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Dynamic Analysis and Design Modification of a Ladder Chassis Frame Using Finite Element Method

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Abstract:
In this paper, dynamic analysis of a ladder chassis frame has been done using Ansys. Firstly, modal analysis of the chassis was done using three different materials namely structural steel, aluminium alloy and carbon/epoxy composite. The first six non-zero natural frequencies and their corresponding mode shapes were extracted, and the results were compared. It was observed that the maximum relative deformation per mode for structural steel chassis was less when compared to the other two materials. The structural steel chassis was thus selected for further analysis. It was observed that the 2nd natural frequency of the chassis was close to the engine excitation frequency at idling condition and the 5th natural frequency was close to the engine excitation frequency at high speed cruising condition. Thus, in the next part, some modifications were made in the chassis design so as to study their effect on the natural frequencies and push the frequencies away from the critical range, so as to avoid resonance. Finally, harmonic response analysis was done on the original and modified chassis to check the response under a harmonic force.

Keywords: Vibration, Resonance, Chassis, Dynamic, Analysis, FEM.

1. Introduction

Vibration problem occurs where there are rotating or moving parts in machinery. The effects of vibration are excessive stresses, undesirable noise, looseness of parts and partial or complete failure of parts [1]. The structures designed to support heavy machines are also subjected to vibrations. The structure or machine component subjected to vibration can fail because of material fatigue resulting from cyclic variation of the induced stress.

Chassis frame is the basic framework of the automobile. All the automobile systems like transmission, steering, suspension, braking system etc. are attached to and supported by the chassis frame. The frames provide strength as well as flexibility to the automobile. When the vehicle travels along the road, the chassis is subjected to excitations from the engine and transmission system as well as due to the road profile. Due to these excitations, the chassis begins to vibrate [2]. If the natural frequency of vibration coincides with the frequency of external excitation, resonance occurs, which leads to excessive deflections and failure [3].

In the current paper, dynamic analysis of a ladder chassis frame has been done using Ansys software. Modal analysis of the chassis was done using three materials and their performance was compared. The structural steel chassis was chosen for further consideration and modifications were tried out to push the natural frequencies beyond the critical range. Harmonic analysis was done on original and modified chassis to check the response to harmonic force.

Ladder chassis frame: The ladder chassis frame consists of two symmetrical long members and a number of connecting cross members. This type of chassis is commonly found in busses, trucks, SUV's and pick-up vans.

Modal Analysis: Modal analysis is used to determine the mode shapes and natural frequencies of a machine or a structure. It is the most basic form of dynamic analysis. The output of modal analysis can further be used to carry out a more detailed dynamic analysis like harmonic response analysis, transient analysis etc.

Harmonic response analysis: From the natural frequencies obtained by modal analysis, the harmonic analysis determines which vibration modes contribute more significantly to the dynamic response of the structure through frequency response curves [4].

2. Dynamic Analysis of Ladder Chassis Frame

A. *Modal Analysis of Chassis Frame Using Three Different Materials and their Comparison*

A ladder chassis frame has been chosen for analysis. The chassis frame consists of long members and cross members as shown in Fig. 1. The FE model of chassis is shown in Fig. 2. Modal analysis of chassis frame has been carried out in Ansys in the free-free condition. Analysis is done using three different materials namely structural steel, aluminium alloy and carbon/epoxy composite. Since free-free condition has been used, the first six natural frequencies are either zero or very close to zero. They correspond to rigid body motion and have been neglected. The first six non-zero natural frequencies and their corresponding mode shapes have been extracted and the results have been compared.

