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Track Modulus Analysis of Railway Track System Using Finite Element Model

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Abstract: With the development of ever faster trains, the problem of excessive ground vibrations has increased. Dealing with ground vibration from surface and underground trains is a challenging issue for the railway industry. In the present work, the analysis of a typical Indian railway track system has been done with special emphasis on "track modulus" for Prestressed Concrete (PSC) sleepers and Wooden (WOOD) sleepers. The track consists of two rails of standard length, rail pads and sleepers with constant sleeper spacing, ballast and subgrade covering the length of the rails as per the Indian Railways standards. Finite Element models have been developed for computer simulation of the dynamic behaviour of the railway track system for 52PSC, 60PSC, 52WOOD and 60WOOD track. In this model, subgrade, ballast and rail pad parameters have been considered for parametric analysis of the track modulus. Finally the track system is excited harmonically over a range of frequencies to predict the dynamic variation in the track modulus.

Key words: Rail pad, sub-grade, track modulus, track stiffness.

1. INTRODUCTION

The problem of ground vibration due to a moving train on a track system is important for trains with heavier axles and for faster train service. Sheng et al. (2006) have reported that the frequencies of ground vibration cover a range from about 2 to 200 Hz. Many researchers have modeled the rail as a Beam (with mass and stiffness) On Elastic Foundation (BOEF), with the ballast being represented by a linear spring (Geena, 1998). In many situations, in the track model the rail is described as an infinitely long beam discretely supported at rail/sleeper junctions by a series of springs, dampers and masses representing a Discretely Supported Model (DSM) (Zhai and Cai, 1997). In dynamic analysis of vehicle-track-soil interaction models at sufficiently high frequencies, the simplest model of a rigid wheelset mass gives reasonable results (Auersch, 2005). In rail transit systems, the abrupt change in track stiffness (support) from the track configuration of ballasted track to nonballasted track is often associated with accelerated rates of change of track geometry and component degradation, resulting in high maintenance cost and poor ride quality (Jenks, 2006). Norman et al. (2004) pioneered mea-

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Figures 1–23 appear in color online: http://jvc.sagepub.com

surement of track modulus from a moving vehicle. Since there was no stationary reference, a laser based vision system was used to measure the relative displacement between the track and wheel/rail contact point.

Track integrity is strongly related to the vertical track modulus, which is the relation between the rail deflection and the vertical load applied on the rail. Both low and high values of track modulus will increase the dynamic loading on the track internally, reducing structural integrity and increasing maintenance requirements (Lu et al., 2007). The track stiffness is defined as the ratio of applied wheel load to the rail deflection. Jenks (2006) defined the track modulus as the supporting force per unit length of rail per unit deflection. Agarwal (2007) has reported that the track modulus, like modulus of elasticity, is an index of the resistance to deformation. In the present study, the analysis of various track systems is done. These analyses focus on computation of track modulus. Computation of dynamic track modulus from harmonic loading of the track at different frequencies has also been attempted. Such work has not been reported in the literature.

2. TRACK SYSTEMS ANALYZED

The static and dynamic analysis of a typical track system of Indian Railways has been done using a finite element model to estimate “track modulus”. The layout of the railway track is shown in Figure 1. The track consists of two rails of standard length, sleepers with a constant sleeper spacing of 0.65 m and subgrade and ballast covering the standard length of the rails as per the Indian Railways standards. In this work four types of track systems as per broad gauge specification of Indian Railways have been analyzed. The track specifications are laid down by Research Design and Standards Organisation (RDSO), Lucknow, India. The four types of tracks are:

(i) 52PSC track
(ii) 60PSC track
(iii) 52WOOD track
(iv) 60WOOD track

The 52PSC and 60PSC track systems consist of an ‘I’ rail cross – section with masses of 52 and 60 kg respectively per meter length of the rail. The rails in these tracks are supported by prestressed concrete sleepers. The track (rail and sleeper) super structure is covered with ballast, which in turn rests on the subgrade (soil). All geometrical and material parameters are from RDSO and Indian Standards (IS) specifications. The 52WOOD and 60WOOD tracks are similar to the PSC tracks described above, the only difference being that here rails are supported by wooden sleepers as against prestressed concrete sleepers.

3. FINITE ELEMENT MODELING OF TRACK SYSTEM

For the present analysis, a 1.95 m length of rail section with other components like rail pads, sleepers, ballast and subgrade has been considered. Rail of length 1.95 m has been chosen since the center to center distance between the two wheelsets in one bogie is 2.896 m; this

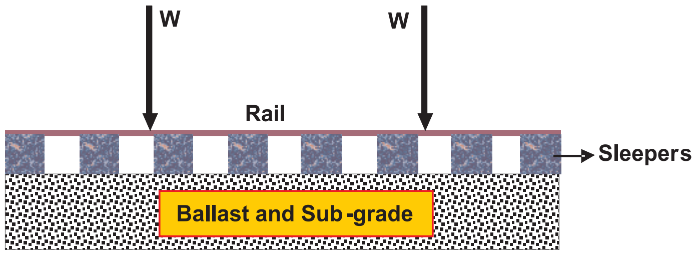

Figure 1. Track model.

