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Analysis of Cracks in Composite Mono Leaf Spring by Vibration Method

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***Abstract*—Composite mono leaf springs are commonly used in automotive and aerospace applications due to their lightweight and high strength properties. However, like any structural component, they can develop cracks over time due to various factors such as fatigue, external loading, manufacturing defects, or material degradation. Understanding the mechanical properties and behavior of the composite material used in mono leaf springs is crucial. To analyze how the material responds to various loads and environmental conditions.**

***Index Terms*—Leaf Spring, Vibration, automotive, aerospace.**

I. INTRODUCTION

A mono leaf spring, also known as a single leaf spring or monoleaf spring, is a type of suspension component commonly used in vehicles to provide support and absorb shocks from road irregularities. It is a simpler alternative to the more traditional multi-leaf spring setup and is often found in applications where space constraints or weight considerations are important. Here's an introduction to mono leaf springs: Design and Construction: A mono leaf spring is a single, curved, and usually tapered piece of spring steel that acts as the main load-bearing element of the suspension system. It is designed to flex and absorb the forces generated by the vehicle's weight and the impact of road conditions. The shape and thickness of the leaf determine the spring's overall stiffness and load-carrying capacity. Advantages: Weight Reduction: Mono leaf springs are generally lighter than multi-leaf springs due to their single-leaf design. This can lead to improved fuel efficiency and reduced unsprung mass, which can enhance the vehicle's handling and ride quality. Simplicity: The single-leaf design simplifies the manufacturing process and can reduce production costs. Space Efficiency: Mono leaf springs take up less space compared to multi-leaf springs, making them suitable for applications where installation space is limited. Customization: Manufacturers can tailor the spring's characteristics by adjusting the shape and thickness of the leaf, allowing for a degree of customization in terms of load capacity and stiffness.

Fig.1 Leaf Spring

II. LITERATURE REVIEW

T. Vo-Duy, [1] et.al; have presented an improved two step differential evolution algorithm based on modal strain energy method and for cracked detection in laminated composite structures. In the first step, potential cracked elements will be identified by the modal strain energy based. Then, the improved differential evolution algorithm is utilized to minimize the mode shape error which can be defined by the shift between the mode shape of the cracked structure and that of the healthy structure. The effect of the noise component is also have been investigated in this work. Kai Zhang [2] et.al; have presented a mathematical model and signal processing method to identifying multi-cracks on cantilever beam with variable cross-sections is presented. Based on the concept of modal strain energy, the cantilever beam's natural frequency is obtained. In order to avoid issues related to frequency resolution and nonlinear vibration observed in fast Fourier transform (FFT), a signal processing method based on Hilbert-Huang Transform (HHT) is also proposed. Validation of this multi-cracks identification method for accuracy, an experiment was also conducted. The results of the experiment accurately validate the location, depth, and extent of cracks.

F. L. M. dos Santosa [5] et.al; have presented experimental results of two cracked detection techniques based on modal properties for a composite helicopter main rotor blade. Co-ordinate modal assurance criterion (COMAC) and the modal strain energy method, are used in this work. They are respectively based on the comparison of vibration modes and on the comparison of the modal strain energy of a beam. By adding mass on the blades, their global properties are artificially altered and their modal parameters were obtained by experimental modal analysis. The results for the original blade and altered blade are compared.

III. DESIGNING

Designing a mono-leaf spring involves considering various factors such as the intended load capacity, vehicle application, material selection, and design parameters. Here's a basic outline of the design process:

1. Determine Requirements:

Identify the intended application, vehicle type, and load capacity. Specify the spring's working conditions, such as maximum load, deflection, and operating environment.

2. Material Selection: Choose a suitable material for the spring. Common choices include high-strength alloy steels like SUP9, SUP10, or similar grades. Material selection depends on factors such as strength, fatigue resistance, and cost.

3. Basic Geometry: Determine the length, width, and thickness of the mono-leaf spring. The length depends on the vehicle's wheelbase and mounting points. Width and thickness influence the spring's load-carrying capacity and stiffness.

4. Calculate Stresses: Calculate the maximum stress the spring will experience under the design load. Use established formulas for stress calculation, taking into account bending stresses and shear stresses.