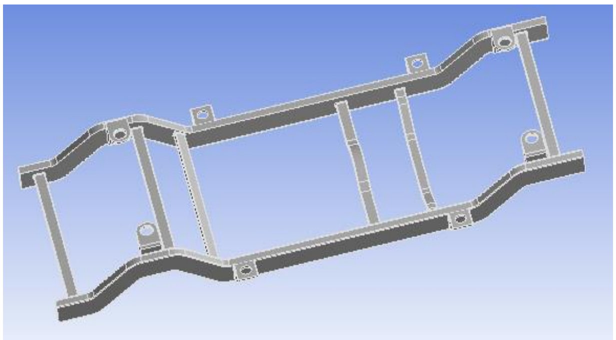


Fig. 1. 3D model of chassis frame.

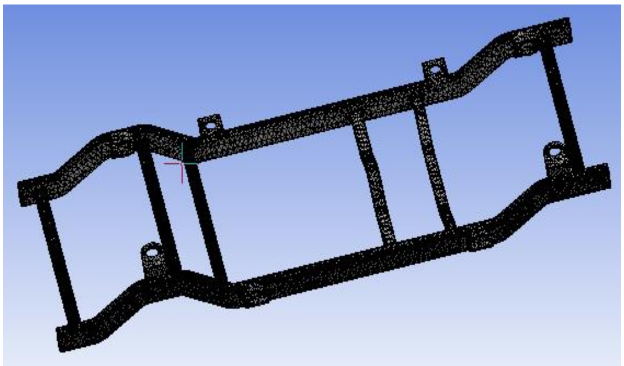


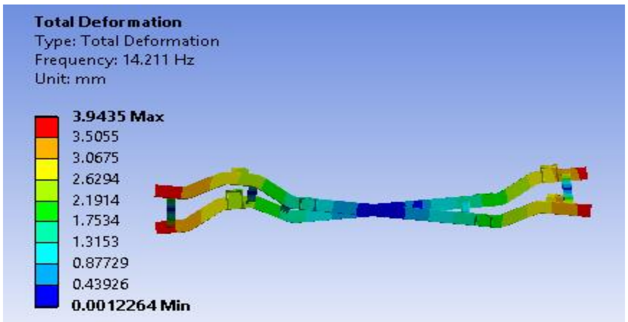
Fig. 2. FE model of chassis frame.

Material: Structural Steel. Material properties: Density=7850 kg/m³, Young's Modulus=200 GPa, Poisson's Ratio=0.3.

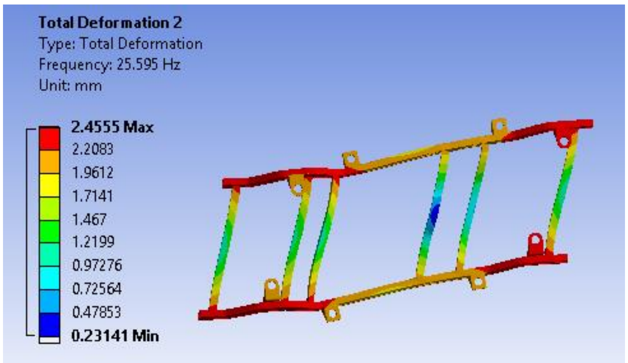
Table 1: Natural frequencies and deformations for structural steel

Mode	Frequency (Hz)	Max. deformation (mm)
1	14.211	3.9435
2	25.595	2.4555
3	36.627	4.2618
4	37.933	4.3112
5	48.59	4.7416
6	62.499	6.561

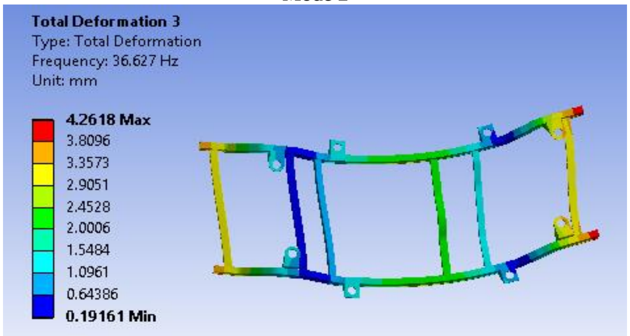
The first six mode shapes for the structural steel chassis are shown in the figure below.