Table 1. Element type used for each system component.

System component		Element type
Rails		SOLID92
Sleepers	PSC	SOLID65
	WOOD	SOLID92
Rail pads		SOLID92
Ballast		SOLID45
Subgrade		SOLID95

length has been considered to accommodate one axle load; periodic boundary condition is applied at the ends of the track, providing an assumption of periodicity of that axle load. This mimics the periodic boundary condition provided by the single-axled track testing vehicle used for measurement of track modulus in the field. The measurement of track modulus from the railway track is done just below the point where one axle load is applied and it is a localized effect. The proposed model takes advantage of the spatial periodicity of the track-soil system. In this manner, one can reduce the analysis for the overall system to a problem posed on a generic cell. For this length, there are three sleepers with sleeper spacing of 0.650 m. This can accommodate a load corresponding to one axle. Subgrade of depth 2 m is considered for the analysis. The distance between the rails is 1.676 m (Broad gauge track section).

The track model used in this study consists of three dimensional fully integrated solid elements generated using the finite element package ANSYS 8.1. Each node has three translational degrees of freedom, i.e., bounce (vertical), lateral and longitudinal degrees of freedom. Table 1 shows the type of elements used for modeling individual system components.

In this study, periodic boundary conditions are imposed on both sides of the track system, especially on subgrade, ballast and rails since the structure is spatially periodic. Making the meshes at the two boundaries identical, matching the nodes on both sides of the boundary and coupling the vertical displacements of the boundary nodes on both sides imposes the periodic boundary condition (Mukhopadhyay, 2000). Fixed boundary condition is imposed at the bottom of the subgrade. Figure 2 shows the PSC track model with the black lines indicating the locations where periodic boundary conditions have been imposed.

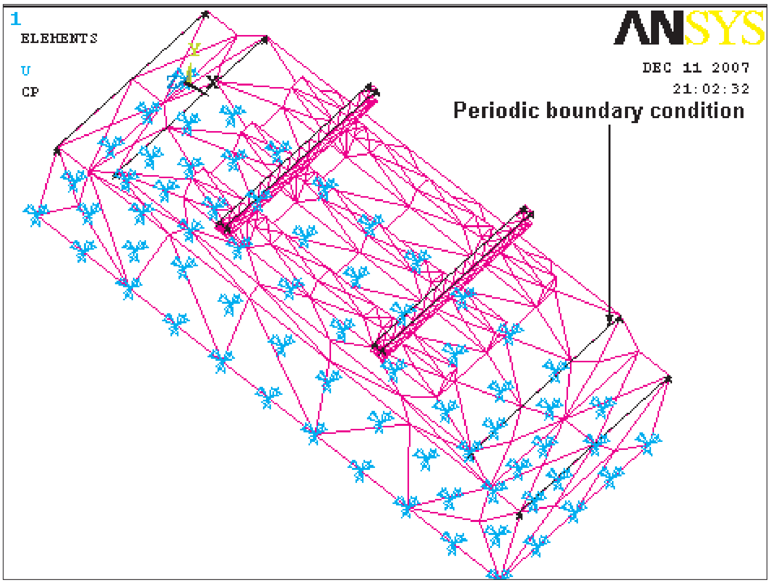

Figure 2. PSC sleeper track system with boundary conditions.

Table 2. Geometrical data for the track system components.

Cross section dimensions of the PSC sleeper	0.24 m × 0.24 m × 0.15 m
Cross section dimensions of the wooden sleeper	0.25 m × 0.13 m
Length of the PSC sleeper	2.74 m
Length of the wooden sleeper	2.75 m
Dimensions of the rail pads	
52PSC track model	0.15 m × 0.136 m × 0.01 m
60PSC track model	0.15 m × 0.150 m × 0.01 m

Table 3. Discretization details for the different track models.

Track model	Number of elements	Number of nodes
52PSC	2590	5224
60PSC	2657	5277
52WOOD	1858	3776
60WOOD	1891	3827

3.1. Modeling of PSC and Wooden Sleeper Track Systems

The details regarding the geometry of the system components which are considered for modeling the different track systems are shown in Table 2. Table 3 shows the details of discretization for each type of track system. The material properties for different components of the track system, some of which have been reported in reference (Kumaran, 2002) are listed in the Appendix. Figures 3 and 4 show the finite element models of the tracks with Prestressed Concrete Sleepers and Wooden sleepers respectively.

