Experimental and Computational Methods to Find the Modal Frequencies of E-Glass/Epoxy Mono Composite Leaf Spring Designed for TATA ACE HD

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***Abstract*— A leaf spring is subjected to vibration due to road profile irregularities, which leads to its fatigue failure. Also, if the natural frequency of the leaf spring matches the excitation frequency of the road profile, resonance occurs and the vibration is transmitted to the upper deck of the vehicle causing damage to fragile goods being transported. Hence, it is important to determine the modal frequencies of the leaf spring. This research work aims to highlight the experimental and computational techniques used to determine the modal frequencies of E-Glass/Epoxy mono composite leaf spring designed for the rear suspension of Tata Ace HD pickup truck. A prototype of E-Glass/Epoxy composite leaf is fabricated using conventional hand lay-up process and subjected to free and forced (harmonic) vibration test using DAQ (Data Acquisition) and DSA (Dynamic Signal Analyzer) system. The fundamental modal frequency obtained from real time test is validated using ANSYS Workbench 14. The first modal frequency of the prototype under free and forced (harmonic) vibration is found to be 62 Hz, whereas using FEA, it is found to be 64.62 Hz. On validation, the higher order frequencies and mode shapes are determined using ANSYS Workbench 14.**

Keywords*— *E-Glass/Epoxy Composite, Leaf spring, Vibration testing, Finite Element Analysis, Modal and harmonic analysis

I. INTRODUCTION

Weight reduction and cost optimization of automotive components are biggest challenges faced by the automotive industry in present scenario. The automotive OEMs and their component suppliers worldwide spend billions on R&D, which does intensive research on advanced materials whose properties are superior to those of the conventional materials, are cost effective and reduces the actual weight of the system/sub-system thus improving the fuel efficiency of the vehicle.

The leaf spring accounts for 10-20% of the unsprung weight of the vehicle [2,3,7]. Any reduction of the unsprung weight would help in achieving improved ride characteristics [2]. Introduction of FRP (Fiber Reinforced Plastic) material for the leaf spring has made it possible to replace the conventional multi-leaf steel spring with a mono composite leaf thereby achieving a weight reduction of nearly 80-90% [2,3,4,7]. One of the most advantageous reasons for considering composites instead of Steel is their weight. Other important characteristics of composites which make them excellent for leaf spring are: high strength to weight ratio, superior fatigue strength, “fail-safe” capabilities, excellent corrosion resistance, smoother ride, higher natural frequency, etc [4].

Over a decade, researchers globally have worked on the suitability of composites for leaf spring. Various scientific papers have been published, which is a proven record of composites being successfully tested and implemented in test vehicles. Shishay [1] (2012) designed a single leaf of E-Glass/Epoxy for a light three wheeler vehicle and simulated it for determining the maximum stress and deflection. Pankaj Saini et al. [2] (2013) designed a mono composite leaf for Mahindra Commander 650 DI using E-Glass/Epoxy, Carbon/Epoxy and Graphite/Epoxy. Using FEA, they validated the design and achieved a weight reduction of up to 91.95%. I.Rajendran et al. [3] (2001) used Generic Algorithm to design a composite leaf to achieve minimum weight with adequate strength and stiffness. With optimization, they achieved a weight reduction of 75.6%. Mahmood.S et al. [4] (2003) designed and optimized composite leaf spring for rear suspension of a light vehicle which weighed 80% less than conventional steel leaf spring. Al-Qureshi [5] (2001) designed a single leaf with variable thickness of GFRP. He made a prototype which was subjected to static load test in laboratory and then further subjected it to test on vehicle. Erol.S et al. [6] (1999) designed and manufactured unidirectional E-Glass/Epoxy composite leaf that weighed around 236 g. Load test was carried out on the prototype and was validated using FEA results. M.Venkatesan et al. [7] (2012) designed and simulated E-Glass/Epoxy composite leaf spring under static loading condition. They found that the composite leaf had 67.35% lower stress, 64.95% higher stiffness and 126.98% higher natural frequency than that of steel. Gulur.S et al. [8] (2006) designed a unidirectional GFRP composite leaf for constant cross sectional area. Using computer algorithm, they obtained the optimum thickness at the ends and at the centre. They further fabricated a prototype using hand lay-up process and tested it following the standard procedures of SAE. Edward.N et al. [9] (2014) designed a mono composite leaf spring for Tata Ace HT truck. They modeled the leaf in ANSYS 14.5 and applied a static load of 3800 N at the free end to determine the maximum Von Mises stress induced.