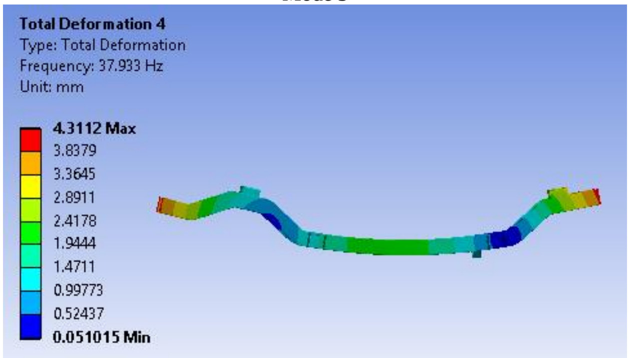
Mode 1



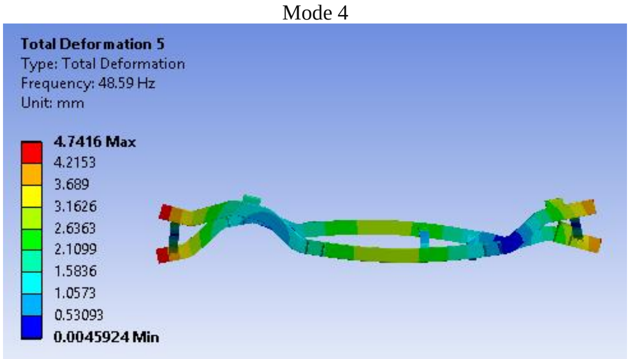
Mode 2



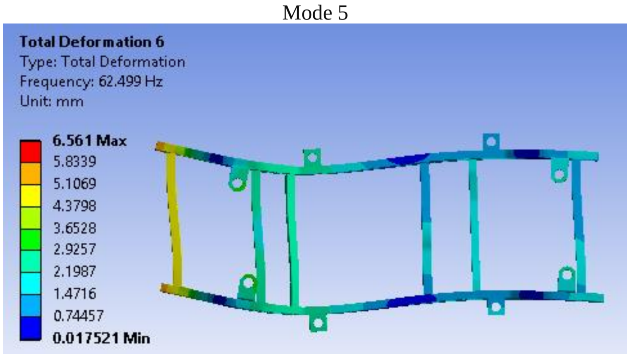
Mode 3



Mode 4



Mode 5



Mode 6

Fig. 3. Mode shapes for structural steel chassis.

It can be seen from Fig. 3 that the first mode shape is the first twisting mode of the chassis and occurs at a frequency of 14.211 Hz. The fourth mode is the vertical bending mode and occurs at 37.933 Hz frequency. The fifth mode occurs at a frequency of 48.59 Hz and is the second twisting mode of the chassis.

Material: Aluminium Alloy. Material properties: Density=2770 kg/m³, Young's Modulus=71 GPa, Poisson's Ratio=0.33.

Table 2: Natural frequencies and deformations for aluminium alloy

Mode	Frequency (Hz)	Max. deformation (mm)
1	14.215	6.6453
2	25.871	4.1339
3	36.864	7.1831
4	38.057	7.252
5	48.724	7.978
6	62.901	11.042

The mode shapes for aluminium alloy chassis are same as that for the structural steel chassis. The only difference is in the values of relative deformations.

Material: Carbon/epoxy. Material properties: ρ=1490 kg/m³, E_x=121 GPa, E_y=8600 MPa, E_z=8600 MPa, ν_{xy}=0.27, ν_{yz}=0.4, ν_{xz}=0.27, G_{xy}=4700 MPa, G_{yz}=3100 MPa, G_{xz}=4700 MPa.
Where, ρ=Density, E= Young's modulus, ν= Poisson's ratio, G=Shear modulus.