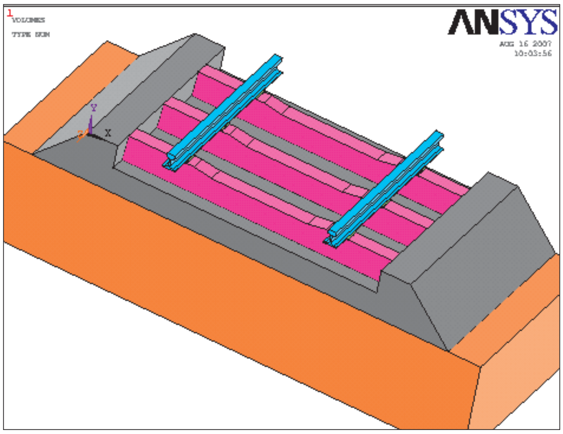

Figure 3. 52 and 60PSC track model.

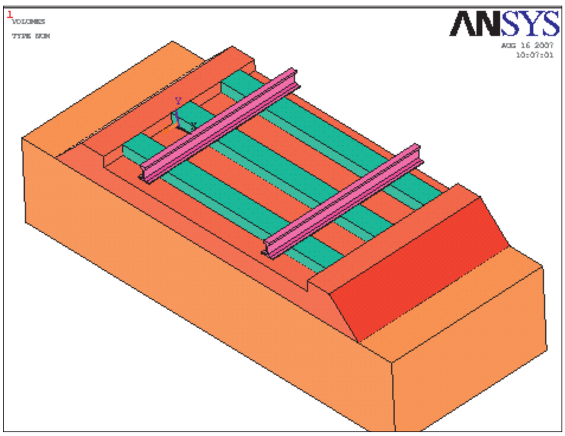

Figure 4. 52 and 60WOOD track model.

3.2. Assumptions Made in Modeling

The analysis of the track system is based on the following assumptions:

(a) The material properties of individual components of the track system like subgrade, ballast and rail pad are homogeneous and isotropic.

(b) The effect of sleeper/rail joint fasteners is not included for analysis. Compared to static axle load or dynamic wheel load and the resulting displacements, the load and displacement due to stiffness of the fasteners is much lower. The track modulus which is measured at the point where the load is applied may not be affected by this small load/displacement value.

(c) All the geometric data and material properties are as per standards of the Research Design and Standards Organisation (RDSO) and IS specifications.

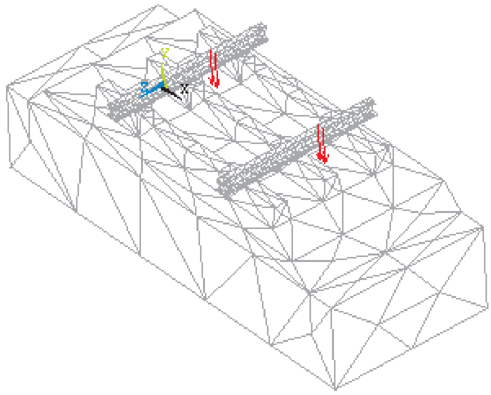

Figure 5. PSC sleeper track system with loading.

(d) The effect of the thrust by the side folder of the ballast on the sleepers has not been considered.
(e) The analysis has been carried out for vehicle gross load condition as per IR specifications.

4. COMPUTATION OF TRACK MODULUS

The track stiffness k has been calculated as

$$k = \frac{W}{y} \tag{1}$$

where W = load applied on the rails and y = displacement of the rail at the loading point.

The track modulus U is defined as

$$U = \left(\frac{1}{64EI}\right)^{\frac{1}{3}} \left(\frac{W}{y}\right)^{\frac{4}{3}} \tag{2}$$

where E = modulus of elasticity of the rail and I = moment of inertia of the rail.

The track moduli have been computed using MATLAB 7.0. Corresponding to a constant (gross) axle load of 25 tonnes, a load of 6.25 tonnes is applied at four nodes on the top surface of the rails as shown in Figure 5 for the computation of track modulus. Subsequently, all the four track systems have been excited harmonically (with the dynamic loads being given at the same excitation locations as for the static analysis) over the range of frequencies 0 to 60 Hz to predict the displacement and acceleration at the loading points. A peak sinusoidal (gross) axle load of 40 tonnes (being around 1.5 times the static load) has been applied at the rails for dynamic analysis. The loads are applied at the nodal level, by assuming that there is a line contact between the rail and wheel.

Table 4. Details of the different soil types.

Type of soil	Modulus of elasticity (Es) (MPa)	Notation used in plots
	Sandy soil	
Dense sand and gravel	108 to 215	Hs
Dense sand	27 to 108	Ms
Loose sand	11 to 27	Ls
	Clayey soil	
Stiff clay and silty clay	54 to 108	Hc
Medium clay	22 to 54	Mc
Soft clay	5 to 22	Lc

5. RESULTS AND DISCUSSION

5.1. Track Modulus-parametric Study

Track modulus has been computed for the four different track systems by applying a vertical static load of 25 tonnes. A parametric study considering Young's modulus for different soil conditions such as (i) dense sand and gravel, (ii) dense sand, (iii) loose sand (iv) stiff clay and silty sand, (v) medium clay and (vi) soft clay has been done. Table 4 shows the various types of soil, their moduli of elasticity and the notations used in Figures 6 and 7 to indicate them. The study has also been extended to include Young's modulus of the ballast and rail pad. For this study, material properties of the track components, except the parameter being varied, have been assumed to be in the middle of the range specified in the Appendix.