5. Design for Bending: Determine the spring's curvature and profile based on bending calculations. Consider factors like the number of leaves (single leaf in this case), curvature radius, and overall shape.

6. Design for Shear: Calculate the shear stress on the leaf spring's center bolt and side clips. Design the center bolt and clips to withstand shear forces without failure.

7. Deflection and Load Rate: Calculate the deflection of the spring under the design load. Adjust the number of leaves and their dimensions to achieve the desired load rate (spring stiffness).

8. End Configurations: Design the spring's eyes (end configurations) where it attaches to the vehicle.

Ensure proper contact and load distribution between the spring and the mounting points.

9. Stress Relief: Incorporate stress relief processes into the design, like shot peening or controlled cooling during manufacturing, to improve fatigue life.

IV. PROBLEM STATEMENT

CRACK DETECTION

Cracked detection is very important aspect of maintenance and quantity control activities. Recent advancements in technologies has given cracked detection a new outlook and it had made the cracked detection susceptible for future requirements such as continuous monitoring systems etc.

- Acoustic emission Method
- Ultrasonic testing
- Infrared thermography
- Lamb Wave Technique
- X-ray inspection
- Vibration based cracked detection

VIBRATION BASED CRACKED DETECTION:

The basic principle of vibration-based cracked detection is that the stiffness, mass or energy dissipation properties of a specimen are affected by cracked. These properties will modify the dynamic response of the system. The crack causes local stiffness reduction. The flexibility of structure increases in the zone crack. Hence by using modal characteristics, following are the vibration based detection techniques,

- Method based on the change of natural frequency.

- Method based on the change of structural flexibility or stiffness.
- Method based on Modal displacement
- Method based on modal curvature.
- Method based on mode shapes

METHOD BASED ON THE CHANGE OF NATURAL FREQUENCY.

The structural natural frequency has been used to indicate structural crack. The natural frequency is easy to measure and is independent of the measured position. The stiffness of a specimen is affected by cracks. This will modify the dynamic response of the specimen locally. Hence the natural frequency of the specimen changes due to the cracked. The change in natural frequency establishes that there is an abnormality or cracked in the specimen. The ratio of the frequency changes in the two modes is only a function of cracked location. The measurement of one pair of frequencies will provide the location of possible cracks. The actually cracked geometry can be given by superimposing the loci for several pairs of frequencies. Due to cracks, there will be a change in structural properties and hence changes in the natural frequency of the structure.

Where,

ω= Natural frequency of the system

k = Stiffness

and further,

$$\omega^2{}_n = \frac{k}{m}, \omega^2{}_n \propto k$$

From the above expression, the natural frequency of the healthy component and the same of the component in the discussion can be compared to constitute the presence of cracked.

METHOD BASED ON MODE SHAPES

Mode shape based methods use the structural modes or change of mode shapes between healthy system and the cracked system are compared to detect the cracked. The co-ordinate Modal Assurance Criterion (COMAC) is one of the prominent ways of identifying and locating system changes in mode shapes. The formulation of COMAC is shown below

$$\text{COMACK} = \frac{(\sum_{r=1}^{n} \emptyset_{k,r}{}^{0} \emptyset_{k,r}{}^{d})^2}{(\sum_{r=1}^{n} \emptyset_{k,r}{}^{0} \emptyset_{k,r}{}^{0})(\sum_{r=1}^{n} \emptyset_{k,r}{}^{d} \emptyset_{k,r}{}^{d})}$$

Where ∅ is the modal vector, the superscripts 0 and d refer to the healthy and cracked system, respectively. The subscripts k and r represent the kth measurement point and rth mode, while n is the number of considered modes. The calculated COMAC values range from 0(lowest correlation) to 1 (highest correlation). In the present work, for detecting, locating the multiple cracks in mono leaf composite spring, two approaches are considered.

1) Analytical approach: Vibration based method

2) For simulation approach: ANSYS software has been considered for determining the modal properties of spring in for both healthy and cracked conditions.

Tools used:

1) For Analytical approach: Vibration based method

2) For Simulation approach: ANSYS software

V. MATHEMATICAL AND SIMULATION APPROACH

In analytical approach, we will calculate modal properties of composite mono-leaf spring for both healthy and cracked condition.

