ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

RAILWAY ENGINEERING STREAM

Master of Science Thesis

On

Dynamic comparison of Conventional ballasted track

Versus

Ballasted ladder track

By: Mengistu Wondimu Jemema

Advisor: Mequanent Mulugeta (Msc)

Addis Ababa, Ethiopia

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Declaration

The work described in this research was conducted at Addis Ababa University, Institute of Technology from 2013-2015. The work contained in this thesis has been not previously submitted for a Master degree or PHD. at any other higher education institution. To the best of my knowlegde and belief,the thesis contains no material previously publshed or written by another person except where due reference is made.

Signature_____________, Mengistu Wondimu

Date_____________

Abstract

In railway transport system there is a continuous demand for railway capacity enhancement. In order to meet the demands in many countries more axle load and higher speed of the train is applied. As a result of these the track responses are becoming big issues that have a great effect on track service. Therefore to develop and utilize appropriate tracks that cover relevant vibration effect, it is necessary to critically analyze and comparatively describing dynamic response of the tracks.

The main purpose of this research is to study and compare dynamic response of ballasted ladder and conventional ballasted of railway tracks by using finite element method. Both tracks are completely different depends on rail support system. Ladder track is continuous support system while conventional ballasted track is discrete support system. Depending on structural nature of tracks, both of tracks have been simulated in two dimensional finite elements by using commercial software Abaqus. Rail is considered as a solid element on discrete support in a conventional ballasted track while in the ballasted ladder track as continuous support system. Spring and dashpot has been used for the simulation of railpads and ballast.

In the model dynamic explicit analysis has been used for the simulation of a moving load and Eigen frequencies and corresponding vibration modes were extracted from both of the models. Finally by using simulation output, dynamic responses of both of tracks are compared in terms of time and frequency domain.

Dynamic responses of both tracks are relatively compared and found that the ballasted ladder track under different speed has lower vibration responses than conventional ballasted track, even if its level of responses at different frequency range is not the same. On contrary, conventional ballasted track shows higher vibration responses irrespective of frequency range. Ballasted ladder track at higher frequency range effectively reduce vibration of track components more than conventional ballasted track. However, at very low frequency range there is no great difference observed. In general the simulations indicate that the ballasted ladder track is effective in reducing vibration at high speed and frequency. Finally this thesis indicates the possible extensive comparative study of dynamics of both tracks by improving the assumption and the modeling approach applied in this research.

Keywords: Dynamics of track, ladder track, conventional ballasted track, finite element analysis, discrete support system, and continuous support system

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Mengistu wondimu

Addis Ababa, Ethiopia

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Abbreviations, Notation and indices

PC	Pre-stressed concrete
RC	Reinforced concrete
BOEF	Beam on Elastic Foundation
GUI	Graphical User Interface
FE	Finite Element
Qd	Dynamic load
Qe	Vehicle Static Load
V	Speed of Vehicle
$H_{\omega F}(f)$	Complex Transfer Function from Force to Displacement
$S_{\omega\omega(f)}$	Auto Spectrum of Displacement
S_{FF} (f)	Auto Spectrum of the Force
ṡ	Factor of the Quality conditions of the track
EI	Bending Stiffness
Ch	Contact stiffness
E-B	Euler Bernoulli Beam
R-T	Rayleigh Timoshenko Beam
K	Shear Factor
G	Shear Modulus
m	Mass
M	Moment
f	Vibration Frequency
f_{pp}	Pin-Pin vibration frequency

CHAPTER ONE

1. Introduction

Technological development paved away for innovation of different track from time to time .Starting from classical track to modern track there were different type of tracks innovated to suit high speed train .Among modern track that was innovated by Japan is ballasted ladder type of track .Gradually this track has been improved to Floating ladder track. Ballasted ladder track is a track structure consists of continuously supported rail and twin parallel pre-stressed concrete beams and transverse steel gauge members to connect the beams. It is effective in significantly minimizing maintenance work compared to conventional ballasted track. Both Ballasted and Floating ladder tracks ensure safety and efficiency of train. Floating ladder track is mostly efficient in reducing structural born noise due to vibration of a track (Wakui, H.,Matsumoto,N.,Okuda,H., and Asanuma,K., 2002).

The main difference of the conventional ballast track and Ballasted ladder track is rail supporting system; rail of ladder track is continuously supported by longitudinal sleeper (ladder sleeper) while in conventional ballasted track it is supported by discrete traversal sleeper. Ladder sleeper is longitudinal precast concrete beam which transversally gauged by steel pipe.

From 1940-1960 experiment were carried out in France, Japan and Soviet union on ladder track but none of the experiment was successful, and idea was abandoned in favor of conventional ballasted track. In 1993 the Structural Engineering Group of Japan's Railway Technical Research Institute (RTRI) examined the reason for failure of ladder track and concluded that there was no enough attention was given in keeping track gauge. Since then ladder track is developed and tested in service (H. Wakui, N. Matsumoto, H. Inoue. , 1997).

With large scale construction of urban rail transit, elevated structure are used more and more in rail transit lines as major form. More elevated rail transit system run often through city down towns and resident areas .They induce series track vibration. The influence of vibration on the living and working environments of people has been brought to the attention of many Engineers and researchers. To surmount the vibration problem, Ladder type of a track is now on application in different country like Japan and America and China (H. Wakui, N. Matsumoto, H. Inoue. , 1997). To analysis efficiency of ladder track, dynamic analysis model of an elevated bridge with ladder tracks under moving train load was established, and vibration of an elevated bridge was analyzed. The result shows that ladder track has good vibration reduction characteristic when compared to conventional ballasted track (Asanuma.k, 2006). Because of this ladder track is mostly used in viaduct, elevated structure and tunnel to reduce ground borne vibration.

In this study both ballasted ladder and conventional ballast tracks are simulated in Abaqus software using two dimensional finite element model. In the model some main parameters like ballast and rail pad stiffness and damping is considered to represent real behaviors of track component. Other relevant parameters that are used in the simulation are parameters of the new high performance tracks in china and

Japan. The values of physical parameters of the tracks that can be considered are typical values based on standard configuration of each type of track and may vary with certain range.

In simulation both of the tracks are modeled differently depending on rail supporting system: ballasted ladder is continuous support while conventional ballast is discrete support system. All components of the tracks are modeled as finite solid element except wheel (rigid element).

Explicit dynamic analysis type has been applied to analyze structural response of a track under moving load. To extract Eigen frequency and corresponding Eigen mode, steady state modal dynamics has been used. The output of the model is presented in acceleration, velocity, displacement versus time and frequency domain, and relative dynamic performance of both tracks are compared precisely.

1.1 Description of the Ladder track Components

Ladder track is new innovative track that composed of ladder sleepers which are reinforced concrete bases. The ladder sleeper is a ladder-shaped mixed structures consisting of twin longitudinal pre-stressed concrete (PC) beams and transverse steel pipe connectors as shown in figure 1.1 and 1.2. Transverse steel pipe connectors inserted into the longitudinal beams. Longitudinal pre-stressed concrete beams and rail bear train load and increase the performance of load dispersion .Ladder track system is also applicable to curved lines ,where the curved track can be realized by laterally displaced rail fasteners, and the growing super elevation in transitions can be realized by varying the thickness of the bottom girder of the L-shaped. Longitudinal beams with concrete casting and transverse steel pipe connection are used to maintain track gauge. (Wakui, H.,Matsumoto,N.,Okuda,H., and Asanuma,K., 2002).

There are two types of ladder track; ballasted ladder track and Floating ladder track. Ballasted ladder track is a new vibration reducing track which has been well used in Japan and America .Several theoretical analyses and Engineering applications performed in Japan proved that the ladder track system, with light weight, sufficient and effective elasticity, and low- maintenance and low-cost properties, is an ideal track system that can effectively reduce vibration and noise of the track while keeping good train-running safety and stability. The comparison of structural vibration induced by train, on vibration mitigation tracks and on common track, can improve the theory of elevated rail transit and also the vibration isolation measures in the elevated bridge structures (Wakui, 2006), (Wakui, H.,Matsumoto,N.,Okuda,H., and Asanuma,K., 2002), (Okuda, H., Sogabe, M., Matsumoto, N., and Wakui, H., 2003), (Okuda, H., Sogabe, M., Matsumoto, N., and Wakui, H., 2003).

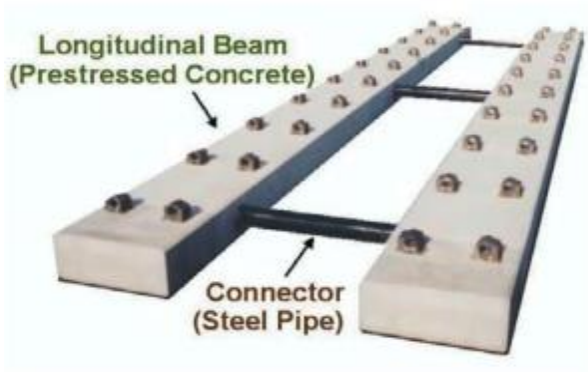


Figure 1.1 3D view of typical ladder track

The ladder structure part consist both ladder beam and transverse pipe connector is so called ladder sleeper, as shown in Fig.1.1, it is a ladder-shaped mixed structure. The transverse steel- pipe connector is inserted into the longitudinal beams with concrete casting. Transversal steel gauge bars are used to maintain the gauge/spacing between the rails and connect the concrete beams at a spacing of approximately 3m. Sometimes ladder track may have sleeper pad under longitudinal beam to increase the performance of the track as shown in figure 1.2.