Table 3: Natural frequencies and deformations for carbon-epoxy

Mode	Frequency (Hz)	Max. deformation (mm)
1	9.6306	9.4919
2	18.72	9.701
3	21.942	6.1095
4	26.046	10.52
5	28.832	8.936
6	45.008	14.301

For composite material chassis, the first mode is the first twisting mode, the second mode is the vertical bending mode, while the fourth and fifth modes are again twisting modes.

Comparison of results: The natural frequencies, maximum relative deformation per mode and weight of chassis have been compared for the three materials used in the following figures.

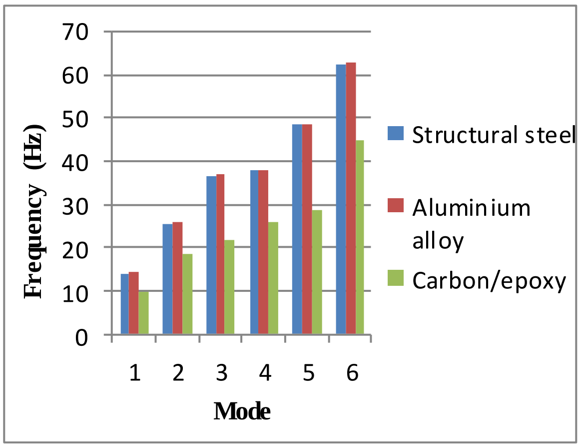


Fig. 4. Natural frequency Vs. mode number.

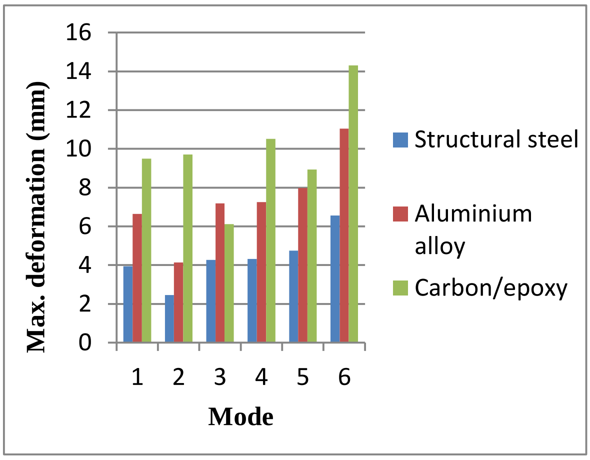


Fig. 5. Max. deformation Vs. mode number.

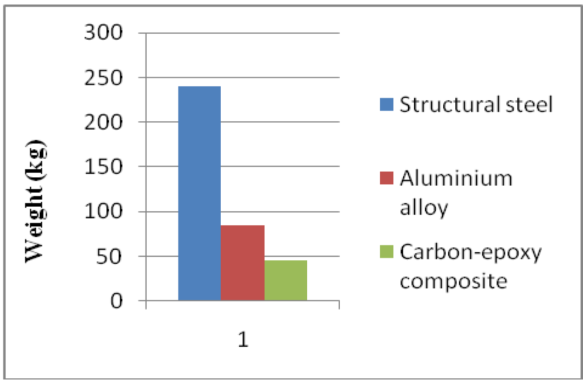


Fig. 6. Comparison of weights.

From the above comparisons, we can say that the frequency values for Structural steel and aluminium alloy chassis are nearly the same, while those for carbon-epoxy composite material chassis are on the lower side. However, the maximum relative deformation per mode is the lowest for structural steel chassis. As compared to the steel chassis, the weight of the composite material chassis is 80% less.

The structural steel chassis was selected for further analysis.