Figure 6 shows the variation in displacement at one of the points of excitation due to variation in Young's modulus for the different soil conditions mentioned above for 52 and 60PSC tracks and Figure 7 shows the same for 52 and 60WOOD tracks. There is a difference between the displacements of the 52PSC and 60PSC track models for the high stiffness (Hs) subgrade; however no such difference is observed for the 52WOOD and 60WOOD tracks. Figure 8 shows the displacement due to variation in Young's modulus of the ballast for the PSC and wooden track models. From this figure it may be inferred that the displacements of the 52PSC and 60PSC track models are well separated for the entire range of ballast modulus values. In the case of WOOD track however, there is only a marginal difference in displacements between 52WOOD and 60WOOD track especially for low ballast modulus values. Figure 9 shows the displacement due to variation in Young's modulus of the rail pads for the PSC track models.

Figure 10 shows the variation in track modulus due to variation in Young's modulus for the different soil conditions mentioned above for 52 and 60PSC tracks and 52 and 60WOOD tracks. Figure 11 shows the change in track modulus due to variation in Young's modulus of the ballast and rail pads for the PSC track. Figure 12 depicts the change in track modulus due to variation in Young's modulus of the ballast for WOOD track.

In the case of subgrade with low stiffness (shown as Ls and Lc in Figures 6 and 7), track superstructure (sleeper and rail) behaves like a rigid body as seen from the displacements plotted in Figure 13. Here the black lines represent the undeflected shapes and the red lines the deflected shapes.

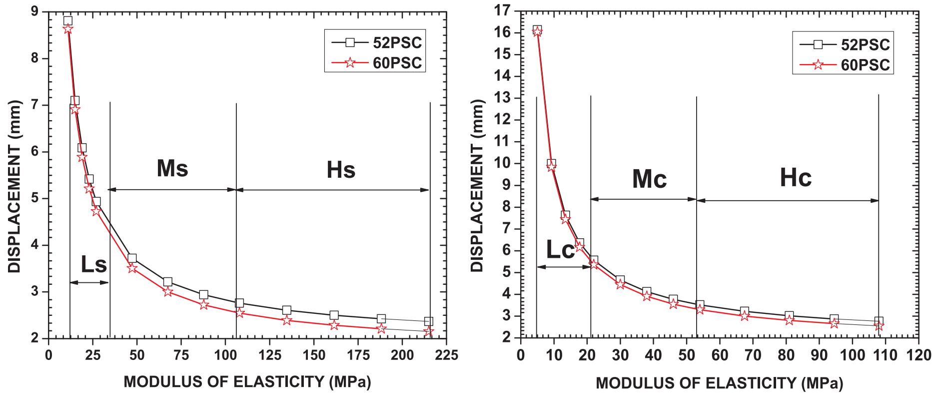

Figure 6. Displacement plots for PSC track model: sandy soil (left) and clayey soil (right).

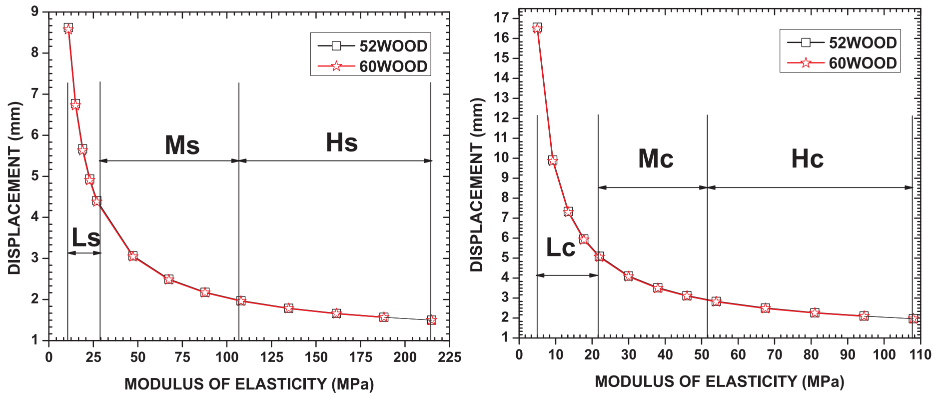

Figure 7. Displacement plots for wooden track model: sandy soil (left) and clayey soil (right).