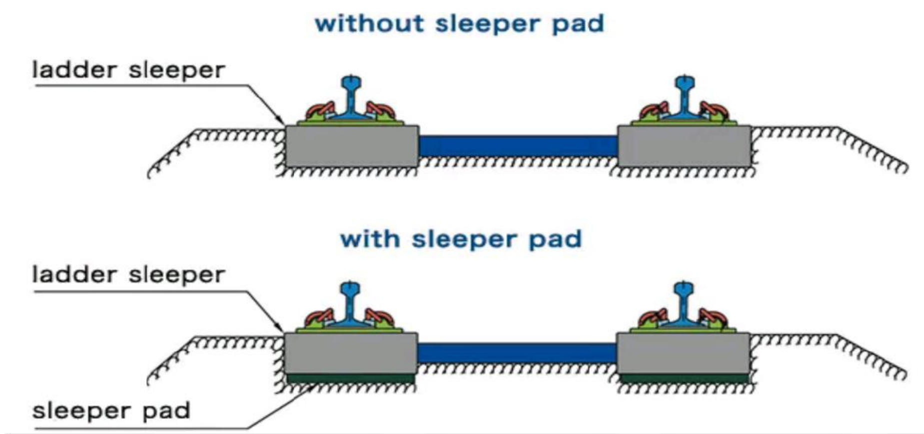
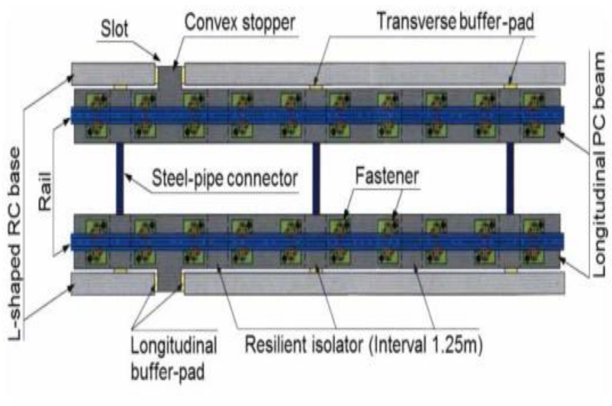


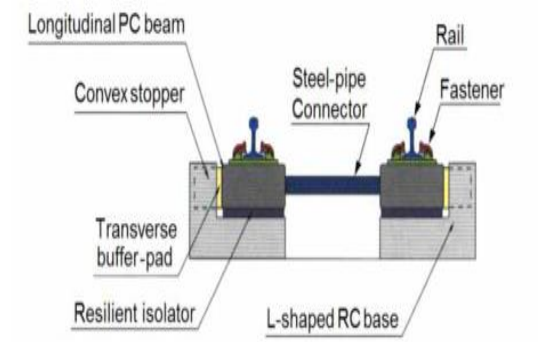
Figure1.2 ballasted ladder track with sleeper pad and without sleeper pad

1.2 Floating Ladder Track

Floating ladder track is a track system which is floated from L-shaped concrete track bed by supporting the ladder sleeper with low stiffness springs at constant intervals. It has also resilient isolators and buffer pads and sleeper pads made of polyurethane damping materials as shown in figure 1.3 a) and b). There are two types of Buffer pads: longitudinal buffer pads and transversal buffer pads which is used to reduce longitudinal and transversal vibration of the track. Ladder sleeper of Floating ladder track minimize vibration and noise of the track and significantly reduce period of maintenance and simplify installation work .It is more effective in reducing construction cost and vibration on elevated structure and viaduct because it is light in weight (Wakui, 2006), (Wakui, H.,Matsumoto,N.,Okuda,H., and Asanuma,K., 2002), (Tahira, M. and Miyahara, K. I. J, 2003).



a)



b)

Figure1. 3 Floating ladder a) Feature of floating ladder track with different buffer pads and connectors b) cross section of floating ladder track with L-shaped RC base

1.3 Conventional Ballasted track

Conventional Ballasted track serves as one of the major infrastructures for freight and passenger transport on the world wide. In the past decades, an increasing demand for such transport has led to the use of considerably heavier and faster trains. The ballast layer is an important component in the dynamic behavior of ballasted track, particularly with regard to noise and vibration. The noise radiated by the sleepers on plain track at-grade is dependent on the direct stiffness of the ballast and, for track on bridges or in tunnels; it is the transfer stiffness that controls the transmission of vibration to the supporting structure. The material damping loss factor is also important. For each of these three parameters, relevant, low amplitude, high frequency information for train-loaded ballast is rare. It is of interest to that studying impact damage on the track components and track formation as well as those interested in noise and vibration. As indicated in figure1.4, ballasted track has superstructure and substructure in which formation layer distribute train load into the ground.

Ballast is the main structural part of railroad where the sleepers are laid. Its main function is to transfer the loads coming from the super structure to the sub-grade without failure and providing good drainage.

The dynamic response of railway ballasted track would be affected by several parameters such as rail pad and ballast stiffness, rail surface roughness, track components condition and the other things. Among these parameters, the principal parameter was the rail pad and ballast stiffness that was related in the track support stiffness (Esveld C. , Modern Railway Track, 2001), (Kaewunruen S., Remennikov A ., 2008).

The vibration that is caused by the moving dynamic load is absorbed on one hand by the elastic rail fastening, the railpad, the base plate pad, and on the other hand by the ballast. However, the ballast has unfavorable properties at certain higher frequencies. It must also be taken into consideration that the static stiffness of the railpad and base plate pad increases with the load. The dynamic stiffness and damping increase with frequency. Furthermore, their stiffness increases with age. The stiffness of the railpad and base plate pad also increases with decreasing temperature.

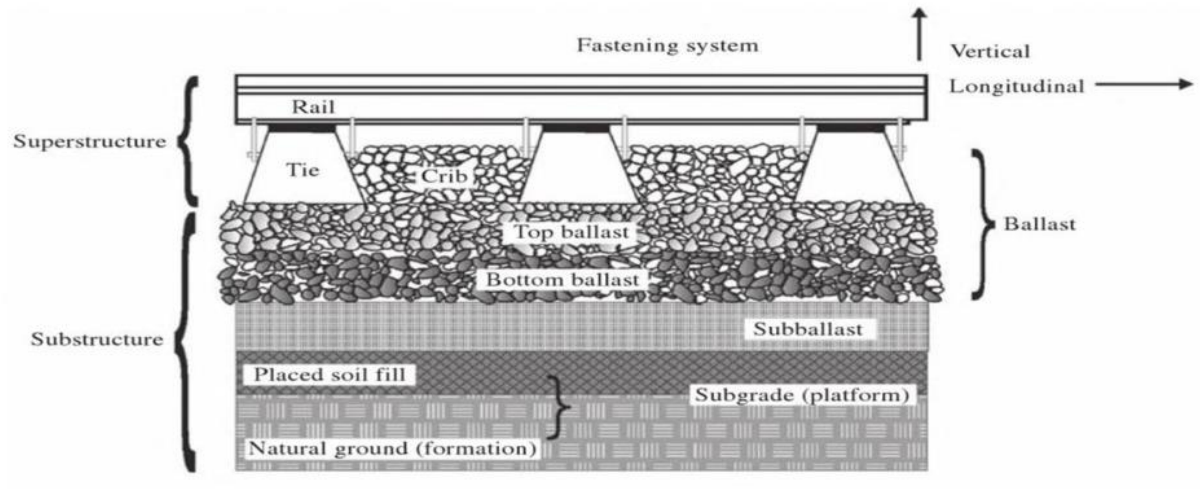


Figure 1.4 Longitudinal view of conventional ballasted track

General Objectives

Nowadays there is high demand for high speed rail way line; however the demand is limited by dynamic performance of the track. Therefore it is necessary to investigate and apply appropriate track which is efficient under high dynamic load and rapid speed. The main objective of this research is so far to conduct detail analysis on dynamic response of both ballasted ladder track and conventional ballasted track to relatively describe their performances.

Specifically the accomplishment of the studies focus on:-

- Reviewing previous literature on the dynamic behavior of conventional ballasted track, and ladder track
- Simulating both tracks in Finite element model using Abaqus software
- Studying the Overall dynamic response of the both track structures under vertical dynamic loading

Responses of both tracks are studied under different speed to see the relative efficiency of ballasted ladder track in comparison to conventional ballasted track.

Scope of the Study

In this thesis both track (conventional ballasted track and ballasted ladder track) are simulated in Abaqus finite element software. For simplification and time cost reduction, two dimensional element models are applied for dynamic explicit and modal dynamic analysis. The responses of both of the tracks under different speed level are also studied. To conduct the research precisely, the calculations performed are limited to the vertical direction of the track. The longitudinal or lateral response of the track is not included. Floating ladder track is not part of this study because it is very efficient in reducing dynamic effect of the track which is difficult to compare with classical track. No experimental test is conducted for validation of the model; instead previous experimental test results conducted by different researcher on both tracks are used to validate the model.

Structure of the Thesis

Here is precise description of each chapter to overview content of the Thesis. In Chapter one literature review related with the scope of the thesis is presented .This section briefly describe the structural nature of both ballasted ladder and conventional ballast track and in chapter two dynamic properties of each components of track and dynamics of overall track is mentioned concisely.

Different mathematical (Numerical) and Finite element model is presented in chapter three. Discrete support and continuous support model approach are models related with this study are briefly explained to have deep understanding of this research. Not only this but also analysis type that are used in this study are highlighted.

In chapter four, modeling approach of both ladder and ballasted track in Abaqus software is presented. In this chapter some assumption and simplification considered and procedure of modeling of the track are mentioned.

The results of the finite element modeling in Abaqus are presented in Chapter five and the dynamic analyses are divided into frequency analysis, steady-state dynamic analysis and explicit dynamic analysis. Vibration modes and Eigen frequency extracted from Abaqus are demonstrated, and the relative dynamic properties of both railway tracks system have been studied and comparatively described through time and frequency domain.

The last chapter which is chapter six consists of conclusion and some recommendation made for further study.

CHAPTER TWO

2.1 Dynamic Properties of Track Components

Railway track is a fundamental part of railway infrastructure that be classified to superstructure and substructure. The most primary parts of the tracks are the rails, rail pads, sleepers (ties), ladder beam, transverse of steel- pipe connector and rail fastening systems. These are referred to as the superstructure, while the substructure is consisted with a geotechnical layer consisting of ballast (gravel), sub-ballast and sub-grade (formation and base). The typical shape and construction profiles of a ballasted track are shown below figure 2.1.

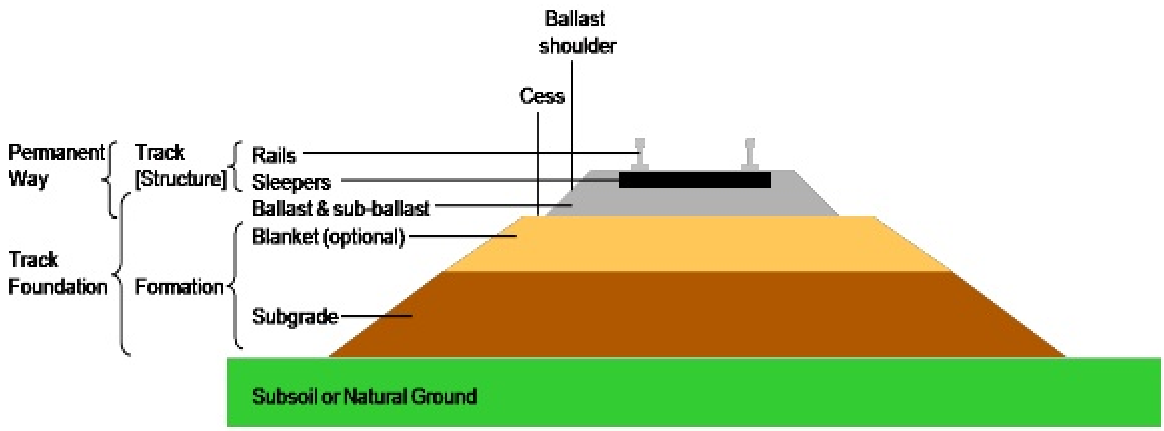


Figure2.1 Typical Railway ballasted track cross section

2.1.1 Rail

The rails provide smooth running surfaces for the train wheels, and guide the wheel sets in the direction of the track. The rails also accommodate the wheel loads and distribute these loads over the sleepers or supports. Lateral forces from the wheel sets and longitudinal forces due to traction and braking of the train are also transmitted to the sleepers and further down into the track bed. The rails also act as electrical conductor for the signaling system.