II. DESIGN METHODOLOGY

A. Leaf Spring Specification (Tata Ace HD)

A Tata Ace HD pickup truck is considered whose rear leaf spring is measured and its specification is given below –

Table 1 Tata Ace HD leaf spring – Specification

S.No.	Tata Ace HD Steel Leaf Spring Parameters	Values
1	Length of the main leaf (eye to eye)	865 mm
2	Curve length of the main leaf (2L)	910 mm
3	Arc height at axle seat (Camber – δ_{max})	75 mm
4	Number of leaves	3
5	Number of full length leaves	3
6	Width of each leaf (b)	60 mm
7	Thickness of each leaf (h)	7.25 mm

The material used for the leaf spring of Tata Ace HD vehicle is 55Si2Mn90. The material properties of 55Si2Mn90 are shown in the table below –

Table 2 Material properties of 55Si2Mn90 [9]

Parameter	Value
Young's Modulus	210 GPa
Poisson's Ratio	0.3
Ultimate Tensile Strength	1962 MPa
Yield Strength	1500 MPa
Density	7850 kg/

B. Design of Composite Laminate

The properties of E-Glass/Epoxy laminate are computed using Autodesk® Simulation Composite Design 2014. The software has an in-built material database of different commercially available fibers, matrices and laminas whose values are taken from ASTM tensile tests.

The software is opened and the "Fabric Builder" utility is selected for creating a user defined lamina of E-Glass/LY556 Epoxy. The areal weight of E-Glass fibers (400 GSM) is entered along with the fiber weight % and void volume % (15% for hand lay-up process). A volume fraction of 50% is considered for E-Glass fiber and the remaining 50% is considered for LY556 epoxy. Hand layup process always leads to a deviation of this ratio due to compaction of the laminate and squeezing out of epoxy resin. With prior experience, it is observed that the actual ratio of volume changes to 55.01% of fibers to 44.99% epoxy, corresponding to 71.42% weight of fibers to 28.58% weight of epoxy. Once the lamina is created, its thickness is determined along with its properties. The longitudinal Young's Modulus E_{11} is used in the design calculation for obtaining the thickness of the mono composite leaf. After when the design thickness is computed, the laminas are stacked in layers using the "Laminate Builder" utility. 55 layers of laminas are stacked to obtain the design thickness. The laminate properties are determined and exported to ANSYS Workbench in *.csv format.

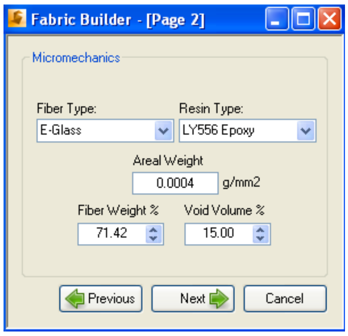

Fig.1 User defined lamina (E-Glass/LY556)

