Weight Optimization of Mono Parabolic Leaf Spring

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***Abstract*— Now a days for the automotive and aerospace industries the weight reduction plays an important role for the components design. For suspension systems, leaf springs are one of the main components for mass reduction ever since it includes in unsprung mass; which related to the drive of the transport system. Various endeavours have been prepared by automotive design engineers by means of plastic leaf springs, tapered leaf spring, warm stress peening and stress etc. To adding some effort to reduce the mass of the leaf spring in this paper we are going to perform optimization of the mono parabolic leaf spring (PLS) with the help of their shape parameters. The response parameters taken were Mass, deflection and the maximum vonmises stress, where as for the input various shape parameters e.g. sectional thicknesses, camber, leaf span etc. The optimization of the PLS has been done with the help of Adaptive single objective optimization algorithm. The outcomes of this work give better and lighter design for the automotive designer to modify the design.**

Keywords*— *Leaf Spring, Composite, static analysis, Shape Optimization

I. INTRODUCTION

With the purpose of saving natural resources and cost effects, mass minimization has been the most important focus of automotive and the aero space industries. Now a day's mass optimization can be attained by the substitution of improved material, design and production process. The leaf spring suspension holds about 10-20% of vehicle unsprung weight. Therefore it becomes a crucial constituent for mass optimization. The mass optimization can be done by selecting enhanced materials and design of leaf spring etc. [7-9].

Parabolic leaf springs are usually used in suspension drives to take up loads in automotives like heavy duty trucks, light vehicles, and in rail systems [1]. The advantage of PLS on top of helical spring is that the last parts of the spring possibly guided beside a specific trail as it repels to operate as a structural member in accumulation to energy absorbing device [14]. The establishment of the composite materials builds it possible to reduce the mass of the PLS without any reduce of weight carrying ability and stiffness. Diverse researches were done on the purpose of the composite materials for leaf springs [2, 3]. Various analyses with the help of FEA through ANSYS software has been already done on typical leaf springs to establish the pay loads and safe design stress and it is observed that at the inner potion of eye sections is the mainly affected segment [4]. In this paper conventional steel and composite mono parabolic leaf springs were tested with integral eye, in static loading circumstance. In addition to material changes an additional crucial intricacy, which is occurs in PLS is the alteration in the dimensions or shape of camber and leaf span due to repeated loading and continual operation of the vehicle. The necessary assessment has been made in this work is with reference to the raise in the camber and decrease in the leaf span after a period of time. This acts as a limitation to spring action. Hence it becomes very essential to restore the spring action to the initial level. This is because the spring is always loaded and the load on it may be due to the cargo or due to its own weight. It is observed that due to the change in dimensions of camber and leaf span there is a decrease in the amount of comfort level both to the rider and the cargo loaded on it. The objective initially is to study the behavior of a PLS under static loading conditions by varying the camber, leaf span, eye distance and section thicknesses.

For the current work, the conventional steel leaf spring has some problems identified which is the Improper shape. The shape of the leaf spring is not unique to justify the effective weight carrying capacity.

The objective of Research Thrust is to develop an approach to reduce the weight through the advance shape optimization technique of

a. *The steel leaf spring and*
b. *Composite leaf spring.*

In order to achieve the previously listed objectives, the following assumptions are made:

1. The vehicle is presumed to be immobile for static analysis.
2. There are 4 mono PLS out of which two are situated at front and two at rear axle.
3. Static examination has to be done for mono PLS.
4. The Material of PLS is considered as 55Si2Mn90 and Carbon-epoxy composite.
5. The non-laminated composite material is considered.

6. An acceptable variation range for each objective function in the optimization.

Some of the studies have already done on the leaf springs as weight saving with the help of material changes[1,5] as from the conventional steel to various composite for static[6,10] and fatigue[7,11] life calculations. For the production of low cost composite leaf springs have also been done[12] and some optimizations studies were performed in the past for stress optimization[1] and new algorithm generations[22,23]. With the help of these studies in this current work the optimization of the mass has been done with the help of stress and deflection as response and some shape parameters as input variables, which is described in next segment.