4.1 Composite mono-leaf spring

Leaf spring is manufactured to suit some utility vehicles. This is made by ARC industries. It is made of glass fiber Reinforcement plastic (GFRP) material with unidirectional fibers below Table shows the geometry dimension of leaf spring. Following are the dimension of mono leaf spring. Geometry dimension of Leaf spring

Sr. No.	**Parameter**	**Dim. (mm)**
1	Length of leaf spring	1230
2	Length of leaf spring frim eye to eye	1210
3	Minimum Width	72
4	Maximum Width	125
5	Minimum Thickness	12
6	Maximum Thickness	18
7	Eye inner diameter	38
8	Eye outer diameter	52

Table 1: Geometry dimension of Leaf Spring

Fig 2 Composite mono leaf spring

Properties of Composite mono leaf spring GFRP material

GFRP material is used for leaf spring, its material properties are shown below in table

Sr. No.	Properties	Value
1	Mass density of the material (ρ)	2.0×10^{-9} T/mm3
2	Tensile modulus along X- direction(E_1)	45000MPa
3	Tensile modulus along Y- direction(E_2)	10000MPa
4	Tensile modulus along Z- direction(E_3)	10000MPa
5	Shear modulus along XY- directions(G_{xy})	5000MPa
6	Shear modulus along YZ- directions(G_{yz})	3846.2MPa
7	Shear modulus along ZX- directions(G_{zx})	5000MPa
8	Poisson ratio along XY-direction(NU_{xy})	0.3
9	Poisson ratio along YZ-direction(NU_{yz})	0.4
10	Poisson ratio along ZX-direction(NU_{zx})	0.3

Table 2 GFRP material is used for leaf spring, its material properties

CALCULATION FOR HEALTHY LEAF SPRING

Step 1: Modeling

In this step the physical model is converted into numerical model i.e. discretization.

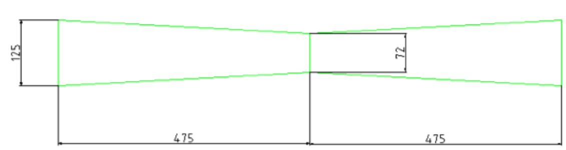

Fig.3 Healthy leaf spring

Since the spring is symmetric,it is divided into two equal parts from the middle of the spring.In order to make calculation easy.Further,half of the spring is then divided into four elements.

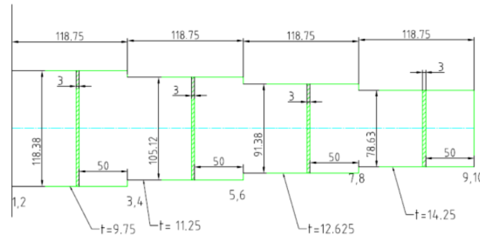

Fig.4 A model of cracked composite mono-leaf spring

SIMULATION APPROACH

The finite element analysis (FEA) is a numerical method for solving problems of engineering a mathematical physics. Useful for problems with complicated geometries, loading, and material properties where the analytical solution cannot be obtained.FEA is widely used in Mechanical, Aerospace, Civil, Automotive Engineering structural, Stress Analysis of Static and Dynamic, Linear/Nonlinear Fluid Flow Heat Transfer, Electromagnetic Fields Soil mechanics, Acoustics and Biomechanics. Design geometry is a lot more complex and the accuracy requirement is a lot higher we need – To understand the physical behaviors of a complex object (strength, heat transfer capability, fluid flow, etc.),

- To predict the performance and behavior of the design;
- To calculate the safety margin;
- To identify the weakness of the design accurately;
- To identify the optimal design with confidence

Modal body by dividing it into an equivalent system of many smaller bodies or units (finite elements) interconnected at points common to two or more elements (nodes or nodal points) and boundary lines and surfaces. Advantages are Irregular Boundaries General Loads different materials Boundary conditions variable element size easy modification dynamics non-linear problems (geometric or material).

A general procedure for finite element analysis.