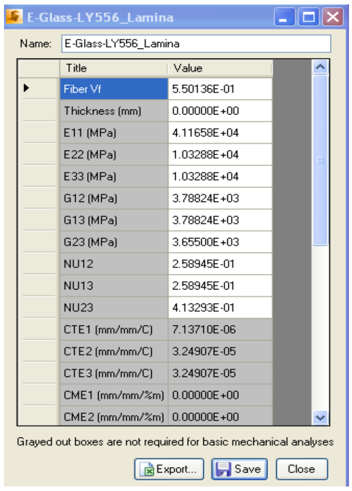

Fig.2 Properties of E-Glass/LY556 lamina

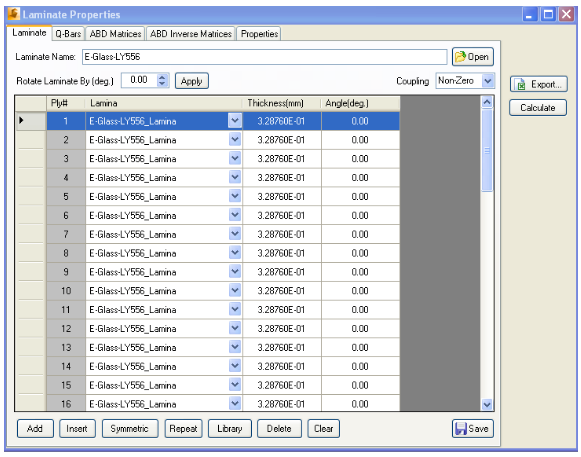

Fig.3 Creation of laminate by stacking laminas (E-Glass/LY556)

The properties of E-Glass/LY556 Epoxy laminate as obtained from the software are shown in the table below –

Table 3 Properties of E-Glass/Epoxy laminate

Properties	E-Glass/Epoxy
Tensile Modulus along X-direction (Ex), MPa	41165.8
Tensile Modulus along Y-direction (Ey), MPa	10328.8
Tensile Modulus along Z-direction (Ez), MPa	10328.8
Shear Modulus along XY plane (Gxy), MPa	3788.2
Shear Modulus along YZ plane (Gyz), MPa	3655
Shear Modulus along XZ plane (Gxz), MPa	3788.2
Poisson's Ratio along XY plane (Nuxy)	0.259
Poisson's Ratio along YZ plane (Nuyz)	0.413
Poisson's Ratio along XZ plane (Nuxz)	0.259
Density (g/mm3)	0.002004

C. *Design of Mono Composite Leaf Spring*

The vehicle specification is shown in the table below –

Table 4 Specification of the vehicle (Tata Ace HD)

Kerb Weight	945 kg
Gross Vehicle Weight	1550 kg
Rear Suspension Type	Parabolic multi-leaf steel spring with hydraulic double acting shock absorber

In order to replace the conventional steel leaf spring with mono composite leaf spring, the geometrical parameters of the leaf spring have to be same because of space constraints. These parameters are the length of the leaf (L) and the width of the leaf (b). The only design parameter which is a variable and of primary importance is the thickness of the leaf (h).

According to SAE standard [4], a leaf spring can be considered as two cantilevers, the fixed end being the axle seat and the free end subjected to half load of the leaf spring.

Total load acting on the suspension system of the vehicle is – 1550 x 9.81 = 15205.5 N

Since there are 4 leaf springs in the vehicle to support the load, the load carried by individual leaf spring is – 15205.5/4 = 3801.37 N

Considering load factor for overloading to be 1.4, the net load acting on individual leaf spring is –

3801.37 x 1.4 = 5321.92 N

The load acting on a half leaf spring is given as – F = 5321.92/2 = 2660.96 N ≈ 2661 N

The spring stiffness of the conventional steel leaf spring is calculated using the analytical relation –

$$R = \frac{(2i+i').E.h^3.b}{12.l^3} \quad [12]$$

R = 38.231 N/mm

The design variable (thickness) for a mono composite leaf spring is computed using the standard design formulae as given below [12, 14, 15] –

1. $$\sigma_{max} = \frac{6FL}{bh^2}$$

2. $$\delta_{max} = \frac{4FL^3}{Ebh^3}$$

From eq.1,

$$h = \sqrt{\frac{6FL}{b\sigma_{max}}}$$

From eq.2,

$$h = \sqrt[3]{\frac{4FL^3}{Eb\delta_{max}}}$$

(Or)

$$h = \sqrt[3]{\frac{4RL^3}{Eb}} \qquad \text{Where, } R = \frac{F}{\delta_{max}}$$

σ_{max} = 473 MPa [16]

The thickness of the mono composite leaf spring is computed using the above equations where the stiffness (R) of the composite leaf is taken to be same as that of conventional leaf spring in order to have the same ride quality and performance characteristics.