For the Problem formulation the data has been taken from the reference [13]. According to which the specification of TATA-ACE-HT are as follows:

Kerb weight: 815Kg

Loading capacity: 1 Tonnes

Max Gross vehicle weight:1550 Kg

Material: 55Si2Mn90 / Carbon-Epoxy UD 395

TABLE I. MATERIAL PROPERTIES OF EXISTING PLS (55SI2MN90)

PARAMETER	VALUE
Young's Modulus (E)	200GPa
Poisson's Ratio	0.3
Tensile Strength Ultimate	1962 MPa
Tensile Strength Yield	1500 MPa
Density	7850 kg/m3
Thermal Expansion	11×10^{-6} / °C

TABLE II. MECHANICAL PROPERTIES OF EPOXY_CARBON_UD_395GPA_PREPREG COMPOSITE PLS[40]

Properties	Value
Tensile modulus along X-direction (Ex), Pa	2.09E+11
Tensile modulus along Y-direction (Ey), Pa	9.45E+09
Tensile modulus along Z-direction (Ez), Pa	9.45E+09
Shear modulus along XY-direction (Gxy), Pa	5.5E+09
Shear modulus along YZ-direction (Gyz), Pa	3.9E+09
Shear modulus along ZX-direction (Gzx), Pa	5.5E+09
Poisson ratio along XY-direction (NUxy)	0.27
Poisson ratio along YZ-direction (NUyz)	0.4
Poisson ratio along ZX-direction (NUzx)	0.27
Mass density of the material (ρ), kg/mm^3	1540

The parabolic leaf spring taken into consideration is of TATA-ACE-HT having a Max Gross Vehicle Weight of 1550 kg.

Total weight acting downwards (i.e. at packed load)

= Gross Vehicle Weight × gravity

= 1550 x 9.81 = 15205.5 N.

There are four suspensions two at the front and two at the back. So, Load on one suspension = 15205.5/4 = 3801.4 N or 3800 N approx.

Factor of safety = Ranges (2 - 2.25) for a leaf spring.

II. METHODOLOGY

Due to continuous running of the mini loader truck there is a decrease in the level of comfort provided by the spring. This happens because of the changes in dimensions of the camber and leaf span. After continuous running of the automobile the portion of PLS near the shackle tends to weaken in a sense that the thickness is reduced which ultimately results in high stress concentration. This is a cumulative effect and after certain period of time the PLS fails. The existing dimensions of PLS have been measured with the help of a measuring tape and a vernier calliper. The measuring tape enabled us to ascertain the dimensions of camber and leaf span; whereas the thickness (varying from centre to the outer side) was measured by vernier calliper. Through the manual measurement of the TATA-ACE-HT front main parabolic leaf spring has been measured for new (unused) and after used condition.
A basic comparison has been made between dimensions of used and unused PLS and is as follows:

TABLE III. COMPARISON OF DEFORMED AND UN-DEFORMED PLS

Basis	Used PLS	Unused PLS
Camber	95 mm	90.81 mm
Leaf Span	1019 mm	1025 mm
Width	60 mm	60 mm
Thickness at centre	10.6 mm	10.81mm

It is very clear from the above comparison in Table 7.1 that due to continuous running, there is a considerable reduction in spring stiffness because of dimensional change. This change is directly proportional to the number of hours the automobile is running (with or without cargo loaded) and as the time progresses the magnitude of change in dimensions increase which leads to improper functioning of spring and reduction in comfort level. During physical examination of used PLS, it was observed that there was a considerable reduction in the thickness near the shackle.

Hence in order to strengthen the existing PLS certain modifications in terms of dimensions have to be carried out and implemented. This would not only increase the life of spring but it will also provide a smooth and comfortable ride.

With having the data's as lower and upper limit for some of the parameters, now the methodology for this paper are shown in figure 1.

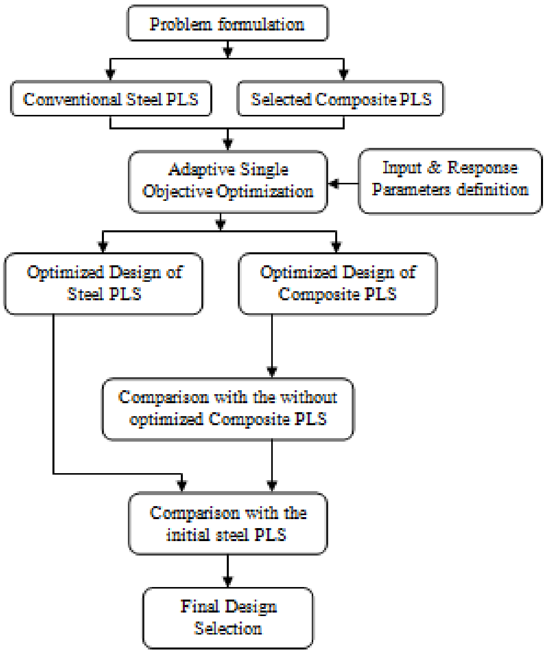

Fig. 1. Flowchart of the methodology

With the help of the above shown flow chart two sub-objectives are going to be achieved as the shape optimization of Conventional steel PLS and the shape optimization of the selected Composite PLS.