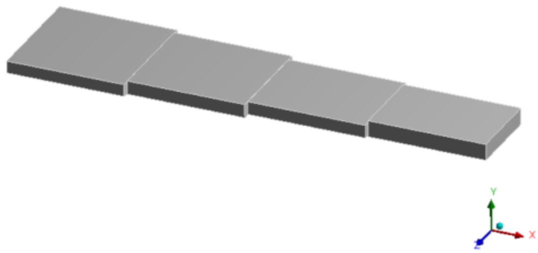

Fig.5 3D model of healthy leaf spring

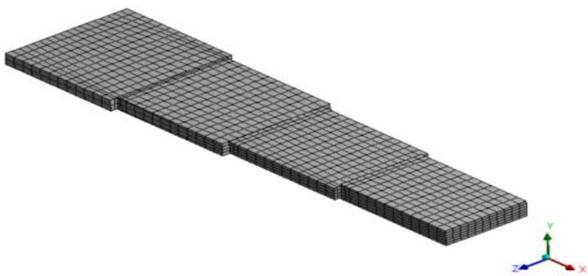

Fig.6 Meshed model of healthy leaf spring

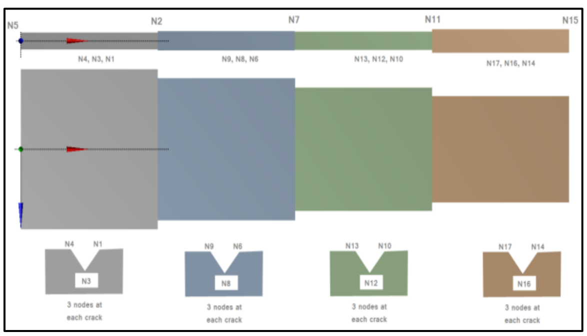

Fig .7 Node locations

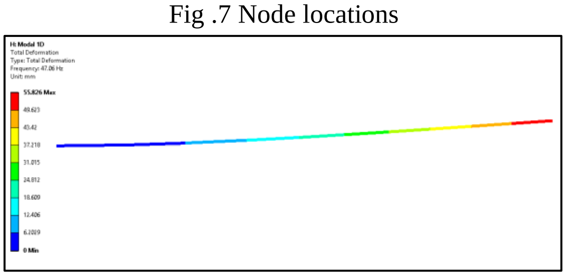

Fig 8 1st mode shape of healthy composite mono leaf spring

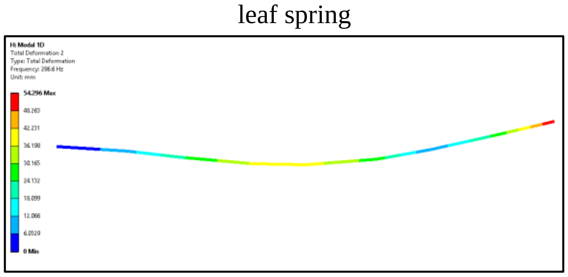

Fig 9. 2nd mode shape of healthy composite mono leaf spring

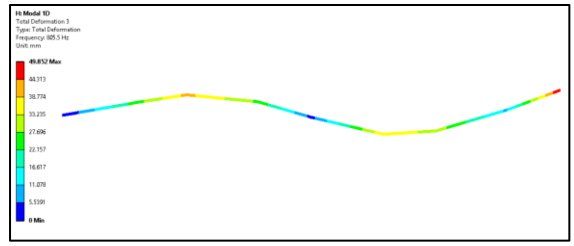

Fig 10 3rd mode shape of healthy composite mono leaf spring

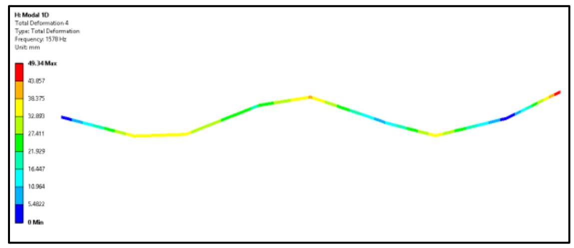

Fig11. 4th mode shape of healthy composite mono leaf spring

MODAL FREQUENCY FOR CRACKED LEAF SPRING

The cracked composite mono leaf spring is analyzed in ANSYS to obtain mode shapes and corresponding natural frequencies. The modal frequencies values and mode shape are shown in the figure.