On solving (1) & (2), we obtain two values for the thickness.

h_1 = 15.83 mm
h_2 = 18.00 mm

From the stress point of view, the design is safe with 15.83 mm, but considering deflection, it exceeds the camber of 75 mm, thus making the design fail. Hence, we select 18 mm as the safe thickness which satisfies both the criteria of maximum stress and maximum deflection.

III. FINITE ELEMENT ANALYSIS

In order to validate the design parameters, FEA is performed using ANSYS Workbench 14. A model of the leaf is created in Pro/E, converted into *parasolid format and imported in ANSYS. The material properties are imported from Autodesk Simulation Composite Design. One side of the model is completely fixed (cantilever) and the free end is subjected to a force of 2661 N in vertically downward direction. Fine meshing is done on the model to achieve accurate results.

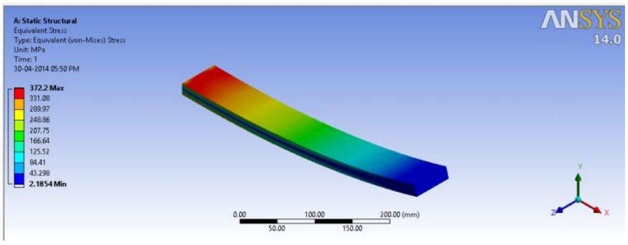

Fig.4 Stress induced in E-Glass/Epoxy composite leaf

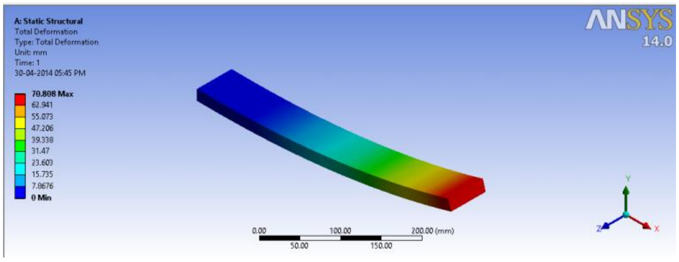

Fig.5 Deflection induced in E-Glass/Epoxy composite leaf

Table 5 Result comparison of FEA with analytical result

Parameter	Analytical Result	FEA Result
Stress (MPa)	373.68	372.2
Deflection (mm)	69.6	70.8
Stiffness (N/mm)	38.23	37.58

The values obtained from analytical calculation and FEA results are in close proximity indicating the design approach to be valid and accurate. With validation of design parameters, we try to find the modal frequencies of the mono composite leaf and also their mode shapes.