Rail is linear element characterized typically by infinite length. This allows modeling rail as a beam. Rails have flexural stiffness in vertical and lateral directions and compression stiffness in the longitudinal direction. It has also a shear stiffness which is often neglected. Rails can be modeled using either Euler Bernoulli or the Timoshenko beam theory (Timoshenko, 1926).

Rail segment in conventional ballasted track subjected to pinned-pinned resonant frequency which occurs at 800-1000Hz; it is corresponding to first bending resonant frequency of segment of rail between two sleepers. (It is so called pinned because the rail is supported by railpad at two ends of sleeper support and allows rotation).

2.1.2 Rail pads

Rail pad is a provision of comforting element between the steel rail and concrete surface. It transfers the rail load to the sleeper and filter out the high frequency force components (K.Knothe, Gleisdynamic,Ernst & Sohn, 2001). The rail pads provides a resilience function between rail and sleeper that helps absorb shock and impact from the wheels to the rails, and reduce a damage of rail supporting point and contact abrasion. The railpads provide electrical insulation of the rails and they protect the sleepers from wear. The railpads also affect the dynamic behavior of the track. The railpad stiffness should be as low as possible to a certain limit. Railpads with a dynamic stiffness between 100 and 200 MN/m and static railpad stiffness between 50 and 100 MN/m are commonly used in Europe. Soft railpad allows larger deflection of rail and train axle load is distributed over wide area .It also decrease high frequency vibration transferred down to substructure ,on contrary stiff railpad directly transmit axle load and high frequency load variation to layer below the wheel (Kaewunruen S., Remennikov A ., 2008). Rail pads are installed on rail supporting Points to reduce the dynamic stress from vehicle loads and dynamic wheel impact force (Esveld C. , Modern Railway Track, 2001). These rail pads are very important because of it reduces the dynamic effect between rail and sleepers. Inappropriate or inadequate uses of rail Pads increase the damage and defect of sleeper such as cracks at rail seat .Further, the wrong use of rail pads increases high settlements of tracks, and ballast/subgrade breakage. This negative effect has a problem on the capacity and integrity of an entire railway ballasted track system.

Several researches have demonstrated the dynamic behavior of rail pads mathematically (linear or nonlinear models). Dynamic rail pad models are usually on both time and frequency domain the previous studies show the frequency domain model implicates dynamic properties such as resonant frequencies and damping.

2.1.3 Fastening systems

Rail fastenings are components which together form the structural connection between rail and sleeper. The fastening system is used to hold the rail onto the sleepers, to ensure fixing of the rails. The choice of fastening greatly depends on the type of sleeper and geometry of the rail (Esveld C. , Modern Railway Track, 2001), (Kaewunruen S., Remennikov A ., 2008).

Fastenings clamp the rail gauge within acceptable tolerances and then absorb forces from the rails and transfer them to the sleepers. Vibration and impact are also dampened and decelerated by fastenings .Fastenings also acts as electrical insulation between the rail and the sleepers (Dahlberg Tore, 2003).

The fasteners withstand the vertical, lateral, and longitudinal forces on the rails, and keeping the place of the rails .The fastener especially transfers the longitudinal forces due to the change of temperature to the adjacent sleepers (Esveld C. , Modern Railway Track, 2001). In a track the rails are fastened onto the sleepers or ladder beam in a case of ladder track.

2.1.4 Sleepers

Sleepers are transverse beams resting on ballast and support .Wooden sleepers were used in the past because timber was available abundantly However, pre-stressed or reinforced concrete sleepers, and to a limited extent steel sleeper, have been adopted in modern railway tracks over the past decades because of their durability and long service life.

Depending on which frequency interval is of interest, the concrete sleeper can be modeled as either a rigid mass (at frequencies below 100 Hz) or as a flexible beam. For frequencies up to 300 or 400 Hz, the Euler-Bernoulli beam theory may suffice (Dahlberg Tore, 2003). At higher frequencies, the Rayleigh-Timoshenko beam theory should be used for an accurate description of the sleeper vibration (Knothe, Ki and Grassie, 1993). At higher frequencies, the mass of sleeper is becomes increasingly important and it is essential to consider the sleeper as a dynamic component that has both mass and stiffness. Because of its distributed mass and stiffness, the sleeper resonates at a series of frequencies, the most significance for typical sleepers being around 200 Hz. Along the rail, the stiffness changes because it is supported by sleepers separated by a distance around 65 cm. The stiffness is higher when the wheel passes at the level of a concrete sleeper. Variation of stiffness along the rail produces vibration of rail on sleeper. These vibrations induced by the sleeper distance have a frequency f (Hz) given by the equation where V is the speed of the train and D is the distance between two sleepers (Esveld C. , Modern Railway Track, 2001)

$$f = \frac{v}{D} \qquad (2.1)$$

Many investigations dealing with the dynamic properties of concrete sleepers have been performed, modal testing in particular (Ford, 1988). Researcher carried out modal testing and numerical modeling of a reinforced concrete sleeper. It was laid on a very soft spring support and excitations were done with an impact hammer and a swept sine loading of a shaker with different load amplitudes. Different types of modal parameter extraction methods were used and showed that linear behavior arises in the low frequency range but is less in the higher frequency range.

2.1.5 Ladder beam (ladder sleeper)

The ladder sleeper is a ladder–shaped mixed structures consisting of twin longitudinal pre-stressed concrete (PC) beams and transverse steel pipe connectors. Transverse steel-pipe connectors inserted into the longitudinal beams and longitudinal buffer pads are used to prevent the sleepers from creeping. (Wakui, H. and Matsumoto, N., 2002). Longitudinal PC beams and rail bear train load and increase the performance of load dispersion (Wakui, 2006).Ladder track system is also applicable to curved lines ,where the curved track can be realized by laterally displaced rail fasteners, and the growing super elevation in transitions can be realized by varying the thickness of the bottom girder of the L-shaped. This connection is used to maintain track gauge. Relative longitudinal movement of rail and ladder is lower than conventional track because of this anti movement of included in the structure between ladder beams in the case of floating ladder track (Wakui, 2006).

2.1.6 Ballast and sub-ballast

Ballast can be considered as one of the most component that forms main source of vibration from the system as a whole. The reason is related to the changing of geometry of track and stability of ballast. Ballast vibration is analyzed as a series of spring and damper under sleeper component. This is explicitly studied by W.M.zhai et al. (W.M.Zhai,K.Y.Wang and J.H Lin, 2004).

The most important functions of ballast is resisting vertical, lateral, and longitudinal forces applied to the sleepers to maintain track in its desired position, provision of resiliency and energy absorption for the track, provision of drainage, and reduction of traffic induced stresses in the underlying layers, and facilitating maintenance operations (Esveld C. , Modern Railway Track, 2001). The sub-ballast is a granular layer between the ballast and sub-grade which serves the purpose of reducing the intensity of stress transmitted from the ballast layer to the sub-grade and facilitates drainage. In addition the sub-ballast layer prevents interpenetration of the sub-grade and ballast, prevents upward migration of fine material emanating from the sub-grade and helps prevent sub-grade attrition by ballast. Basic functions of ballast have been summarized as follows (Kaewunruen S., Remennikov A ., 2008):

- Resist vertical, lateral and longitudinal forces applied to the sleepers
- Absorb impact from the rough particles as a spring element with limited action
- Give resiliency and energy absorption to the sleeper
- Reduce bearing stresses from the sleeper to acceptable stress levels
- Provide an insulating layer and fast drainage of fluid
- Allow suitable global and local track settlement

2.1.7 Dynamic response of a ballast layer

For a railway track supported by a soft subgrade the wavelength of the surface waves is usually relatively long, typically ranging from 5 to 20 meters for a peat or clay formation. These long wavelengths are caused by the soft nature of the subgrade layer. When the superstructure is supported by Stiff substratum, such as a rock formation, waves which propagate at the surface of the track are not necessarily restricted to the domain of long wavelengths (Esveld C. , Modern railway technology, 2001).

This is because a stiff substratum reflects body waves of all wavelengths back into the superstructure, consequently a ballast layer on a concrete bridge or tunnel acts as a waveguide, conveying waves of both long and short wavelengths.

The shorter waves in the ballast layer can have a wavelength of the order of magnitude of the ballast particle size which may perturb the individual particles. In order to model relative motions by the ballast particles, it is necessary to incorporate the particle size into a mechanical track model. This can be done either by employing continuum models that are derived from the micro-mechanical particle behavior or by using discrete particle models. In these models the particles are assumed to have an ideal spherical shape the interaction with neighboring particles is prescribed at particle contact points by means of a contact law. Moving load analyses carried out with these models have demonstrated that a ballast material consisting of large particles increases the intensity of the wave radiation, especially when the damping capacity of the ballast is low. Hence, to suppress such effects, the damping capacity of a ballast material should be sufficiently high.

The damping capacity of ballast generally depends on two effects. The inter particle friction and the distribution of particle sizes. When the friction between the particles is high (i.e. coarse-grained ballast) relatively large amount of energy is dissipated at the particle contacts, thus causing the ballast to have a high damping capacity (Esveld C. , Modern railway technology, 2001).

The second effect is when a ballast wide particle size distribution excludes a dominant appearance by large particles that may act as a resonator accordingly; a ballast material with a random distribution of various particle sizes has a better damping capacity than a ballast material which consists of identical particles of a relatively large size.

2.1.8 Sub grade

Subgrade is also referred to as the formation layer. It includes the existing soil and rock, which possess slopes, ditches and other structures or materials. The subgrade is the last support, i.e., bearing and distributing the dynamic loading resultant downward. This layer must have sufficient bearing capacity; provide good drainage and a smooth settlement to ensure track serviceability. Recently, some synthetic materials (e.g., geo-textile, fabric, etc.), have applied to improving the subgrade performance (Kaewunruen S., Remennikov A ., 2008).

2.2 Dynamic Properties of the Track

2.2.1 Introduction

The dynamic responses of a track depend on the track component properties, the contact condition between components, and the dynamic loads. Rail and sleepers with mass and geometrical (inertia) properties keep the track stable under vehicle loads. Rail pads and ballast with elastic properties reduce the impact energy and dampen the dynamic frequency (Coenraad, 2001). However, in a well-ballasted track structure, the rail pad does not plays significant role in softening transient load action and dampen the vibration of sleeper (S.L., Grassie, 1989).