As to attain the goal the present work follows the above flow chart, which uses Adaptive single objective optimization algorithm. Adaptive optimization is a hybrid optimization system which uses Latin hypercube sampling (LHS) as design of experiment generator, kriging metamodel as response surface generator and finally non linear programming for Quaterdic Langrangian (NLPQL) and which is shown in the figure 2.

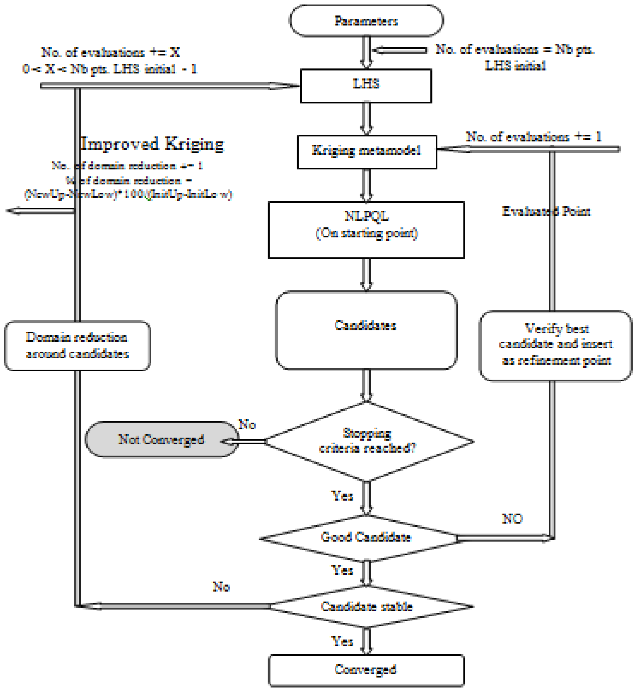

Fig. 2. Flowchart of Adaptive single objective optimization algorithm

III. ASSESSMENT OF PLS

In this section the steel spur gear will be analysed to see the various results from the static analyses. The software used to perform the analysis is ANSYS® 15.

The meshing and boundary conditions are taken from reference [13]. As the initial result of the analysis for the conventional steel and carbon epoxy composite material are shown in the figure 3 and 4.

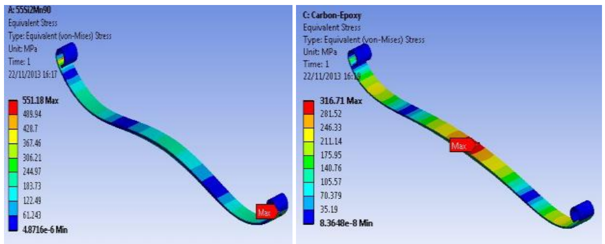

Fig. 3. Von-Mises Stress generated for 55Si2Mn90 and carbon epoxy PLS

As per the results shown above the maximum Von-Mises stress generated in conventional steel leaf spring is 551.18 Mpa, and Carbon-Epoxy composite material is 316.71 Mpa.

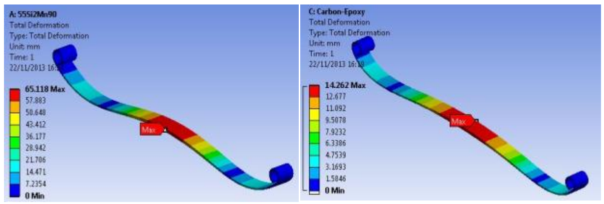

Fig. 4. Total Deformation generated for 55Si2Mn90 and carbon epoxy PLS

The mass of the conventional leaf spring is 4.613 kg, and the mass for the Carbon-Epoxy composite leaf spring is measured as 0.905 kg, which means Carbon-Epoxy composite leaf spring reduce the weight about 80% from conventional one.

IV. SHAPE OPTIMIZATION OF MONO PLS

In any optimization whether linear or non-linear there has to be an objective function which is supposed to be either maximised or minimised. In this case, Mass is selected as objective function and maximum VonMises Stress and maximum total Deflection as constraint functions. As we know that mass is directly depends on the dimensions of the existing PLS and stress, hence in order to perform the optimization and compute various values of mass, stress and deflection, the input parameters such as camber, leaf span and sections thickness will be varied. This optimization has been performed in ANSYS 15.0 and the algorithm used to optimize is the 'Adaptive Single Objective', which is a hybrid optimization method combines an online Kriging response surface and the NLPQL algorithm in a Direct Optimization system. It uses the same general approach as NLPQL, but extends it by using the Kriging error predictor to reduce the number of evaluations needed to local the global optimum.