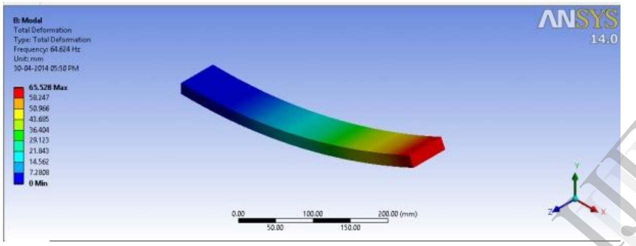

Fig.6 First Mode Shape

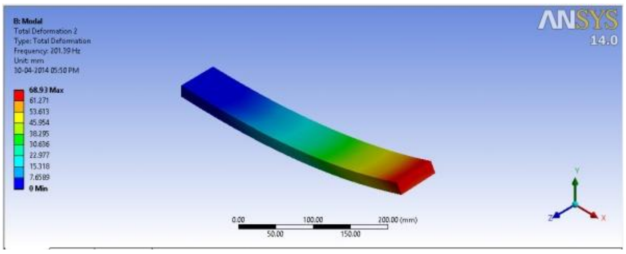

Fig.7 Second Mode Shape

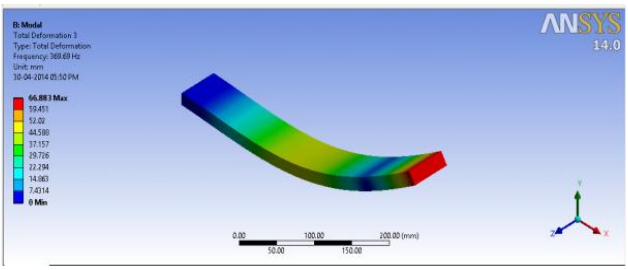

Fig.8 Third Mode Shape

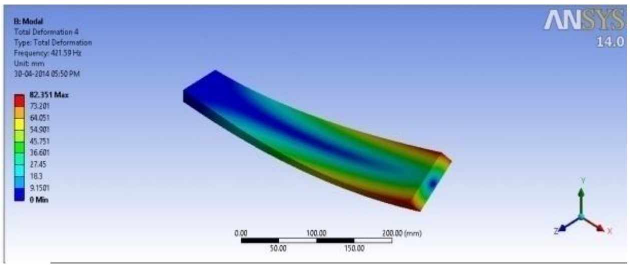

Fig.9 Fourth Mode Shape

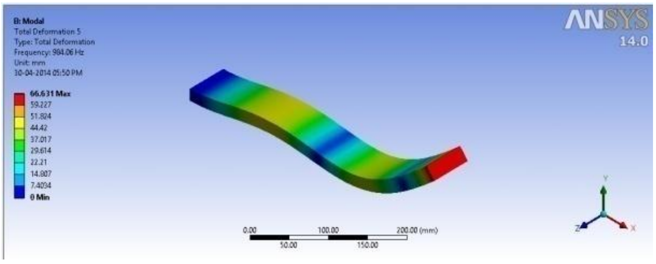

Fig.10 Fifth Mode Shape

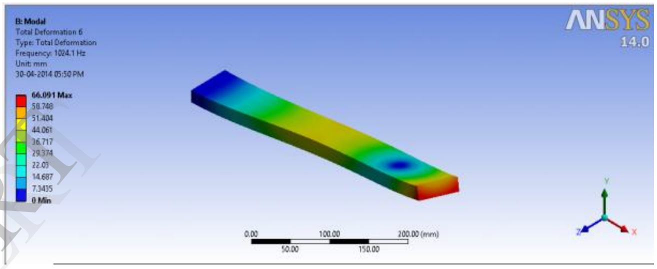

Fig.11 Sixth Mode Shape

Table 6 Modal Frequencies of E-Glass/Epoxy Composite (FEA)

Mode	Frequency (Hz)
1	64.62
2	201.39
3	369.69
4	421.59
5	984.06
6	1024.1

IV. FABRICATION OF PROTOTYPE

As per the SAE standards for analyzing leaf spring, only half leaf spring is required [4]. A half leaf of E-Glass/Epoxy composite without eye is fabricated using hand lay-up process.

- A wooden mould is prepared following the geometrical dimensions of the leaf as calculated from design formulae.
- The fiber sheets of E-Glass (400 GSM) are cut into rectangular pieces of dimension 940 x 80 mm, keeping the allowance for cutting/trimming.

- From the calculation, for E-Glass/Epoxy, 55 such layers are required. The total weight of these 55 layers is found to be 1022.3 gm.
- For achieving the required volume fraction of 50% fibers and 50% matrix, epoxy (LY556) is taken to be half of the weight of fiber sheets, i.e. 511.2 gm.
- Hardener HY951 is mixed with epoxy in the ratio of 1:10. The mixture is then stirred to get a homogeneous compound.
- OHP sheets are pasted on top of the mould and wax polish is applied over it for easy removal of the composite after curing.
- First coat of Epoxy is applied over the wax polish and the fiber sheet is placed over it. The fiber sheet is roll-pressed in order to remove the voids between fiber and the epoxy inter-layer.
- The epoxy is applied over the fiber sheet and a new layer of fiber sheet is placed over it and roll-pressed again.
- The process is repeated until all the 55 layers of fiber sheets are stacked one above the other to achieve a thickness of 18mm.
- Once all the fiber sheets are stacked, wax polish is applied over the topmost layer and OHP sheet is placed over it. It is roll-pressed again for even distribution of wax polish.
- The setup is left undisturbed to cure at room temperature for about 2 days and after that, the composite leaf is removed from the mould for trimming the extra fibers and epoxy from the sides.