B. Chassis Modifications to Avoid Resonance

As can be seen from the previous discussion, the first six natural frequencies for the structural steel chassis lie in the range from 14-63 Hz. In practise, the road excitation has typical values varying from 0-100 Hz. At high speed cruising, the excitation is about 3000 rpm or 50 Hz [2, 5, 6]. Diesel engine is known to have operating speed varying from 8-33 rps [7]. In low speed idling condition, the speed range is about 8-10 rps. This translates into excitation frequencies varying from 24-30 Hz [2]. From modal analysis results of structural steel chassis, we can see that the second natural frequency lies in the 24-30 Hz range, while the fifth frequency is close to 50 Hz. Thus, the chassis may experience structural resonance at idling and high speed cruising condition. We will try to modify the chassis and try to push the natural frequencies away from the critical range. The modifications will lead to either change in mass or change in stiffness or both. An increase in mass will reduce the natural frequency, while an increase in the stiffness will increase the natural frequency.

The original chassis is as shown in Fig. 1 and consists of six cross members. The long members are of hollow rectangular box-section with 5 mm thickness. The weight of original chassis considering structural steel material is 240.1 kg. The overall length is 3825 mm.

Modification 1: In this iteration, two changes have been made to the original chassis. The thickness of the long members has been reduced from 5 mm to 4 mm and an additional steel cross member has been added. Material of chassis is structural steel. The modified chassis 1 is shown in Fig. 7 below.

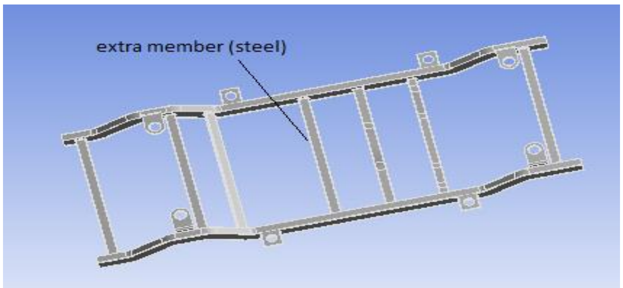


Fig. 7. Modified chassis 1.

The natural frequencies obtained are compared with the original case as follows:

Table 4: Comparison of natural frequencies for original chassis and modified chassis 1.

Mode	Frequency (original) (Hz)	Frequency (modification 1) (Hz)
1	14.211	13.681
2	25.595	21.888
3	36.627	32.031
4	37.933	34.891
5	48.59	46.63
6	62.499	52.998

It can be seen from the above comparison that due to the modification; all the six natural frequencies have reduced and the second and fifth frequencies have moved away from the critical zone. Also, this modification decreases the weight of chassis to 223.36 kg. Thus, the effect of this modification is to reduce the natural frequencies.

Modification 2: In this iteration also, two changes have been made to the original chassis. Firstly, the overall length has been reduced from 3825 mm to 3675 mm. Also, two extra cross members made of steel have been added. Material of chassis is structural steel. The modified chassis 2 is shown in Fig. 8.

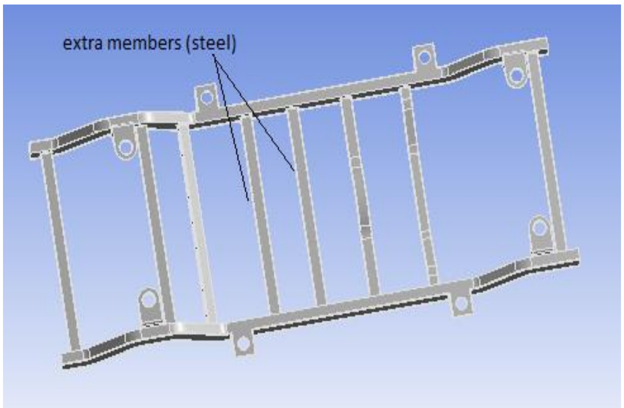


Fig. 8. Modified chassis 2.

The results as compared to the original chassis are given below:

Table 5: Comparison of natural frequencies for original chassis and modified chassis 2.