A. Steel Leaf Spring Shape Optimization

In this part of the thesis, an optimization system will be implemented to optimize the mass of the conventional leaf spring (steel) available in the market, with the help of Adaptive Single objective optimization algorithm by ANSYS ®15.0. From the initial analysis, which has been done at earlier stage, the initial results come for steel leaf springs are: Total mass of the spring as 4.613 kg, maximum VonMises stress as 551.18 Mpa and the total deflection as 65.118 mm. Now further, the optimization of total mass with a specific level of stress and deflection is going to be done. To do this the problem formulations are given in the tabular form in the Table IV.

TABLE IV. OPTIMIZATION PROBLEM FORMULATION FOR STEEL PLS

Objective Function	**Minimization Mass**	
Subject to Constraints	1	VonMises Stress < 1120 Mpa
	2	Deflection < 90 mm
	3	Mass <5 kg
Input Parameters	1	90 mm < Camber < 95 mm
	2	1020 mm < Leaf Span < 1030 mm
	3	55 mm < Width < 65 mm
	4	9.5 mm < t_1< 11.5 mm
	5	9 mm < t_2 <11 mm
	6	7 mm < t_3 < 9 mm
	7	5 mm < t_4 < 7 mm

The Adaptive Single-Objective method is a gradient-based algorithm to provide a refined, global, optimization result. It supports a single objective, multiple constraints and aims at finding the global optimum. It is limited to continuous and manufacturable input parameters. The configuration of the Single objective optimization is to find 3 candidates in a maximum of 160 evaluations and 20 domain reductions.

The optimization of the response has been converged after 76 evaluations and the three best candidates have been chosen which are shown in the figure 5.

	Candidate Point 1	Candidate Point 2	Candidate Point 3
P1 - DS_EYE	1022.6	1025.7	1026.3
P3 - DS_WIDTH	55	56.826	57.314
P2 - DS_CAMBER	86.728	87.964	89.717
P4 - DS_T1	10.458	9.9368	10.529
P6 - DS_T3	7.1062	7.1253	7.6042
P7 - DS_T4	5	5.1957	5.0225
P5 - DS_T2	9.3718	9.6666	9.6594
P9 - Equivalent Stress Maximum (MPa)	761.59	732.02	757.62
P8 - NEWPLS Mass (kg)	3.681	3.8589	3.9384
P10 - Total Deformation Maximum (mm)	89.997	89.732	88.972

Fig. 5. Shape optimization result for Steel PLS

The candidate point has been selected as our main objective was to reduce the mass of the leaf spring, which has been done with the controlled stress and deflection.

B. Composite Leaf Spring Shape Optimization

Here, one optimization system is used to optimize the mass of the composite leaf spring (carbon-epoxy), which has been selected from the first objective, with the help of Adaptive Single objective optimization algorithm by ANSYS ®15.0. From the first objective analysis, which has been done at earlier stage, the initial results come for Composite (carbon-epoxy) leaf springs are: Total mass of the spring as 0.905 kg, maximum von-mises stress as 316.71 Mpa and the total deflection as 14.262 mm. Now, the optimization of mass with a specific level of stress and deflection is going to be done. To do this the problem formulations are given in the tabular form in the Table V.

TABLE V. OPTIMIZATION PROBLEM FORMULATIONS FOR COMPOSITE PLS

Objective Function	**Minimization Mass**	
Subject to Constraints	1	VonMises Stress < 1120 Mpa
	2	Deflection < 90 mm
Input Parameters	1	90 mm < Camber < 95 mm
	2	1020 mm < Leaf Span < 1030 mm
	3	55 mm < Width < 65 mm
	4	9.5 mm < t_1< 11.5 mm
	5	9 mm < t_2 <11 mm
	6	7 mm < t_3 < 9 mm
	7	5 mm < t_4 < 7 mm

The optimization of the response has been converged after 71 evaluations and the three best candidates have been chosen which are shown in the figure 6.

