and a teacher can only move the mean of a class up to some extent depending on the capability of the class. This follows a random process depending on many factors.

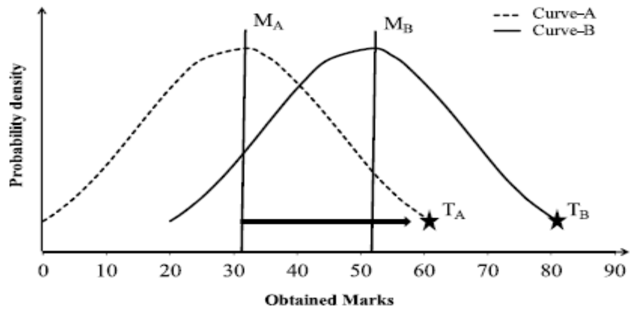

Fig. 1 Model for obtained marks distribution for a group of learners.

Let, M_i be the mean and T_i be the teacher at any iteration i. T_i will try to move mean M_i towards its own level, so now the new mean will be T_i designated as M_{new}. The solution is updated according to the difference between the existing and the new mean given by

$$\text{Difference\_Mean}_i = r_{i*} (M_{new} - T_F * M_i)$$

T_F (Teaching factor) is decides the value of the mean to be changed, and r_i (Random number) is in the range [0, 1].The value of T_F can be either 1 or 2 which is again a heuristic step and decided randomly with equal probability as T_F = round[1 + rand(0,1){2 - 1}]

This difference modifies the existing solution according to the following expression

$X_{new,i} = X_{old,i} + Difference\_Mean_i$

B. Learner Phase

Learners increase their knowledge by two different means: one through input from the teacher and other through interaction between themselves. A learner interacts randomly with other learners with the help of group discussions, presentations, formal communications, etc.

A learner learns something new if the other learner has more knowledge than him or her. Learner modification is expressed as,

For i = 1: Pn

Randomly select another learner X_j, such that $i \neq j$

If $f(X_i) < f(X_j)$

$X_{new,i} = X_{old,i} + r_i*(X_i - X_j)$

else

$X_{new,i} = X_{old,i} + r_i*(X_j - X_i)$

Accept X_{new} if it gives a better function value.

The flow chart for the TLBO method is given in Fig. 2.

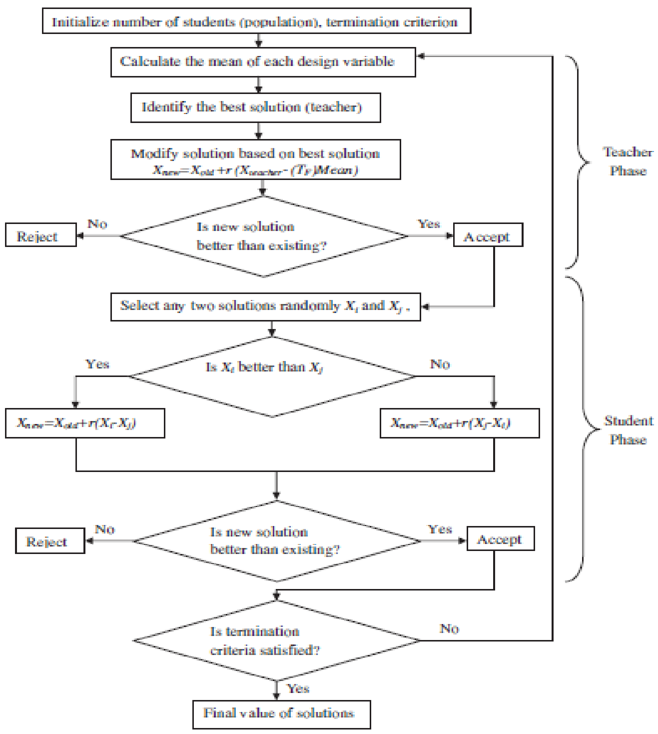

Fig. 2 Flow chart shows the working of TLBO algorithm.