Mode	Frequency (original) (Hz)	Frequency (modification 2) (Hz)
1	14.211	14.955
2	25.595	30.714
3	36.627	37.687
4	37.933	38.366
5	48.59	50.316
6	62.499	65.116

The above table shows that due to this modification, the natural frequency of chassis for all six modes has increased. The second natural frequency has moved beyond 30 Hz and the fifth natural frequency has moved beyond 50 Hz. The weight of chassis after this modification is 247.68 kg, which is slightly more than that of the original chassis. Thus, the effect of this modification is to increase the natural frequencies.

Modification 3: In this iteration, the length of chassis has been reduced from 3825 mm to 3675 mm and two extra cross members made of carbon-epoxy composite material have been added. The remaining body of chassis is made of structural steel. The modified chassis 3 is shown in Fig. 9 below.

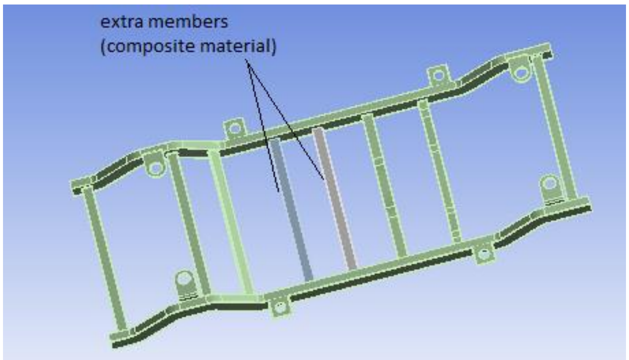


Fig. 9. Modified chassis 3.

The comparison of frequencies is given in the table below:

Table 6: Comparison of natural frequencies for original chassis and modified chassis 3.

Mode	Frequency (original) (Hz)	Frequency (modification 3) (Hz)
1	14.211	14.525
2	25.595	30.352
3	36.627	38.343
4	37.933	39.306
5	48.59	50.775
6	62.499	65.09

From the above table, we can say that this modification also results in an increase in the natural frequency values for all modes. The second and fifth mode frequencies have moved beyond the critical range. Also, the weight of chassis has reduced from 240.1 kg to 237.93 kg due to this modification. Thus, the effect of this modification is to increase the natural frequencies.

C. Harmonic Response Analysis of Original and Modified Chassis

In this part, a harmonic force having magnitude equal to engine weight (1000 N) is applied to one of the cross members and the average response of the entire chassis to this harmonic force at different frequencies is recorded. The output is the frequency response curve, where the peaks correspond to the natural frequencies corresponding to the vertical bending modes of the chassis.

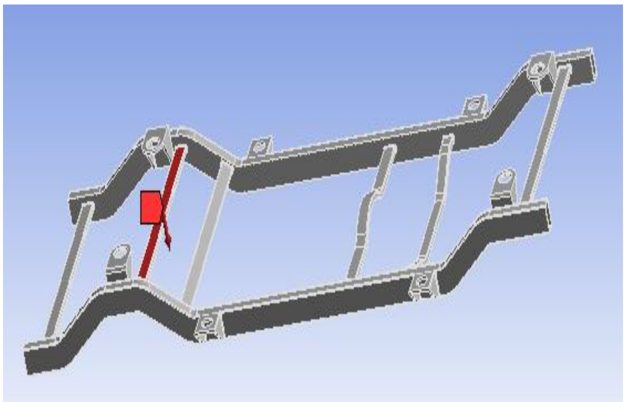


Fig. 10. Harmonic force applied to chassis.

The frequency response curves for the original chassis and the three modified chassis are shown in the figures below.