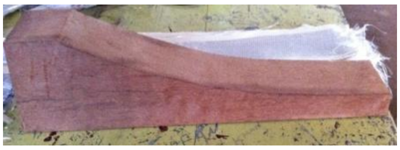

Fig.12 Wooden Mould

Fig.13 Epoxy/Hardener mixture applied over fiber sheet

Fig.14 Squeezing out extra Epoxy (Compaction)

Fig.15 Prototype after trimming the sides

V. EXPERIMENTAL VIBRATION TEST

A. Free Vibration Test Procedure

One end of the prototype is fixed to a firm base (table) with a C-Clamp. The accelerometer is mounted at the free end and connected to the DAQ NI 9234. The DAQ is connected to PC using USB cable and LabVIEW® is opened. The accelerometer is calibrated and range over which the signals are to be captured is defined. DAQ NI 9234 is programmed to capture signal from accelerometer and convert it into FFT plot. Once the setup is done, the free end of the prototype is struck with an impact hammer. Since the impact is in vertically downward direction, the DSA captures only those modal frequencies which tend to produce transverse bending. The time domain plot and the FFT plot are observed. A peak in FFT plot represents the resonating frequency.

Figure 16 a) Test Setup b) Impact hammer (free vibration)

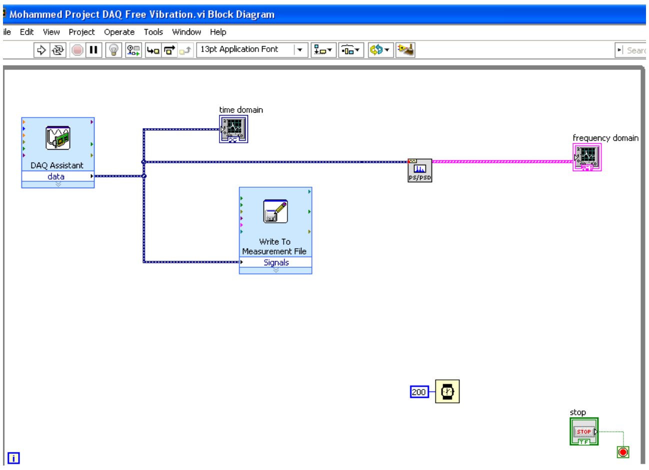

Fig.17 LabVIEW program for DAQ Setup

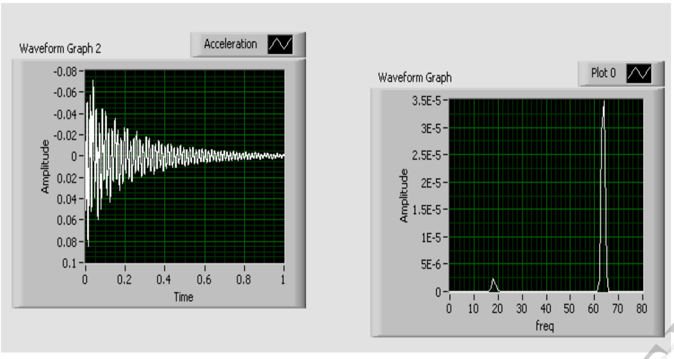

Fig.18 Free Vibration Response (LabVIEW)

DEWESoft™ is also used to determine the free vibration response of the prototype. The accelerometer is auto-calibrated and there is no need of programming.

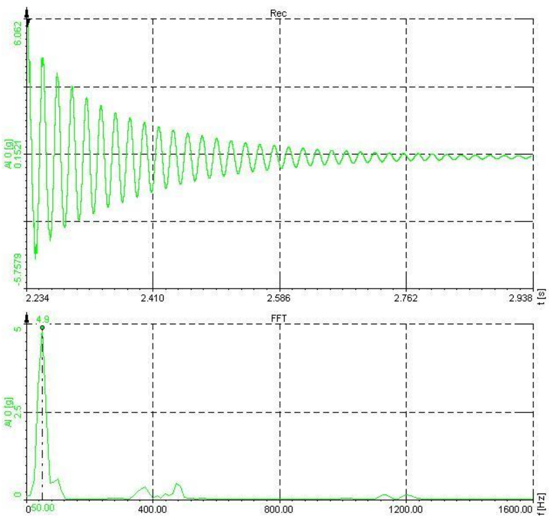

Fig.19 Free Vibration Response (DEWESoft)