2.2.2 Dynamic load

Dynamic load is a load where its magnitude, direction and position vary with time and corresponding structural response are time varying deflection and stress. The imposed load on a railway track can be divided into three categories corresponding to the direction of loading: vertical, lateral and longitudinal. The vertical loading on the track consists of the static load of the vehicle and any additional dynamic contribution (dynamic impact). These dynamic contributions are often the dynamic impact forces due to track defects and vehicle parameters, such as

- Irregularities in the geometry of the track structure
- Irregularities on the surface of the rail and wheel
- The vehicle speed and the mass and suspension characteristics of the vehicle

Dynamic component is a function of speed, vehicle mass, and sources of irregularity in the wheel, running surface, or vertical track geometry. Dynamic effects increase significantly track loading especially when vehicles which have out of round wheels are operating at high speeds.

The load of train represents tons per wheel transmitted by the train to the track. The vehicle static load differs from the actual of load transmission due to dynamic forces that appear in the wheel-rail interface as a result of vertical movement. In this model the value of the increased dynamic load was calculated using Eisenmann's formula

$$Q_d = Q_e[1 + t.\dot{s}(1 + \frac{v-60}{390})] \quad (2.2)$$

Where: - Q_d = dynamic load,

Q_e = vehicle static load,

t =statistical security coefficient,

ṡ =factor of the quality conditions of the track and

v = speed of the vehicle.

In the calculation of dynamic load the statistical security coefficient (t) is 2, corresponding to the percentile of 95.9% and ṡ is 0.2, regarding the good conditions of the track.

2.2.3 Receptance

One way to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force and then analyze the receptance. The receptance is the ratio of the track deflection and the force put on the track, thus giving deflection in meters per Newton of the load. The receptance is the inverse of dynamic track stiffness. Receptance functions show the vibration amplitudes of track structures as a function of vibration frequencies, in particular the deflection of a track structure under a unit load. (Dahlberg Tore, 2003). The formal description of the Receptance function is:

$$\mathrm{H}_{\omega\mathrm{F}}(f) = \frac{s_{\omega\omega(\mathrm{f})}}{s_{\mathrm{FF}}(f)} \quad (2.3)$$

Where

$\mathrm{H}_{\omega\mathrm{F}}(f)$: Complex transfer function from force to displacement [m/N]

$s_{\omega\omega(\mathrm{f}))}$: Auto spectrum of displacement [m^2 s]

$s_{\mathrm{FF}}(f)$: Auto spectrum of the force [N^2 s]

f: vibration frequency [Hz]

2.2.4 Resonance

Due to the physical nature of track structures, a chain of their structural vibration modes exists depending on the resonant frequencies on the vertical, lateral and longitudinal direction. The lowest possible vertical resonant frequency of the track structure is the full track resonance as shown in figure 2.2. Track resonance is usually obtained in the frequency range of 50–300 Hz. This resonance is obtained when the track structure (rails and sleepers) vibrates on the ballast (Dahlberg Tore, 2003).The rails and the sleepers provide the mass element, and the ballast provides the spring-damper element for the resonance (Knothe, Ki and Grassie, 1993). The resonance frequency of less than 100 Hz is found due to a sufficient damping capacity of the ballast (Dahlberg Tore, 2003), (Knothe, Ki and Grassie, 1993).

For ballasted railway tracks in generally good conditions are full track resonant frequencies, between 40-140 Hz. Its second vibration mode occur between 100-400 Hz, and third vertical vibration mode are between 250-1500 Hz (Dahlberg Tore, 2003).

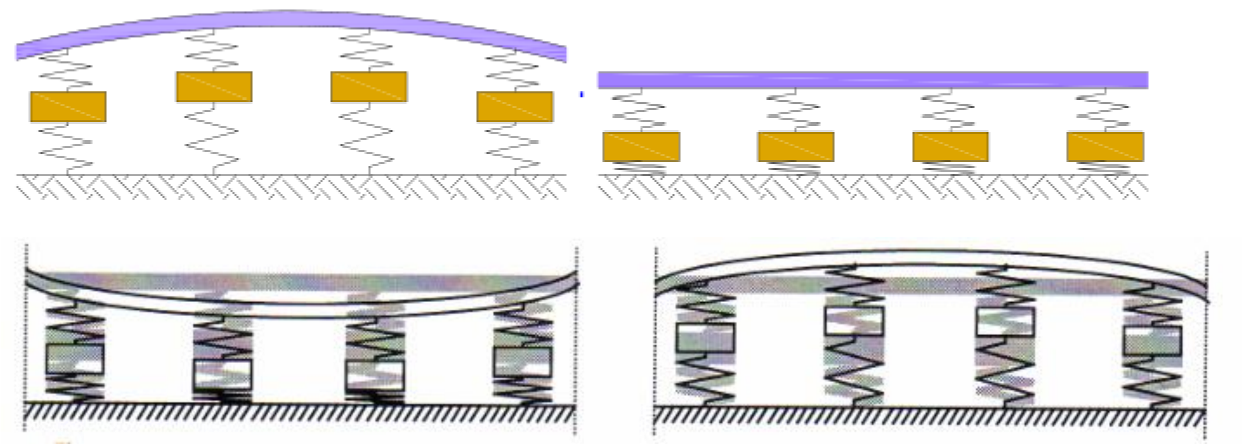


Figure2.2 Full track vertical resonant frequency mode shapes

The first resonance is an in-phase mode at about 100 Hz, which is moved together with the sleeper and rail on the ballast (Coenraad, 2001). The second resonance is the out-of-phase mode at the frequency approximately between 300–500 Hz (Grassie S.L., Gregory R.W., Harriswon D., and Johnson K.L., 1982). It is depending on the rail pad parameters, and it was moved to the opposite vibration direction of sleepers on ballast and rails over the rail pad (Knothe, Ki and Grassie, 1993).

Rail resonant frequency is when the rail vibrating on the Supports and is highly dependent on the rail pad properties but It is independent to the sleeper and ballast properties. The vibration modes and shapes depend on the sleeper support spacing.

Vibration of rail between two sleeper form pin-pin resonance mode .This types of resonance creates higher frequency as shown in figure 2.3 and figure 2.4. The first pin-pin resonant frequencies range occurs between 400-1200 Hz and second occurs at higher frequency around 1500Hz (Knothe, Ki and Grassie, 1993).

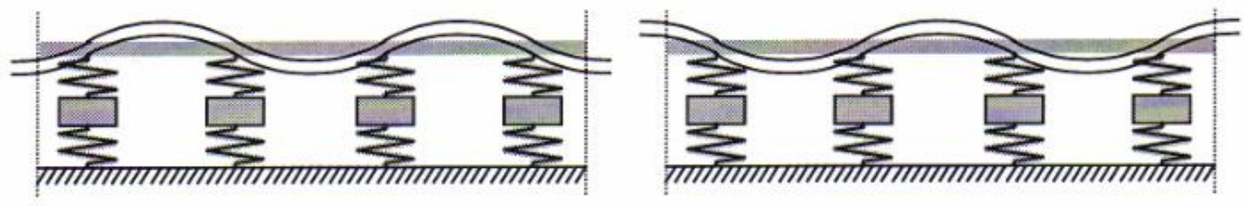


Figure2.3 First order pin-pin resonant frequency mode shape

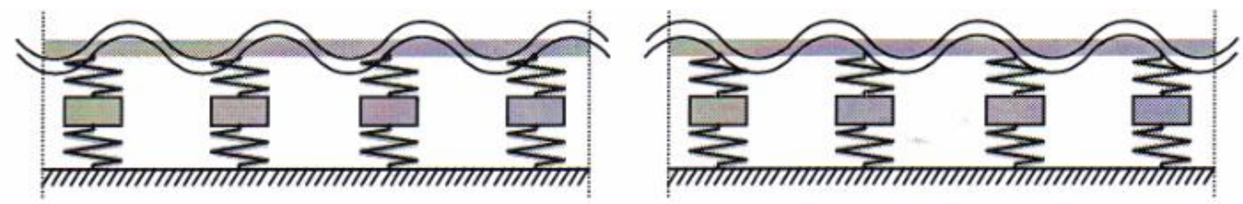


Figure2.4 Second order pin-pin resonant frequency mode shape

With some simplified assumptions, the pin-pin vibration resonance occurs at a specific frequency (f_{pp}), which can be calculated by (Dahlberg Tore, 2003):

$$f_{pp} = \frac{\pi}{2l}\sqrt{\frac{EI}{m}} \qquad (2.4)$$

Where:

l :distance between two supports [m]

EI: bending stiffness of rail (static) [Nm 2]

m: mass of the rail per unit length [kg/m]

Different frequency range has different effect on track component. Those are

- Low frequency range (0-40) Hz produces damage to the substructure
- Middle frequency range 40-400 Hz damages superstructure
- High frequency range (400-1500 Hz) produce damage to rails and distortion to fasteners.

2.2.5 Vertical Track Stiffness

Track stiffness is a basic parameter of a track design which influences the bearing capacity of the track, the dynamic behavior of passing vehicles and, in particular, the quality of track geometry and the life of track components. In general, relatively high track stiffness is beneficial as it provides sufficient track resistance to applied loads and results in decreased track deflection, which reduces track deterioration (Dahlberg Tore, 2003). However, very high track stiffness leads to increased dynamic forces in the wheel-rail interface as well as on sleepers and ballast, which may cause wear and fatigue of track components (Li M.X.D., Berggren E.G. , 2010). Also, a particular problem is changes in track stiffness along the track, which causes variations in vehicle-track interaction forces and leads to differential settlement and therefore differential track geometry deterioration and potentially vibration problems. There are different types of track stiffness: static stiffness, quasi-static stiffness and dynamic stiffness. The static stiffness can be obtained from load-displacement diagram in which load is slowly increased slowly from zero to certain value. The static stiffness value is used to simulate track around switch yard and very low speed operated track. The stiffness (quasi-static stiffness values) are determined from harmonic loading the track with frequency range of 1-25Hz.The third and last stiffness is dynamic stiffness which is important for modeling of high speed line track. This stiffness is determined by impulse excitation methods which consider vertical vibration of track (Esveld C. , Modern railway technology, 2001).