IV. DESIGN OF COMPOSITE LEAF SPRING

Considering several types of vehicles that have leaf springs and different loading on them, the various kinds of composite leaf spring have been developed. It has been studied that in multi-leaf composite leaf spring the interleaf spring friction plays a spoil spot in damage tolerance. Flexural rigidity is an important parameter in the leaf spring design, and it should increase from two ends of the spring to its centre. This idea gives different design possibilities of mono-leaf composite spring for manufacturing easiness are considered.

1. Constant thickness, constant width design.
2. Constant thickness, varying width design.
3. Varying width, varying thickness design.

The constant cross-section design is selected due to its capability for mass production, and to accommodate continuous reinforcement of fibres. The design of composite leaf spring aims at the replacement of multi-leaf steel spring of an automobile with a mono-leaf composite spring. The design requirements are taken to be identical to the existing steel leaf spring [1]:

- Design load, W = 4500 N.
- Maximum allowable vertical deflection, d_{max}=160 mm.
- Distance between eyes in straight condition, L =1220 mm.
- Spring rate, K = 28-32 N/mm.

A. Benefits of design optimization over conventional design

Whatever may be the geometric variation of the leaf spring, it is desirable that the leaf spring is designed to have minimum weight. This should be compatible with the other requirements of a particular suspension to keep the vehicle weight to a minimum. It is desirable for a suspension to provide the required deflection to enhance cushioning ability together with adequate rigidity. Therefore, the common goal in designing a leaf spring is to obtain the lightest spring under the given functional and geometrical constraints (load, spring rate, camber and desired length). The conventional design method for leaf spring is by "trial and error". This process depends on the designer's intuition, experience and skill. He selects the design parameters and checks whether these satisfy the design constraints. If not, he changes these parameters till the desired result is achieved, which is a tedious exercise & time consuming process [1, 2].

It is therefore a challenge for the designers to design efficient and cost-effective systems. The ability to bring the highest quality products to the market within the shortest lead-time is becoming highly necessary. Scarcity and need for efficiency in today's competitive world has forced designers to evince greater interest in economical and better designs. The design optimization of the leaf spring aims at minimizing the weight of leaf spring subjected to certain constraints. In general, there will be more than one acceptable design and the purpose of design optimization is to choose the best one out of the many alternatives available. An attempt has been made by S. Vijayarangan et al. to develop a powerful and efficient computer program using c language to design a minimum weight leaf spring. Here, the multi leaf steel spring has constant leaf thickness and leaf width along the length. The mono-leaf composite spring has varying thickness & width along the length, but maintains a constant cross-sectional area. [1, 2]

B. Problem Formulation for TLBO Algorithm

The purpose of the formulation is to create a mathematical model of the optimal design problem, which can be solved using an optimization algorithm i.e. TLBO. Optimization problem must be formulated as per the format of the algorithm. The problem formulation for steel leaf spring is reported by S. Vijayarangan, et al. in the article [6]. As well as Problem formulation of composite leaf spring for GA is reported by S. G. Shiva Shankar, et al. in the article [2]. Hence, here the problem formulation of composite leaf spring for only TLBO algorithm is given as below.

- Objective function:

The main objective is to minimize the weight of the Composite mono-leaf spring with the prescribed strength and stiffness. The objective function identified for the leaf spring problem is given below:

$$f(w) = \rho L b t \quad (2)$$

where, ρ is the material density, t is thickness at centre, b is the width at centre and L is the length of the leaf spring. The double tapered composite leaf spring is designed based on the constant cross-section area. Hence, centre thickness and centre width is considered for optimization. The end thickness and end width can be determined based on the taper ratio. The constant cross section area ensures that the fibres pass continuously without any interruption along the length. This is advantageous to the FRP structures. Moreover, higher efficiency with low level of shear stress can be obtained using this shape [1].

- Design variables:

A design problem usually involves many design parameters, of which, some are highly sensitive. These parameters are called design variables in the optimization procedure. In the present problem, the following variables are considered: (1) centre width, b and (2) centre thickness, t.