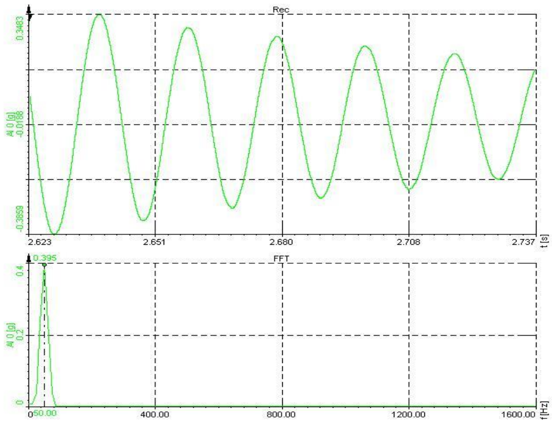

Fig.20 Logarithmic Decrement

B. Forced (Harmonic) Vibration Test Procedure

The physical setup is same as that of free vibration test. A vibration exciter (shaker) is placed at the free end and excited between the frequency range of 0-100 Hz. The FFT plot of the prototype is observed in DEWESoft.

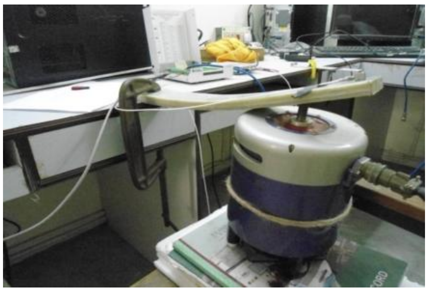

Fig.21 Forced Vibration Setup (Harmonic Exciter)

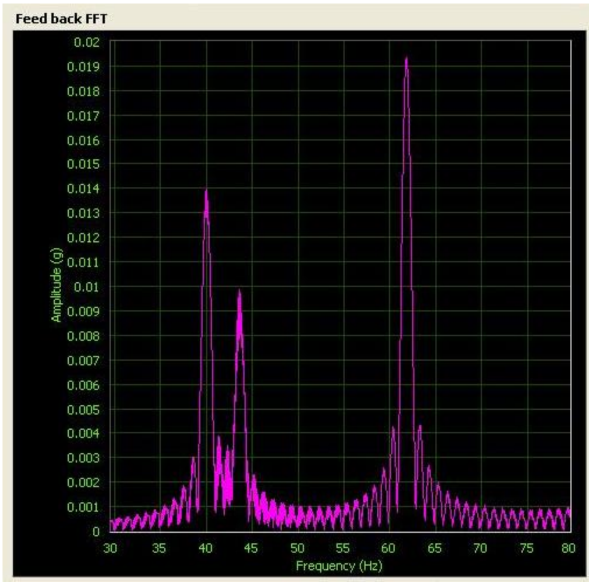

Fig.22 Forced Vibration Response (FFT) – DEWESoft

Table 7 Validation of Vibration Test Results with FEA

1st Modal Frequency - FEA (Hz)	64.62
1st Modal Frequency - Free Vibration - LabVIEW (Hz)	62
1st Modal Frequency - Free Vibration - DEWESoft (Hz)	60
1st Modal Frequency – Forced (Hz)	62

VI. CONCLUSION

- With this design approach, a weight reduction of 78.96% is achieved and the cost is reduced by 55.25%.
- It is observed that the experimental test results are in close proximity with the FEA results. The 1st modal frequency as obtained from experimental test is 62 Hz and that obtained from FEA is 64.62 Hz.
- The fractional deviation between the two results is very small which validates the design methodology.
- Modal frequencies are important in determining the performance of composite leaf spring over various road profiles as classified by ISO 2631-1, which is beyond the scope of this research work.

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