Vertical track stiffness (k) can be defined in a number of ways and in its simplest form is the ratio of track load (F) to track deflection (z) as a function of time (t), where the force can be either axle load or wheel load (Li M.X.D., Berggren E.G. , 2010):

$$K(t) = \frac{p(t)}{\delta(t)} \tag{2.5}$$

Note .Track stiffness is sometimes called track modulus

2.2.6 Ballast stiffness determination

Ahalbeck et al (Ahalbeck D.R, meacham H.C. and prause R.H. , 1975) developed the theory of the ballast pyramid model. In this model, the pressure is assumed to be uniform in a pyramid under sleepers and independent of the depth. The friction between particles transmits the loading from the top layer to bottom of the ballast. Thus, the ballast is divided in a block of each sleeper (see figure 1.9).Each ballast block can be modelled by a single degree of freedom system with a mass M,a stiffness K and a damping C. Ahlbeck suggested an internal friction angle of the ballast and subballast 20^o and 35^o respectively. Analysis of ballast vibration can be represented as methemathical model by considering the stress distribution with in the cone region.To determine the stiffness of ballast mass of the ballast under each sleeper forms an overlapping cone region as shown in figure 2.5 and figure 2.6, (W.M.Zhai,K.Y.Wang and J.H Lin, 2004).

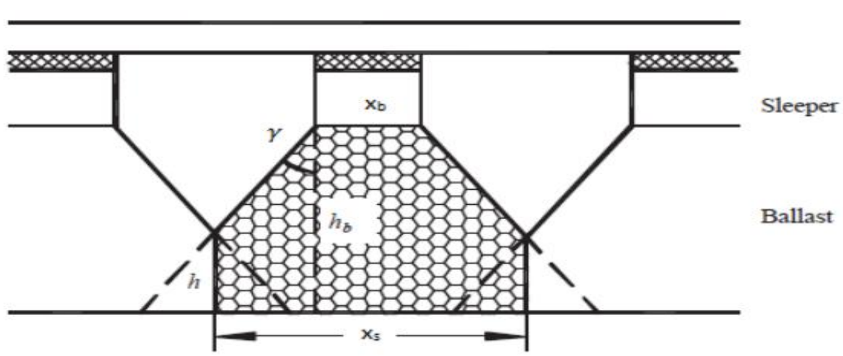


Figure2.5 Ballast model in case of overlapping

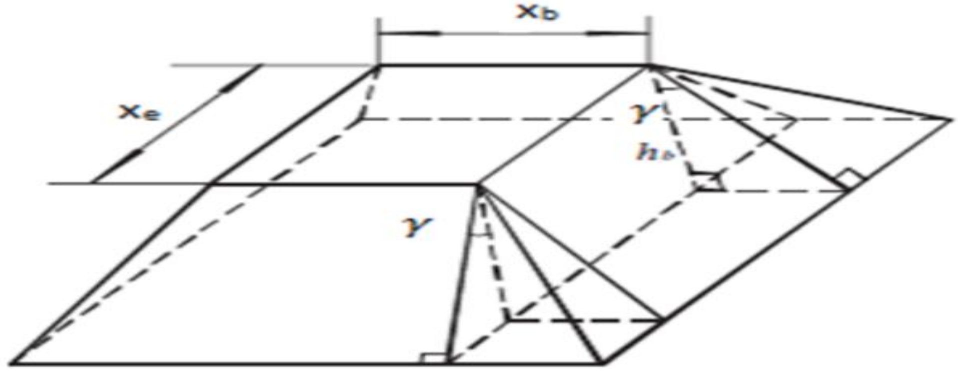


Figure2.6 Ballast mass

Ballast stiffness has two parts:

The first part of ballast stiffness is

$$k_{b1}=\frac{2(xe-xb)tan\gamma}{ln[(xexs)/(xb((xs+xe-xb))]}E_b \quad (2.6)$$

Second part of the ballast stiffness

$$K_{b2}=\frac{2(xe-xb)tan\gamma}{Xb-Xs+2hbtan\gamma}E_b \quad (2.7)$$

Combination of two parts

$$K_B=\frac{Kb1.kb2}{kb1+kb2} \quad (2.8)$$

Where

h_b=the height of ballast;

X_e=the length of half sleeper;

X_b=the width of sleeper;

X_s=distance between two sleepers;

K_b=stiffness of ballast

γ =The angle of stress distribution for ballast

2.2.7 Hertzian contact spring

During the vehicle-track interaction the forces are transmitted by means of the wheel rail contact area. On account of the geometry of the contact area between the round wheel and the rail, the relationship between force and compression, represented by the Hertzian contact spring. The hertzian contact theory calculates the contact stress and force between two contacting surfaces based on several assumptions like (Li M.X.D., Berggren E.G., and Berg M., 2009):

- Two bodies interacting are regarded as half-space; the contact zone is small compared to the dimension of the two bodies
- Small strain and displacement
- Smooth (frictionless) contact surfaces with constant radii of curvature
- Homogeneous and isotropic material on only elastic foundation

The relationship between force F and indentation y of the contact surface can be written as:

$$F = C_h Y^{3/2} \qquad (2.9)$$

Where C_h is a constant depending on the radius and the material properties

Since a description of the wheel-rail relationship using transfer functions requires that all components are linear, the Hertzian spring must also be linearized. This linearized value of the stiffness can be found by considering the relationship between the force and displacement increments around the static wheel load. The linearized Hertzian spring stiffness k_H is can be expressed as written in equation 2.10; furthermore equation 2.10 can be decomposed to equation 2.11 by including diameter of wheel and flange as a parameter.

$$K_h = 3/2 C_h^{2/3} F^{1/3} \qquad (2.10)$$

$$K_{h=} \left(\frac{3N}{2}\right)^{1/3} . \left(\frac{E}{1-v^2}\right)^{2/3} . (R_w . R_r)^{1/6} \qquad (2.11)$$

For dynamic analysis Hertz constant (wheel-rail contact stiffness) is very important. On account of the contact geometry, the relationship between force and deformation of the contact surface is not linear (Esveld P. , 2001).

CHAPTER THREE

3. 1 NUMERICAL MODEL OF TRACK DYNAMICS

In 1867, Winkler advanced the Elastic foundation beam theory which was used for modeling of the track soon, and then in 1926, Timoshenko researched the vibration of the rail by the elastic foundation. Rapid development of railway on the entire world made a great achievement for modeling the dynamic of the rail system (koglund, 2002).

3.1.1 Beam on elastic foundation (Winkler beam) model

Beam on elastic foundation model is by far the Classic Method and also forms the backbone of many subsequent improvements made to track design (See Figure 3.1). This model is still in use for easy and quick track deflection (koglund, 2002).

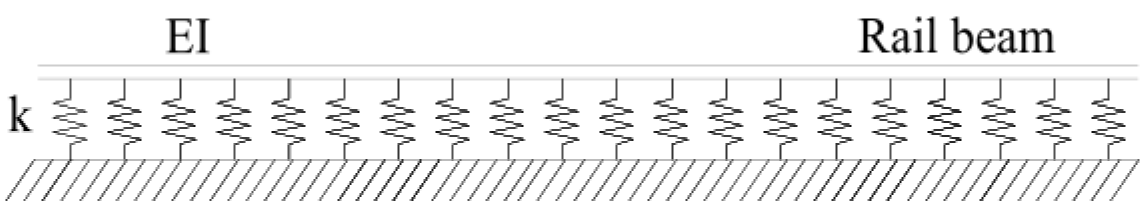


Figure3.1 Beam on elastic foundation (Winkler beam) model

The model has a sound mathematical formulation with quite clear simple physical interpretation. It assumes the rail modeled as an infinite Euler-Bernoulli beam with a continuous longitudinal support from a Winkler foundation, which may be regarded as equivalent to an infinite longitudinal line of vertical, uncoupled and elastic springs. The distributed force supporting the beam then is proportional to the beam deflection. By only using two track parameters the rail deflection w(x) could be obtained from the differential equation (koglund, 2002).

$$EI\frac{d^4w(x)}{dx^4} + Kw(x) = q(x) \qquad (3.1)$$

Where,

x = the length coordinate

q(x) = the distributed load on the rail

EI = the beam bending stiffness EI (Nm ^{2})

k = the foundation stiffness (N/m ^{2}, i.e. N/m per meter of rail).

This model may be acceptable only for static loading of a track on soft support without accounting for dynamic effects because it contains no mass.

The rail may be modeled either as an ordinary Euler-Bernoulli beam (the conventional beam theory is used) or as a Rayleigh-Timoshenko beam. The Rayleigh-Timoshenko beam theory includes the rotational inertia of the beam cross section and beam deformations due to the sheer force. The drawback arises from the Beam on Elastic Foundation (BOEF) model:

- Sleeper mass and bending flexibility are ignored
- Shear distortion and rotary inertia of the rail that is important factor for high frequency vibration, and not accounted for by simple Bernoulli-Euler theory
- The discrete rail supports from individual sleepers are neglected and replaced by a uniform underlying foundation
- Impact load associated with high frequency vibration is not considered
- Detailed dynamic behaviors of track component are not obtained

3.1.2 Beam (rail) on discrete supports

The discrete supports, i.e., a series of a spring and a damper element could be discrete spring-damper systems or spring-mass-spring system, and it is consisted of rail pads, sleepers and ballast bed as shown in Figure 3.2 (G.P.Raymond , Z. CAl, 1994).

The rails, sleepers, railpads and ballasts are modeled by a beam (Euler-Bernoulli or Rayleigh-Timoshenko beam), a rigid mass and a spring-damper respectively. Therefore, the rail is linked with the sleeper by spring-damper element (rail pad) and between sleeper and elastic foundation also connected by spring-damper element (ballast).

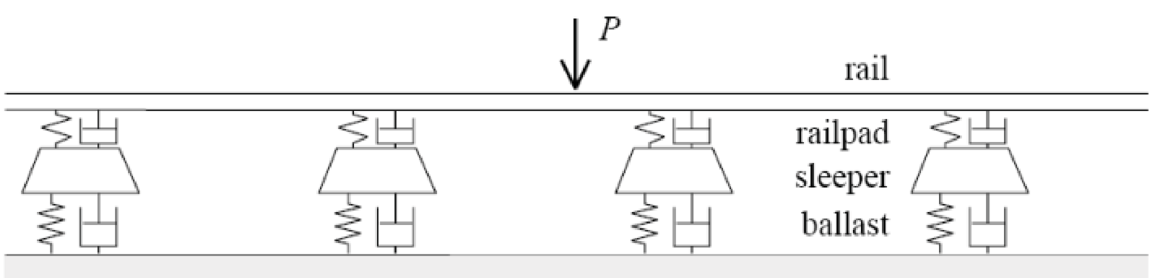


Figure3.2 Rail on discrete supports

Using this track model, three resonance frequencies have been produced: the sleeper vibration on the ballast, the rail and sleeper vibration on the railpad and the pinned-pinned frequency at each spring between the two masses.

3.1.3 Discretely supported track including ballast mass

Several researchers have investigated that a resonance frequency at low frequency (below 40 Hz) of the track model by considering more masses into the simple model as shown in Fig 3.3. A resonance at low frequency can be produced by considering the mass of ballast and subgrade is much larger than those of sleeper and rail, and by adjusting the subgrade stiffness. The ballast-subgrade masses vibrate on the subgrade stiffness (Dahlberg Tore, 2003).