The upper and lower bound values of design variables are given as follows:

b_{max} = 50 mm and b_{min} = 20 mm.

t_{max} = 50 mm and t_{min} = 10 mm.

- Design parameters:

Design parameters usually remain fixed in relation to design variables. Here, the design parameters are length of leaf spring, L. design load, W, material properties- (i) density, ρ, (ii) modulus of elasticity, E and (iii) maximum allowable stress, S_{max}.

- Design constraints:

Constraints represent some functional relationships between design variables and other design parameters, which satisfy certain physical phenomenon and resource limitations. In this problem, the constraints are the bending stress, S_b, vertical deflection, d & spring rate, K.

$$S_b = \frac{1.5\,WL}{bt^2} \quad (3)$$

$$d = \frac{WL^3}{4Ebt^3} \quad (4)$$

$$K = \frac{W}{d} \quad (5)$$

$$FOS = \frac{S_{max}}{S_b} \quad (6)$$

When considering both static and fatigue behaviour of composite leaf spring, the factor of safety (FOS) is taken as 2.5, [1]. The upper and lower bound values of constraints are given as follows:

S_{bmax} = 48O MPa, S_{bmin} = 400 MPa,

d_{max} = 160 mm, d_{min} = 120 mm,

K_{max}= 32 N/mm, K_{min}=28 N/mm,

- Computer Program:

Computer program using MATLAB R2010a has been developed to perform the optimization process, and to obtain the best possible design parameter for composite leaf spring. The approach consists of minimizing the weight of composite leaf spring with required strength and stiffness.

V. RESULT AND DISCUSSION

The procedure described in the previous sections has been applied to the design of minimum weight double tapered composite leaf spring to replace the multi-leaf steel spring. The design parameters such as distance between spring eyes, camber, spring rate and load are kept as same in both steel and composite leaf springs. The input parameters used in this work are listed in Table 1. The geometric models of steel and composite leaf springs considered for optimization are shown in Fig. 3. The number of leaves in steel spring is fixed as seven and all leaves have the same thickness and width. By applying GA procedure, optimization is performed by I. Rajendran, et al. to decide the best possible combination of thickness and width of the leaves of steel spring by satisfying the above said constraints [6]. The same procedure has been carried out to determine the optimum centre thickness and centre width of mono-leaf composite spring in the article [1] and results of both the cases shown in Table 2. Also the optimum design parameter values of present work by using TLBO algorithm are mention in Table 2.

Table 1
Input parameters of composite leaf spring (for TLBO)

Parameters	**Composite Spring**
Spring Length under straight condition (mm)	1220
Arc height at axle seat (Camber) (mm)	160
Modulus of Elasticity of material (MPa)	$32.5*10^3$
Material Density (Kg/m^3)	2600
Load (N)	4500
Maximum allowable Stress (MPa)	1200

It has been clearly observed that TLBO algorithm gives the best solution (optimal value of width and thickness) than GA for given constraints, so it gives minimum weight of composite leaf spring than GA. In TLBO algorithm during the process of search for optimum, the variation of design variables in each generation for composite leaf spring are shown in Figs. 4 and 5, as TLBO search global solution randomly, Hence the variables are highly fluctuated during initial generations, after that it reduced and then it converges to optimum value, due to the improvement of solution in Teacher phase & Learner phase of the algorithm. Figs. 6, 7 & 8 shows the variation in constraints (stress, deflection & spring rate) of composite leaf spring with number of generation during TLBO algorithm search. It is observed that the constraints are fluctuating only in initial generations and the values are within the maximum limits. Fig. 9 shows the fluctuation in weight of the composite leaf spring with generations only in initial generation then it constant after 30-40 generations.