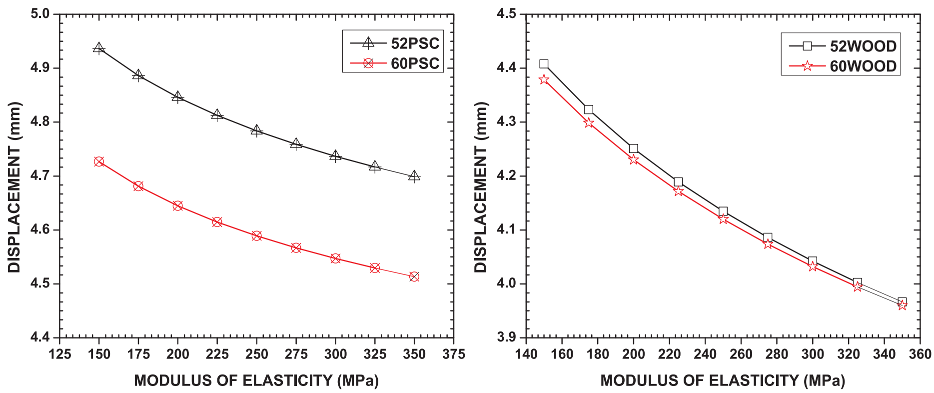

Figure 8. Displacement plots for both track models due to variation in ballast modulus: PSC (left) and WOOD (right).

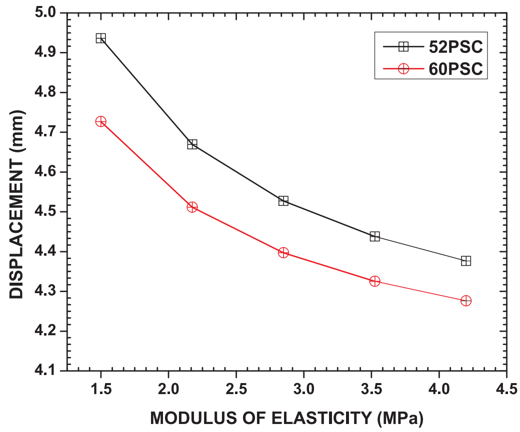

Figure 9. Displacement plots for both track models due to variation in rail pad modulus.

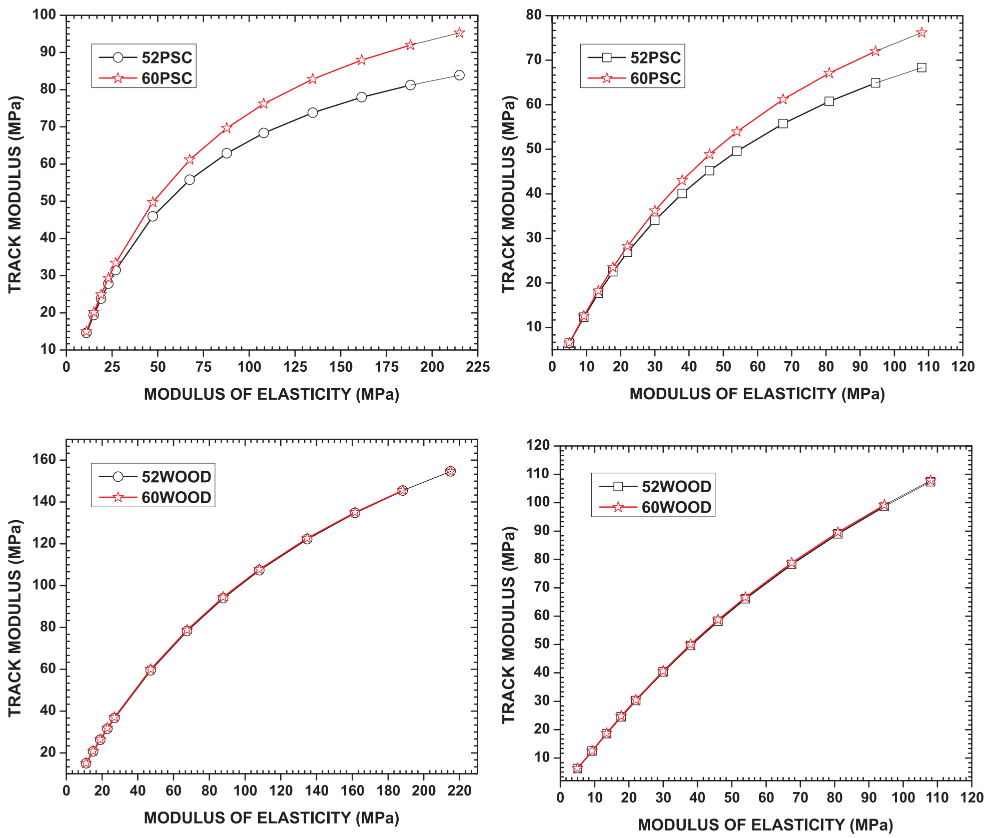

Figure 10. Track moduli due to variation in soil modulus: PSC track with sandy soil (top-left) and clayey soil (top-right); WOOD track with sandy soil (bottom-left) and clayey soil (bottom-right).