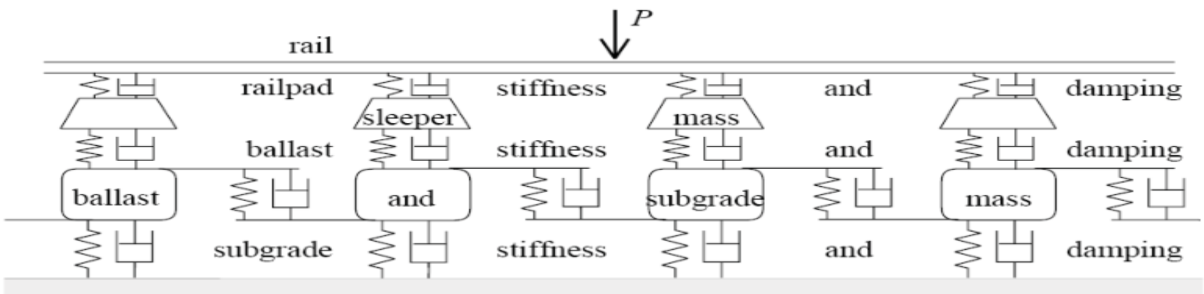


Figure3.3 Rail on discrete supports with rigid masses modeling the sleepers

The influence of the ballast density on the wheel-rail contact force at a rail joint and the ballast acceleration could also be studied by this model.

3.1.4 Beam theory

Euler Bernoulli Beam

The rail may be modeled either as an ordinary Euler-Bernoulli (E-B) beam or as a Rayleigh-Timoshenko (R-T) beam. In the E-B beam theory only bending of the rail is taken into account, and in case of vibrations, only the mass inertia in translation of the beam is included. To obtain an equation for the transverse vibration in a two-dimensional beam the following structure is studied. The beam is subjected to an external force and has a distributed mass m = ρA and flexural rigidity EI which can vary with position and time, which is shown in figure 3.4.

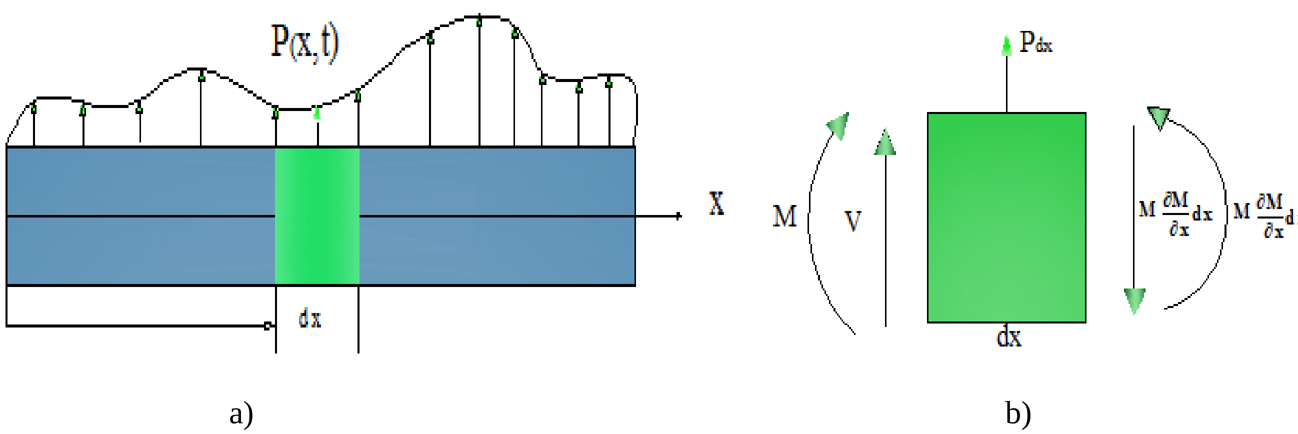


Figure3.4 (a) Beam and applied force, (b) force acting on an element

The differential equation describing the beam deflection w(x, t)

$$EI\frac{\delta^4 w(x,t)}{\delta x^4} + \rho\frac{\delta^2 w(x,t)}{\delta x^2} = q(x,t) \qquad (3.2)$$

Where,

EI = the bending stiffness of the beam

ρ = the density of the beam

A = cross-sectional area of the beam

q(x, t) = load on the beam

t = time

Damping of the beam is not included in this model. For stationary vibrations of the undamped beam, the solution to (the homogeneous part of) this equation 3.2 may be written in the form as equation (3.3). Where X(x) gives the form of the beam vibration mode and ω is the vibration angular frequency.

$$W_{hom}(x,t) = X(x).T(t) = X(x)\sin \omega t \qquad (3.3)$$

Rayleigh-Timoshenko Beam (R-T beam)

The R-T beam theory includes rotator inertia and shear deformation of the beam. In this case, two differential equations are needed to describe the vibrations. The deflection w(x,t) and the shear deformation Ψ(x, t)are unknown functions. The differential equation for the deflection w(x, t) becomes:

$$EI\frac{\delta^4 w(x,t)}{\delta x^4} + \rho A\frac{\delta^2 w(x,t)}{\delta t^2} + I(I + \frac{E}{KG}\frac{\delta^4 W(x,t)}{\delta x^2 \delta t^2} + \frac{\rho^2 I}{KG}\frac{w^4(x,t)}{\delta x^4} \qquad (3.4)$$

Where, EI = the bending stiffness of the beam, G = shear modulus, k = shear factor, ρ= the density of the beam, A = cross-sectional area of the beam, q(x, t) = load on the beam, t = time

If the shear deformation of the beam is suppressed, i.e. if one gives k a very large number, then the two last terms on the left hand side tend to zero. Further, if the mass inertia in rotation of the beam cross section is eliminated (noting that $\rho I = \rho r^2 A = mr^2$, and let r tend to zero) then also the third term tends to zero and the E-B differential equation is obtained (Dahlberg Tore, 2003). It was found that shear deformation of the rail can be neglected only for frequencies below 500 Hz (20) (Jian Bian, YuantongGu and Martin Howard Murray, 2013).

3.2 FINITE ELEMENT MODEL

3.2.1 Track Modeling in Abaqus

Recently, using the commercial computer package programs, the railway track can be modeled by two-dimensional or three-dimensional finite elements and with various elements (shell, solid, beam, spring-damper with linear or non-linearity) regarding to a real track properties. Finite element models are created in ABAQUS/CAE which includes the Graphical User Interface (GUI). This method of creating models is easier than coding an input file, especially when the models are large, as in the case with 3D models.

Abaqus contains an extensive library of elements that can model virtually any geometry. It has an equally extensive list of material models that can simulate the behavior of most typical Engineering materials. Abaqus offers a wide range of simulation of linear and nonlinear applications. Problems with multiple components are modeled by associating the geometry defining each component with the appropriate material models and specifying component interactions (ABAQUS Online Documentation: Version 6.12.1, 2012).

3.2.2 Modeling Procedures in ABAQUS/CAE

ABAQUS/CAE environment is divided into different modulus as shown in figure 3.5, where each module defines a logical aspect of the modeling process; for instance, defining the geometry, defining the material properties, and generating a mesh. The GUI interface generates an input file with all information of the model, to be submitted to the solver, using ABAQUS/Standard or ABAQUS/Explicit routines. The solver performs the analysis and sends the information back to ABAQUS/CAE for evaluation of the results (ABAQUS Online Documentation: Version 6.12.1, 2012).

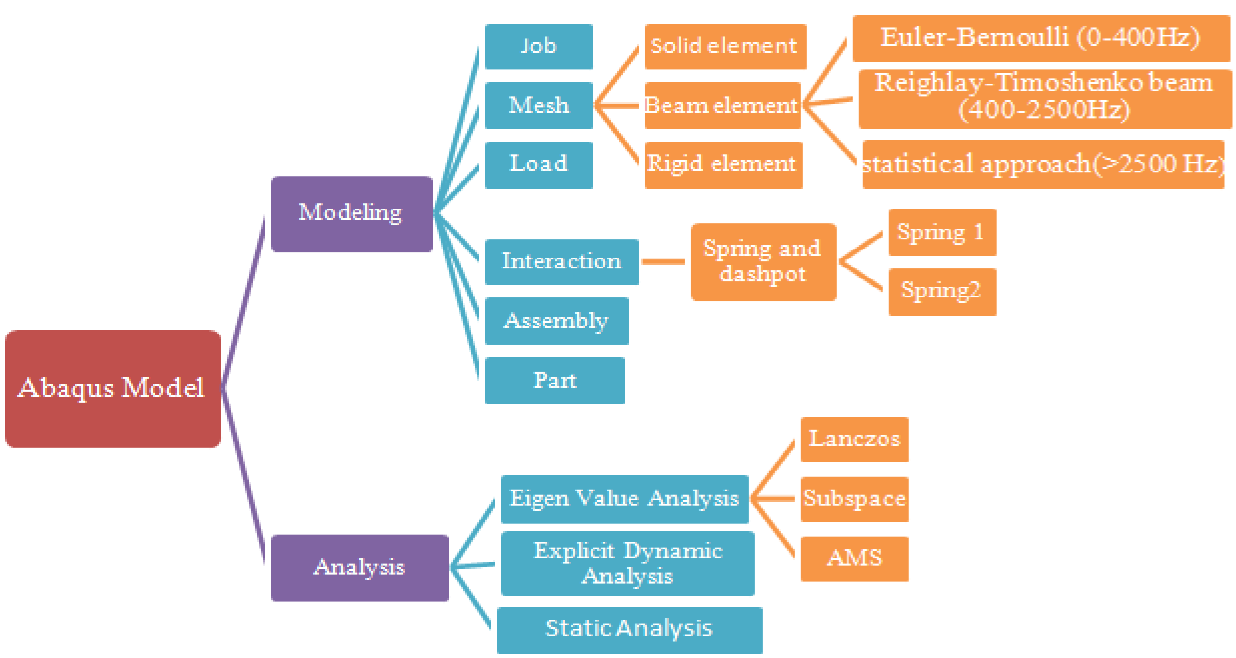


Figure3.5 Flow chart of the modeling and Analysis approach

3.2.3 Analysis Type

Linear Eigen value Analysis

Linear Eigen value analysis is used to perform an Eigen value extraction to calculate the natural frequencies and corresponding mode shapes of the model. The analysis can be performed using two different Eigen solver algorithms, Lanczos or subspace. The Lanczos Eigen solver is faster when a large number of Eigen modes are required while the subspace Eigen solver can be faster for smaller systems. When using the Lanczos Eigen solver, one can choose the range of the Eigen values of interested while the subspace Eigen solver is limited to the maximum Eigen value of interest.