	Candidate Point 1	Candidate Point 2	Candidate Point 3
P30 - DS_T3	7	7.732	7.1724
P31 - DS_T4	5	5	5.2072
P29 - DS_T2	9	9	9.5802
P28 - DS_T1	9.5	9.5	9.8216
P25 - DS_EYE	1020	1020	1023.1
P26 - DS_CAMBER	90	90	94.12
P27 - DS_WIDTH	55	56.192	55.9
P34 - Total Deformation Maximum (mm)	23.183	22.057	24.85
P32 - NEWPLS Mass (kg)	0.70121	0.73306	0.74438
P33 - Equivalent Stress Maximum (MPa)	471.74	470.2	458.11

Fig. 6. Shape optimization result for composite leaf spring

The candidate point 1 has been selected as our main objective was to reduce the mass of the leaf spring, which has been done with the controlled stress and deflection. So by the means of shape parameters we can reduce the mass of the mono parabolic leaf spring. The next chapter will discuss about the result achieved through various analyses and optimization of the PLS.

Further optimization of the weight with shape optimization with the help of adaptive single objective optimization has been done. It was tried to optimize the conventional steel parabolic leaf spring and the composite (carbon-epoxy) parabolic leaf spring with the help of their shape parameter. The result for the conventional steel leaf spring has been shown in the table VI.

TABLE VI. COMPARISON OF OPTIMIZATION RESULT FOR CONVENTIONAL STEEL LEAF SPRING

	Total mass in Kg
Before Optimization	4.613
After optimization	3.681
% Reduction	20.2 %

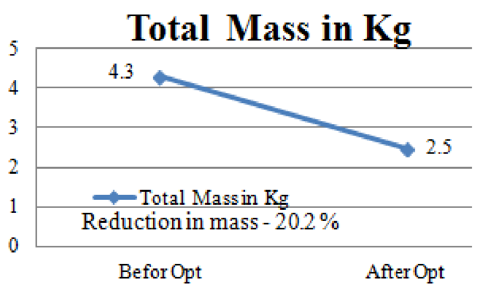

Fig. 7. Mass reduction of steel PLS by shape

Then optimization of the composite (carbon-epoxy) leaf spring and the composite leaf spring has been done with the help of their shape parameter. The result for the conventional steel leaf spring has been shown in the table VII.

TABLE VII. COMPARISON OF OPTIMIZATION RESULTS FOR COMPOSITE LEAF SPRING

	Total mass in Kg		**Total mass in Kg**
Before Optimization	0.905	**Initial result of steel PLS**	4.613
After optimization	0.701	**Optimized result of comp. PLS**	0.701
% Reduction in composite PLS	22.5 %	**% reduction from steel to composite PLS**	84.8 %

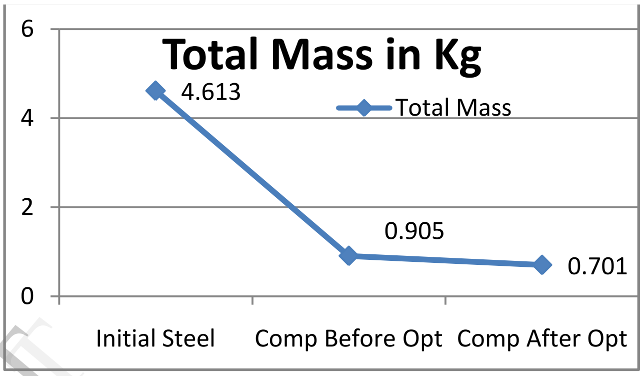

Fig. 8. Reduction in Total Mass of PLS

As per the table we can achieve 22.5% reduction from the composite PLS shape optimization and 84.5% as compare to the initial conventional PLS.

V. CONCLUSION

Through various literatures it is clear that there is a possibility to reduce the weight with the help of material change but after shape optimization of the steel and composite PLS, there is still a good chance to reduce the mass within the controllable limit of responses. After implementation of Adaptive single objective optimization the mass of the steel PLS has been reduced by 20% as compare to the initial conventional steel PLS and for the composite PLS it has been reduced up to 22% as compare to the un-optimized composite PLS. The total mass has been reduced by 85% by the optimized composite PLS as compare with the initial conventional steel PLS.

By the reduction of weight and controllable stress and deflection, the mass of optimized Carbon- Epoxy composite leaf spring is to be lesser than that of steel leaf spring. In totally it is found that the optimized Carbon- Epoxy composite leaf spring could be the better design that of steel leaf spring, which means the proposed new (optimized Carbon- Epoxy composite) material and shape can be used to satisfy the second objective.

So as conclusion it can be said that the present work is demonstrated that optimized Carbon- Epoxy composites can be used for mono PLS for light weight vehicles and achieve the necessities, simultaneously with significant weight reduction.

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