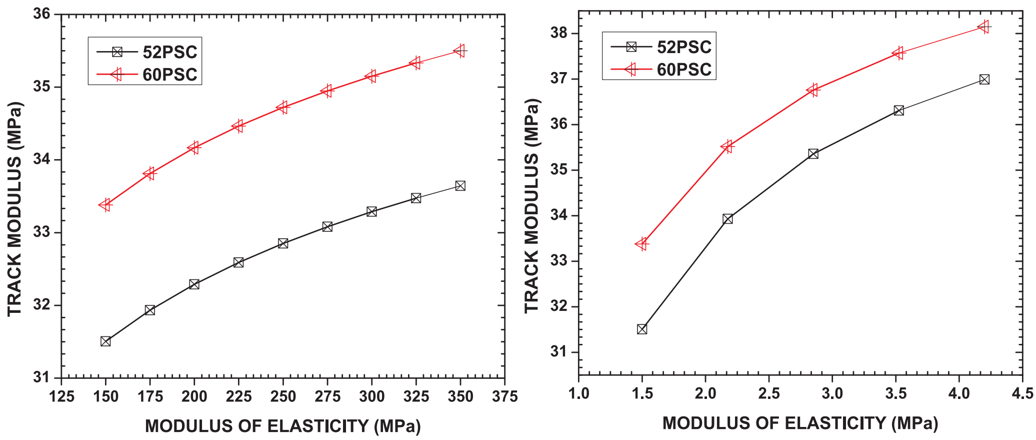

Figure 11. Track moduli for PSC track model due to variation in ballast (left) and rail pad modulus (right).

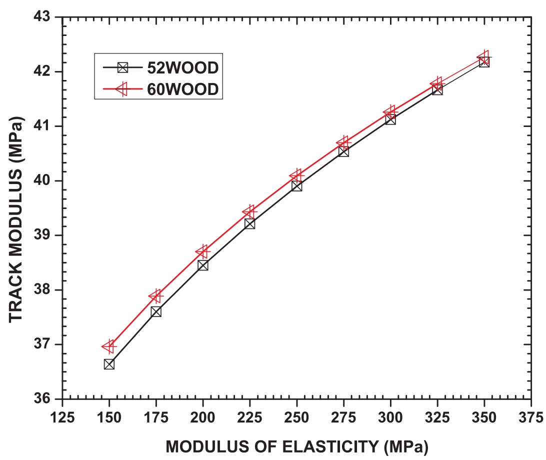

Figure 12. Track moduli for wooden track model due to variation in ballast modulus.

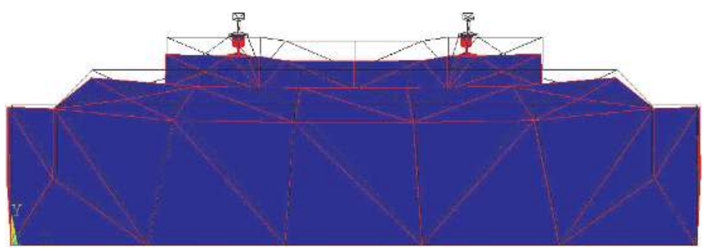

Figure 13. Displacement pattern for the track system due to subgrade with low stiffness.

5.2. Harmonic Analysis of Track System

All the four track systems have been subjected to harmonic loads of 40 tonnes (0-peak) over the frequency range 0 to 60 Hz to predict the displacement and acceleration at the loading points. For this analysis, material properties of all track components have been assumed as the lowest values in any range given in the Appendix. For the subgrade alone, modulus of elasticity of 27 MPa has been assumed. Figures 14 to 17 show the vertical displacement, acceleration, vertical track stiffness and the track modulus for the two different track system models 52PSC and 60PSC respectively. The peaks in Figure 14 may be attributed to a resonance condition as proved by the results in Figures 18 and 19. Figure 18 shows the mode shape plot for the 52PSC track system with eigen frequency of 33.404 Hz. Figure 19 shows Power Spectral Density plot for the 52PSC system, from measured acceleration data taken at the top surface of the rail, with vehicle speed around 80 kmph. Figures 20 to 23 show the vertical displacement, acceleration, vertical track stiffness and the track modulus for the two different track system models 52WOOD and 60WOOD respectively.

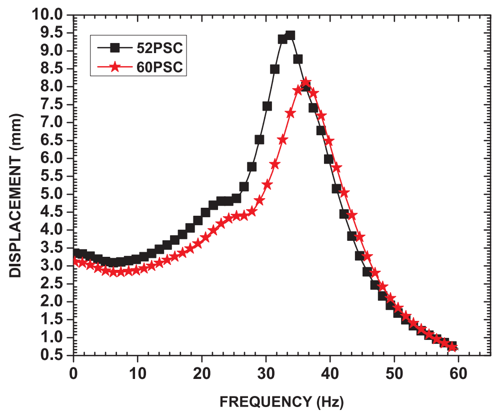

Figure 14. Vertical displacement of PSC track model.