Explicit dynamic analysis

The explicit dynamics procedure performs a large number of small time increments efficiently. An explicit central-difference time integration rule is used; each increment is relatively inexpensive (compared to the direct-integration dynamic analysis procedure available in Abaqus/Standard) because there is no solution for a set of simultaneous equations. The explicit central-difference operator satisfies the dynamic equilibrium equations at the beginning of the increment, t; the accelerations calculated at time t are used to advance the velocity solution to time and the displacement solution to time an explicit dynamic analysis:

- Is computationally efficient for the analysis of large models with relatively short dynamic response times and for the analysis of extremely discontinuous events or processes
- Allows for the definition of very general contact conditions
- Uses a consistent, large-deformation theory models can undergo large rotations and large deformation;
- Can use a geometrically linear deformation theory strains and rotations are assumed to be small.

Steady State Dynamic Analysis

One way to investigate the dynamic properties of a railway track is to load the track with a sinusoidal force. At frequencies up to about 200Hz, this can be done by using hydraulic cylinders. If one wants to investigate the track response at higher frequencies, the track may be excited by an impact load, for example from a sledge-hammer. In ABAQUS steady-state dynamic analysis provides the steady-state amplitude and phase of the response of a system due to harmonic excitation at a given frequency. Usually such analysis is done as a frequency sweep by applying the loading at a series of different frequencies and recording the response; in Abaqus/Standard the direct-solution steady-state dynamic procedure conducts this frequency sweep. In a direct-solution steady-state analysis the steady-state harmonic response is calculated directly in terms of the physical degrees of freedom of the model using the mass, damping, and stiffness

3.2.4 Review on Experimental and Finite Element Analysis

Conventional Ballasted Track

At different time several researches have been done on deflection and vibration behavior of ballasted track. Some of those researches are conducted experimentally while the others using numerical or finite element model. One of the researches that were done on conventional ballasted track was Coelhho's research. He did experimental studies on dynamic response of ballasted track around transition zone under train moving with speed of 114km/hr. The response of the component of the track was recorded by Geophone and Accelerometer. The analysis was conducted to study deflection and acceleration of formation layer in time history response. Figure 3.7 indicates the acceleration recorded by Accelerometer while figure 3.6 shows displacement of the formation layer of ballasted track (Coelho, 201)

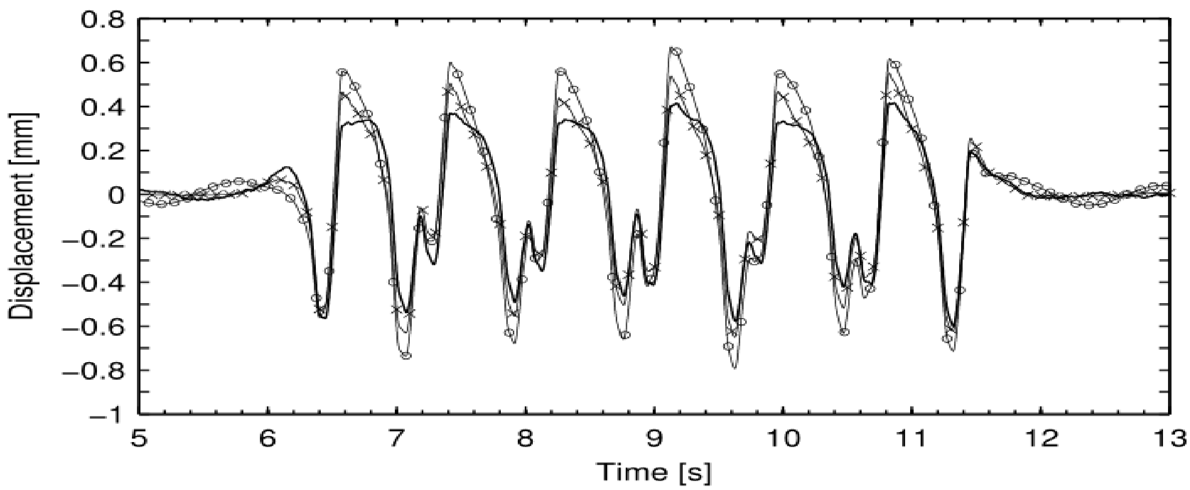


Figure3.6 Displacement of formation layer

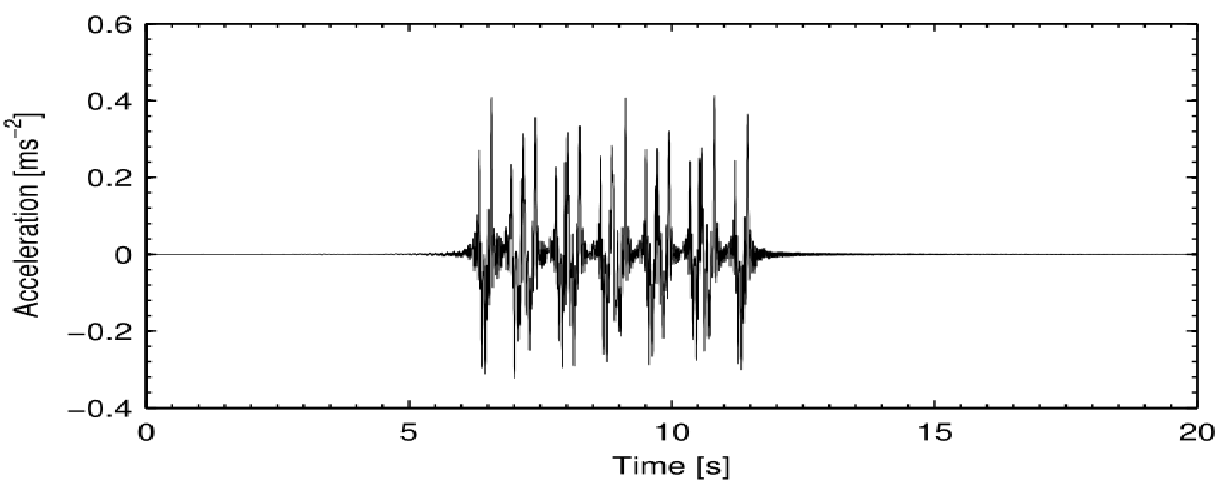
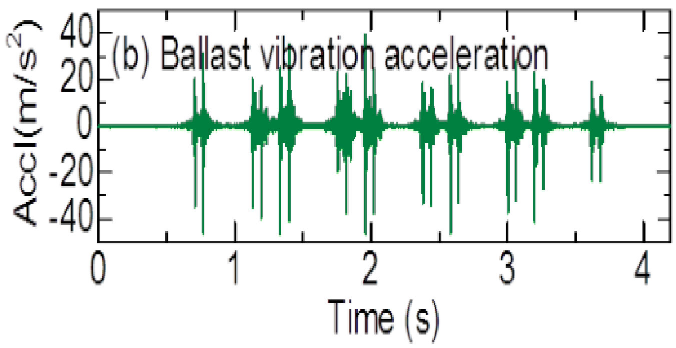
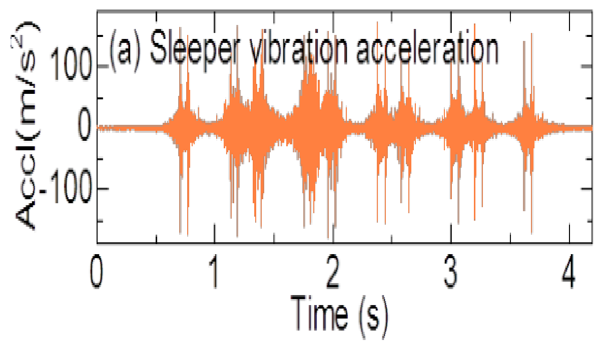


Figure3.7 Vibrations of formation layer due to the passage of a train at 114 km/h: accelerations from accelerometer measurements.

There was also experiment done on dynamic characteristics of ballast under transient impact loading. The characteristics of dynamic loads acting on the ballast layer were examined based on the measured dynamic response during train operation at a speed of 122 km/h. Figure 3.8 shows some exemplary time (Aikawa, 2013).



a)



b)

Figure3.8 Acceleration of ballast and sleeper in time history response

Figure 3.8 indicates that the pattern of acceleration response of both ballast layer and sleeper are nearly similar but sleeper acceleration is more than the ballast layer. The maximum acceleration of sleeper is nearly 100m/s^2 while that of ballast is about 40m/s^2 which indicates that sleeper accelerates 2.5 times that of ballast layer.

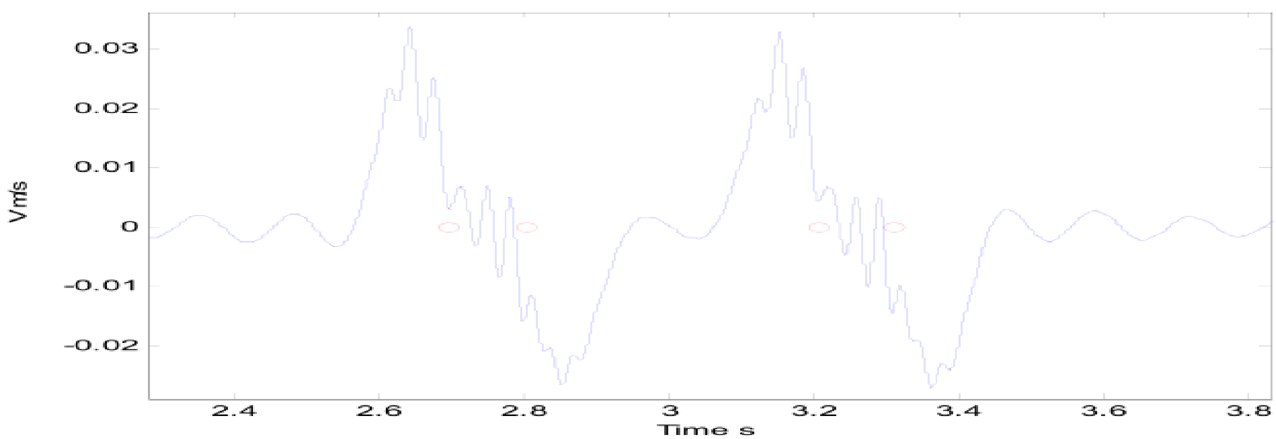


Figure3.9 Velocity of a rail when train travel with speed of 60km/hr

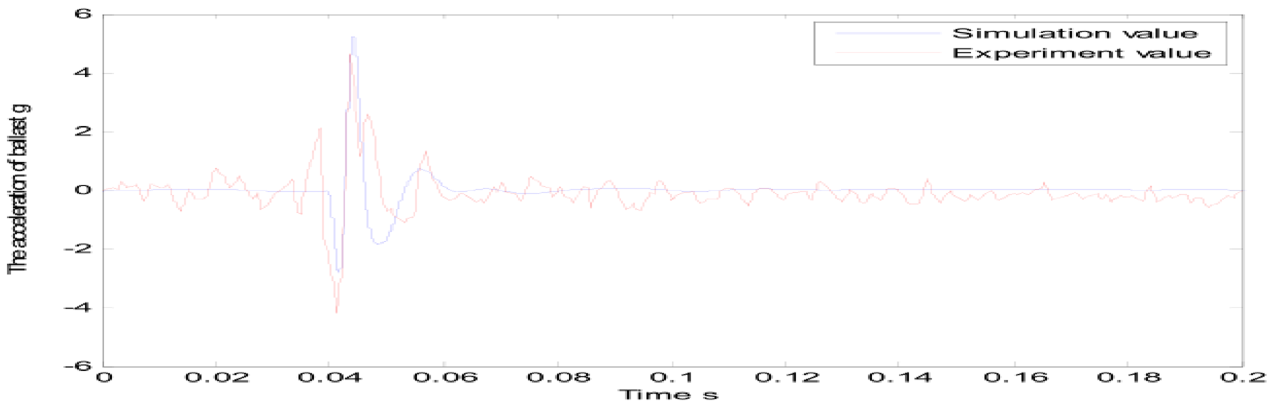


Figure3.10 Comparison of simulation and experimental data of ballast layer acceleration

There was also research done on conventional ballasted track under analysis of train induced vibration on single span composite bridge. As indicated in figure 3.11, 3.12, 3.13, vertical acceleration of sleeper, ballast and bridge deck was analyzed by Lorieux (lorieux, 2008). The acceleration of component of the track along the path of train indicates that peak acceleration of sleeper is greater than acceleration of ballast and rail.