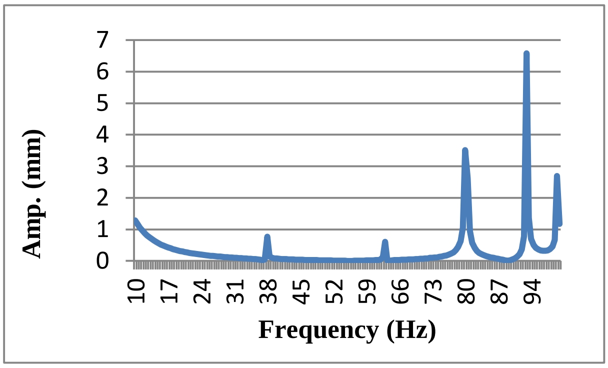


Fig. 11. Frequency response curve- original chassis.

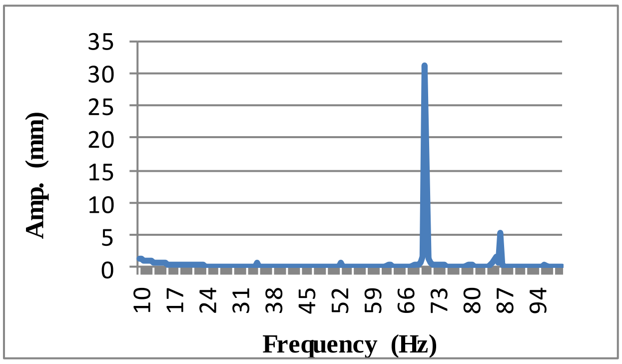


Fig. 12. Frequency response curve- modified chassis-1.

Fig. 13. Frequency response curve-modified chassis 2.

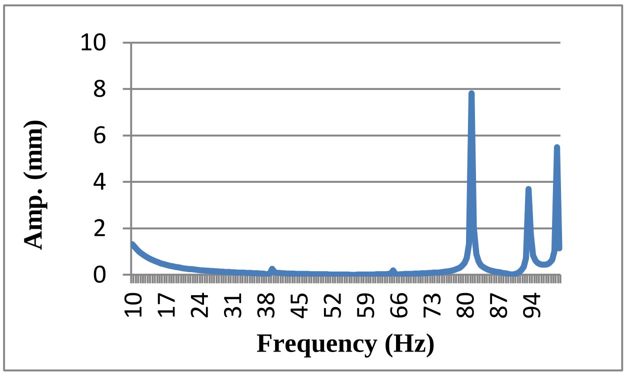


Fig. 14. Frequency response curve-modified chassis 3.

From the above four frequency response curves, we can see that the maximum amplitude of vibration is 6.5799 mm at 93 Hz for the original chassis, 31.227 mm at 71 Hz for modification 1, 15.97 mm at 78.5 Hz for modification 2 and 7.8215 mm at 81.5 Hz for modification 3. Thus, out of the three modifications, the amplitude of vibration is minimum for modification 3.

3. Conclusion

In this paper, dynamic analysis of a ladder chassis frame was carried out and based on the results, some modifications were made to the chassis to study their effect on the natural frequencies of the chassis. The modifications included reduction in overall length of chassis, reduction in thickness of long members, addition of extra cross members and use of alternate materials for cross members. These modifications helped in pushing the frequencies away from the critical range. The following conclusions can be drawn from this work:

- The frequency values for Structural steel and aluminium alloy chassis are nearly the same and lie in the range 14-63 Hz, while those for carbon-epoxy composite material chassis are on the lower side (9-45 Hz). However, the maximum relative deformation per mode is the lowest for structural steel chassis. By using composite material for the chassis, there is a reduction in weight by 80 % over steel chassis.
- These frequencies lie in the range of excitation frequencies due to engine vibrations and road profile excitations.
- Reducing the length of chassis increases its stiffness and hence increases its natural frequencies.
- Extra cross members added to chassis mainly affect its second natural frequency and increase it significantly.
- Using these methods, we can alter the natural frequencies of the chassis and place them in the natural range and hence prevent resonance and unusual chassis vibrations.
- Out of the three modifications made, harmonic analysis showed that for the given inputs, the amplitude of vibration is minimum for modification 3. It also reduced the weight of chassis by 3 kg.

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