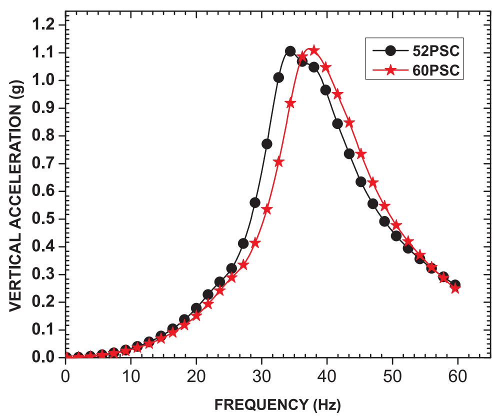

Figure 15. Vertical acceleration of PSC track model.

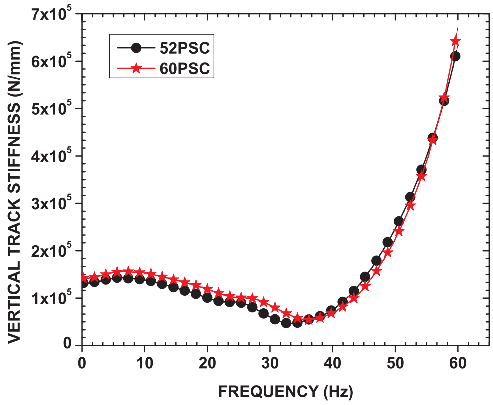

Figure 16. Track Stiffness of PSC track system.

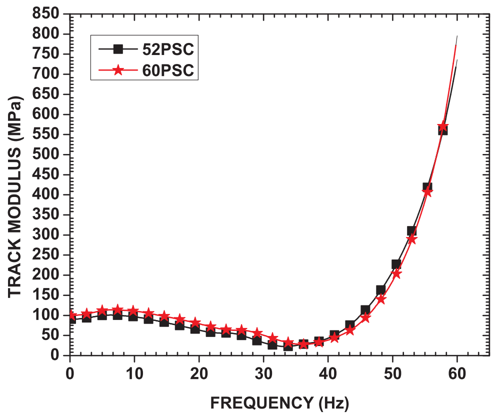

Figure 17. Track Modulus of PSC track system.

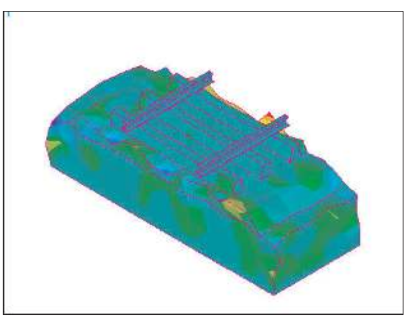

Figure 18. Mode shape (33.404 Hz) for 52 PSC track system.

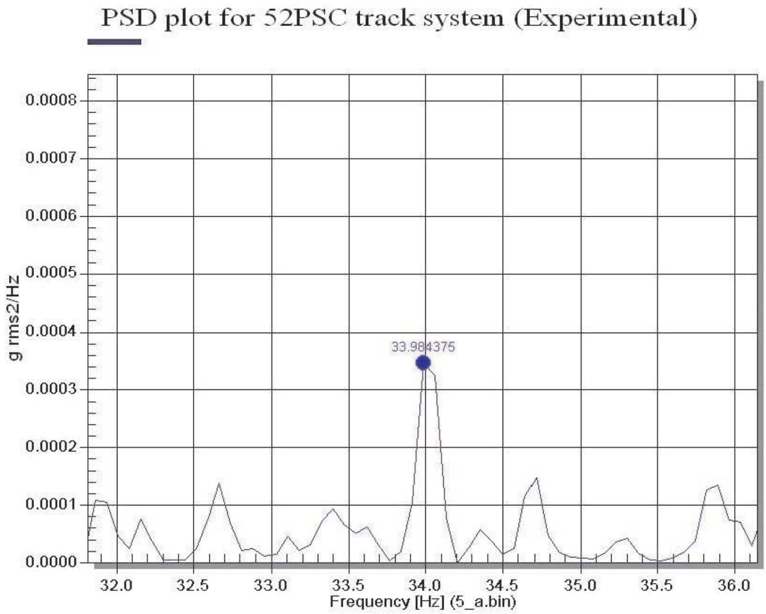

Figure 19. Power Spectral Density plot for 52PSC track system.

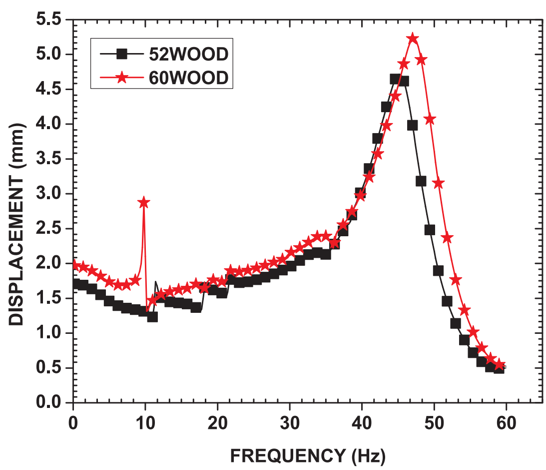

Figure 20. Vertical displacement of wooden track system.