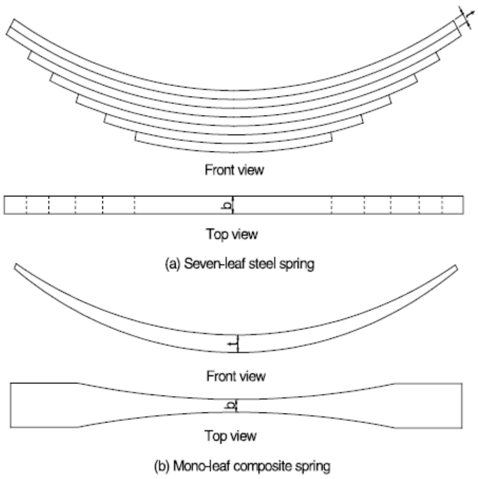

Fig. 3 Model of Steel and Composite Spring

Table 2
Optimal design values of steel and composite leaf spring by GA & TLBO

Parameters	Steel Spring	Composite Spring	
		GA	TLBO
Width (mm)	35.25 (each leaf)	28.475	25.275
Thickness (mm)	6.55 (each leaf)	25.015	26.05
Maximum Stress (MPa)	799.52	462.17	480.00
Maximum Deflection (mm)	144.10	141.03	140.625
Spring Rate (N/mmm)	31.23	31.91	32.00
Estimated weight (Kg)	8.54	2.26	2.088