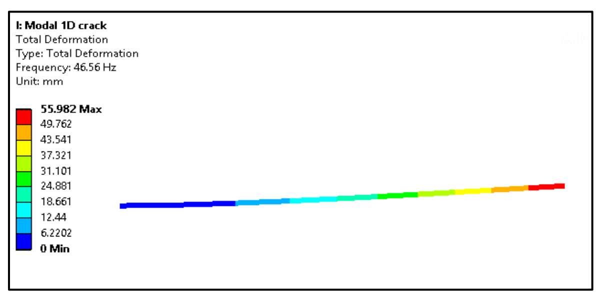

Fig 12 .1st mode shape of cracked leaf spring

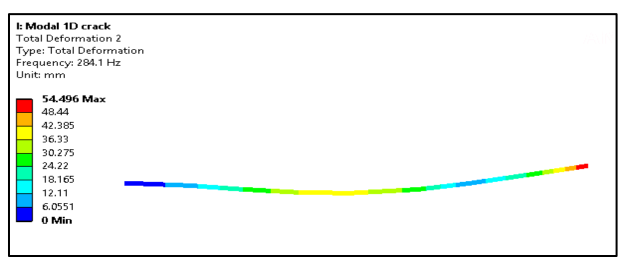

Fig 13 2nd mode shape of cracked leaf spring

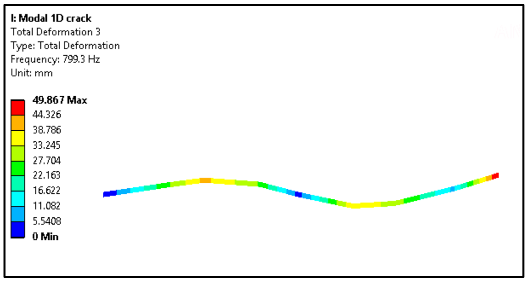

Fig 14 3rd mode shape of cracked leaf spring

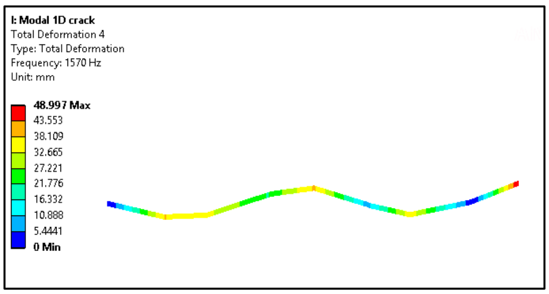

Fig 15 4th mode shape of cracked leaf spring

VI. RESULTS AND CONCLUSIONS

Determination of the section of spring where the crack will affect the life of the spring by the difference in Modal curvature at nodes for healthy and cracked leaf spring

Node no.	Difference in modal curvature for healthy and cracked spring			
	k1*-k1	k2*-k2	k3*-k3	k4*-k4
3	0	0	0	0
8	5.46E-07	3.35E-07	4.11908E-05	2.34E-06
12	1.34539E-07	4.11794E-06	4.2659E-05	4.06388E-06
16	4.95388E-07	6.65E-07	5.66206E-07	4.63E-06

Table 3 The difference of Modal curvature for healthy and cracked spring

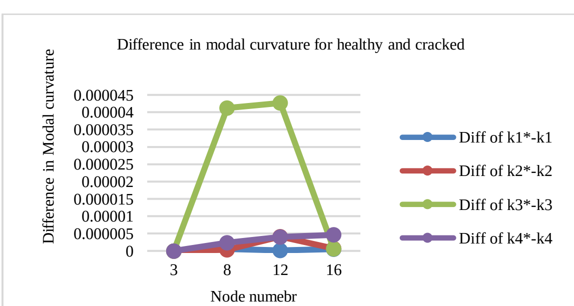

Fig 16 The difference of Modal curvature for healthy and cracked spring

The deviation in modal displacement and modal curvature for all the three sections of healthy and cracked spring have been recorded in table 11 and 12. This indicates that the deviation in modal displacement and curvature in the section of the spring between nodes 8 and 12 is higher compared to the other sections of the spring. Hence the section of the spring between node 8 and node 12 is critical and cracks in this section will impact the life and reliability of the spring.

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