6. SUMMARY AND CONCLUSIONS

6.1. Parametric Analysis of Track System

From the parametric analysis it is seen that ballast and rail pad stiffness may be the predominant parameters controlling the displacement behavior of both PSC and WOOD track

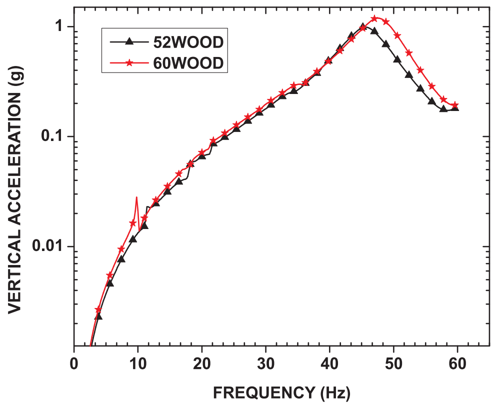

Figure 21. Vertical acceleration of wooden track system.

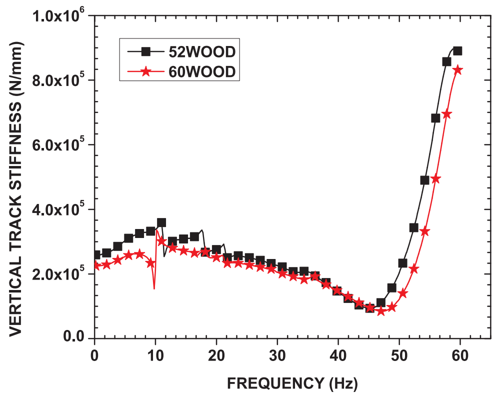

Figure 22. Track stiffness of wooden track system.

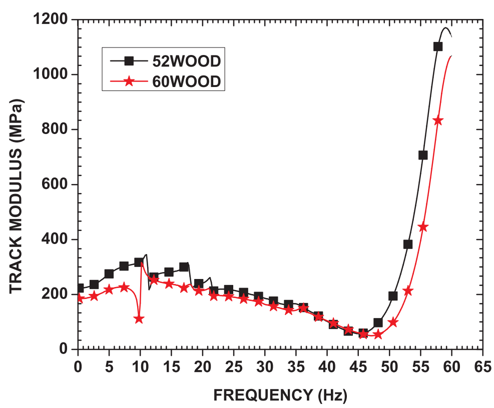

Figure 23. Track modulus of wooden track system.

systems. It is also seen that there is noticeable difference in the displacements between 52PSC and 60PSC track models. Such a difference is not perceptible between 52WOOD and 60WOOD track models as shown in Figure 20. The difference in the former can be attributed to the contribution from the rail pad (which is absent in the latter). Track moduli obtained from parametric studies (60 MPa) are comparable to the measured value of 50 MPa as reported by Agarwal (2007) and Lu et al. (2007). The results obtained from the present track modulus analysis model are comparable to the results of *Federal Railroad Administration, Office of Research and Development,* (65 MPa) (Norman et al., 2004) and GEOTRACK models (56 MPa) (Jenks, 2006) reports.

6.2. Harmonic Analysis of Track System

The harmonic analysis reveals that the average track (dynamic) modulus is around 100 MPa for PSC track system and 200 MPa for WOOD track system. The high peaks around 30 Hz and 60 Hz may be the effect of the natural frequency of the track system. From this analysis, it is seen that these track systems can withstand the present load up to a speed of approximately 250 kmph assuming a maximum wave number of 0.3 cycle/m. Due to the effect of resonance, in the long run there may be chances of fatigue failure in these track systems for continuous vehicle speed of 250 kmph and above. From Figures 18 and 19 it may be inferred that the high peak at 33.984 Hz in the PSD of the 52PSC track system may be due to the effect of the subgrade, validating the analytical findings.

APPENDIX

MATERIAL PROPERTIES OF TRACK COMPONENTS

Component/ properties	Modulus of elasticity (E) (MPa)	Poisson's ratio	Density (kg/m^3)	Damping ratio	Damping coefficient Ns/m
Rails	2.07×10^5	0.30	7.8×10^3	0.001–0.002	–
Rail pads	1.5–4.2	0.50	1.26×10^4	0.05	1.24×10^5
Concrete sleepers	0.384×10^5	0.15	2.5×10^3	0.04–0.07	–
Wooden sleepers	9400	0.40	320–720	0.09	–
Ballast	150–350	0.30	2×10^3	0.4	5.88×10^4
Subgrade	0.5–250	0.25	1.8×10^3	0.01–0.03	3.12×10^4

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