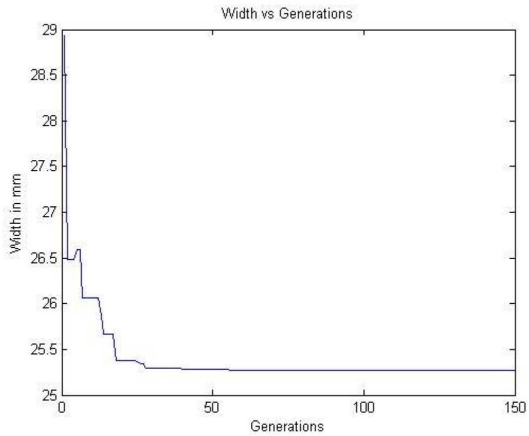

Fig. 4 variation of Width Vs generation for composite leaf spring

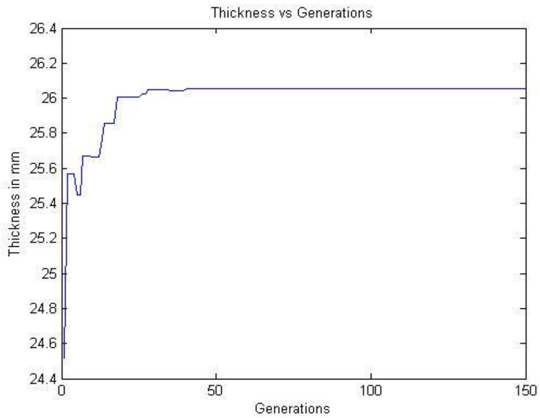

Fig. 5 variation of Thickness Vs generation for composite leaf spring

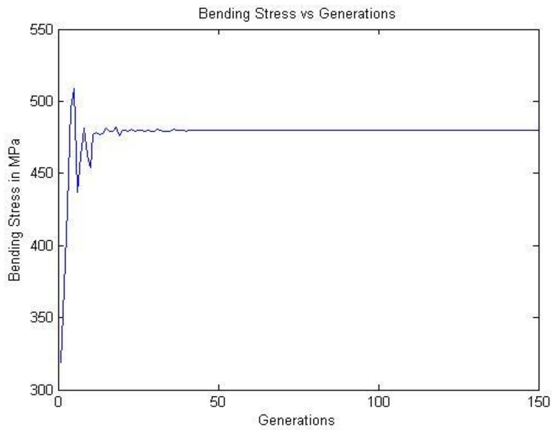

Fig. 6 variation of Bending Stress Vs generation for composite leaf spring

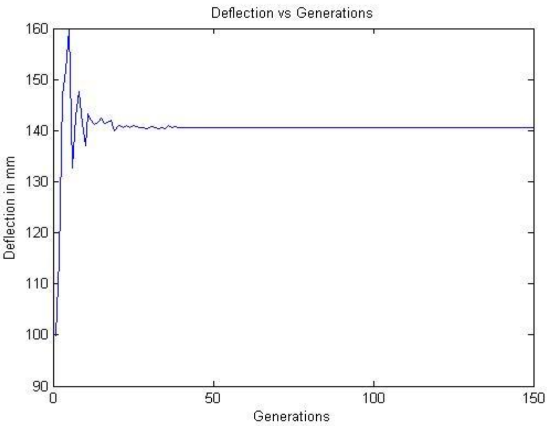

Fig. 7 variation of Deflection Vs generation for composite leaf spring

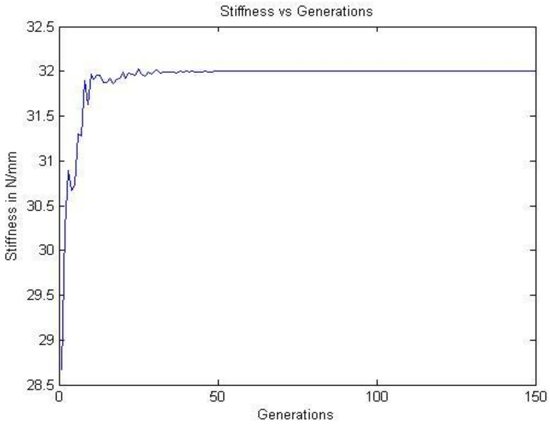

Fig. 8 variation of stiffness Vs generation for composite leaf spring

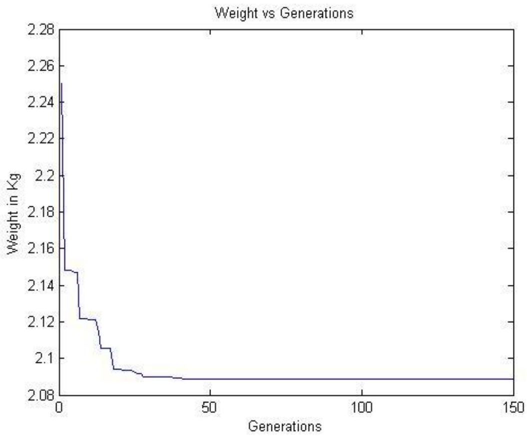

Fig. 9 variation of weight Vs generation for composite leaf spring

The initial design of steel leaf spring had a weight of 9.28 Kg [1]. After replacing steel spring with composite spring & design parameter optimization of composite leaf spring by TLBO algorithm, the final weight is 2.088 Kg. It observed that the overall reduction in weight is 77.5% (when optimized composite spring is considered in comparison with conventional steel spring). During this process of weight reduction, adequate strength, deflection and stiffness requirements are kept as constraints. The automotive suspension leaf spring contributes for about 10-20% of unsprung weight. If the unsprung weight is reduced, then the stress induced is also reduced. Hence, even a small amount of weight reduction in leaf spring will lead to improvements in passenger comfort as well as reduction in vehicle cost. In the present study, 77.5% of existing spring weight is reduced. This heavy reduction of leaf spring weight will improve the performance of the vehicle in all respects.

VI. Conclusions

1. It is observed that it is easy and beneficial to use the non-traditional method than the traditional design method.
2. TLBO algorithm gives the best solution as compare with the GA solution.
3. In the present work, optimization using TLBO has contributed to the overall weight reduction of 77.5%.
4. It is observe that optimization using TLBO algorithm leads to larger weight reduction due to the search of global solution.
5. This result are encouraging and suggest that TLBO algorithm can be used effectively and efficiently in order to find out the optimal solution for other complex and constrained engineering problems.
6. It is observed that the use of composite material leads to great contribution in weight reduction without affecting the load carrying capacity of leaf spring, so it suggest that the use of composite material can be beneficial for other engineering component.

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