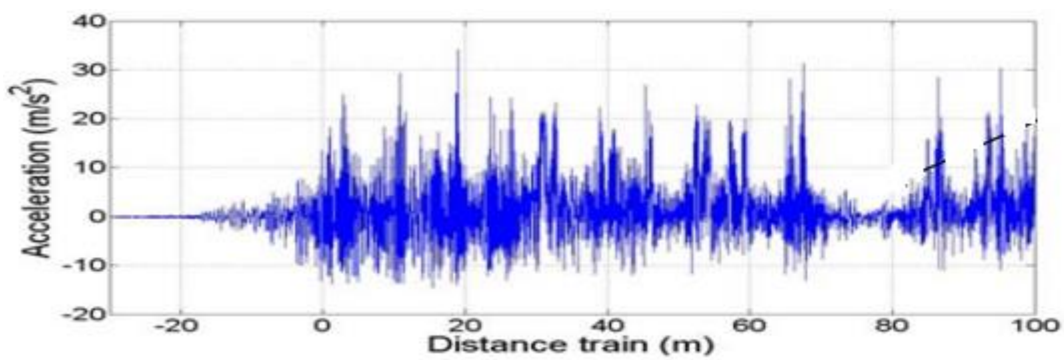


Figure3.11 Acceleration of sleeper along the path of the train

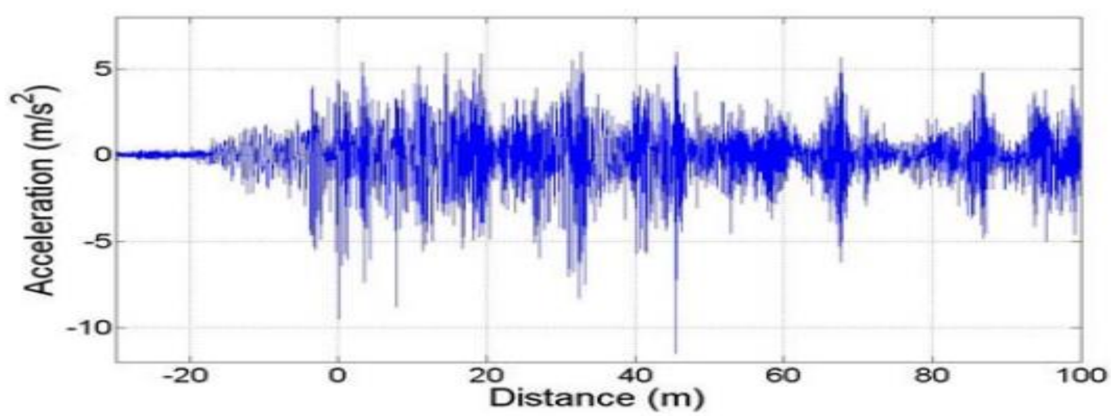


Figure3. 12 Acceleration of ballast along the path of the train

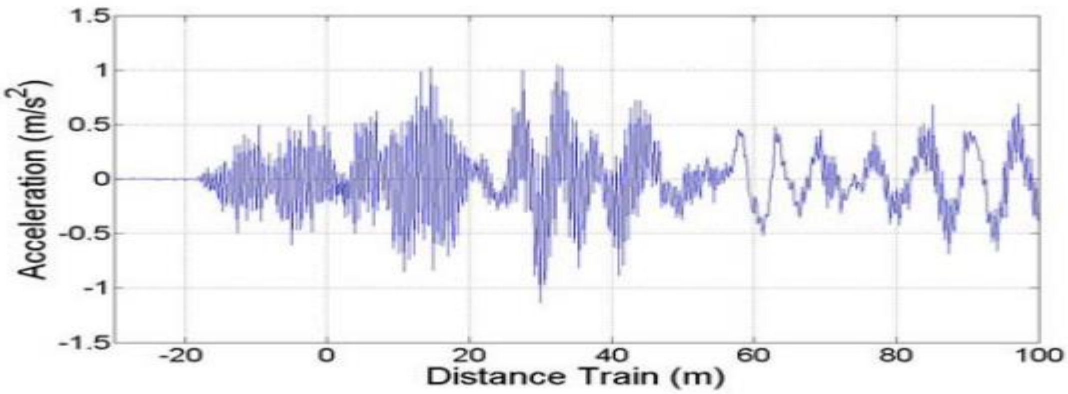


Figure3.13 Acceleration of rail along path of the train

Ballasted Ladder Track

Regarding ballasted ladder track there was a report undergone by meng Ma et al. (Meng Ma, Weining Liu, Weifeng Liu and Hao Jin, 2013) of which the project was funded by European Commission within the seventh frame work program. One of the main purposes of this study is to identify the track with good vibration mitigation. In this project both 3D finite element analysis and laboratory test were conducted on ballasted ladder track, Floated ladder track and Conventional ballasted track. In the laboratory 22.5 tone (for freight tone in Europe) and 120 km/hr. operation speed are considered. It is indicated in figure 3.14 how the ballasted ladder track in the laboratory was arranged and conducted. Time history of acceleration responses on the rail, sleeper and ground at all measurement sections are indicated in figure 3.14. For ballasted ladder track, ballast has good effects on vibration reduction in both time domain and frequency domain. Vibration responses are at the same order of magnitude (10 g) on the rail and sleeper, while they attenuate with two orders of magnitude on the ground (0.1 g) see figure 3.15 and 3.16

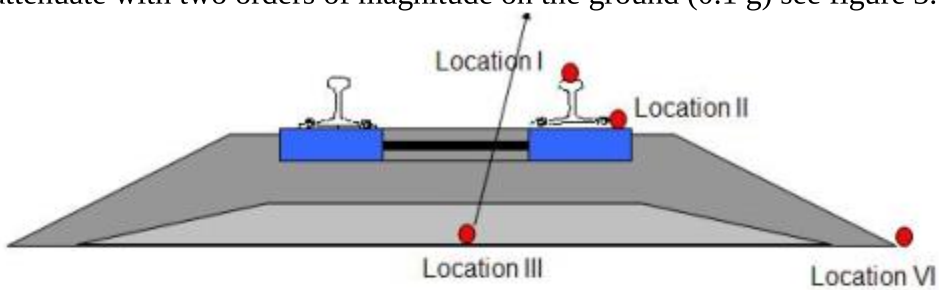


Figure3.14 Layout of acceleration sensors and impulse location

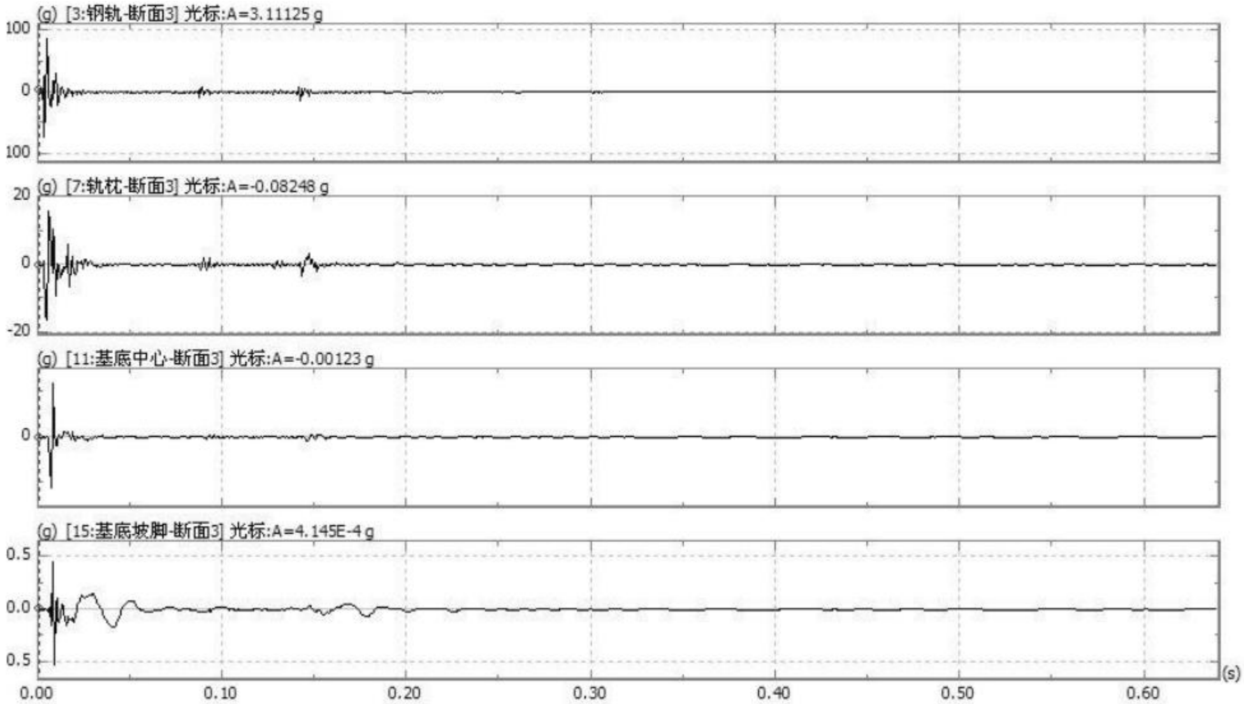


Figure3.15 Typical time history of Section (all four locations) under impulse force of 140 kN

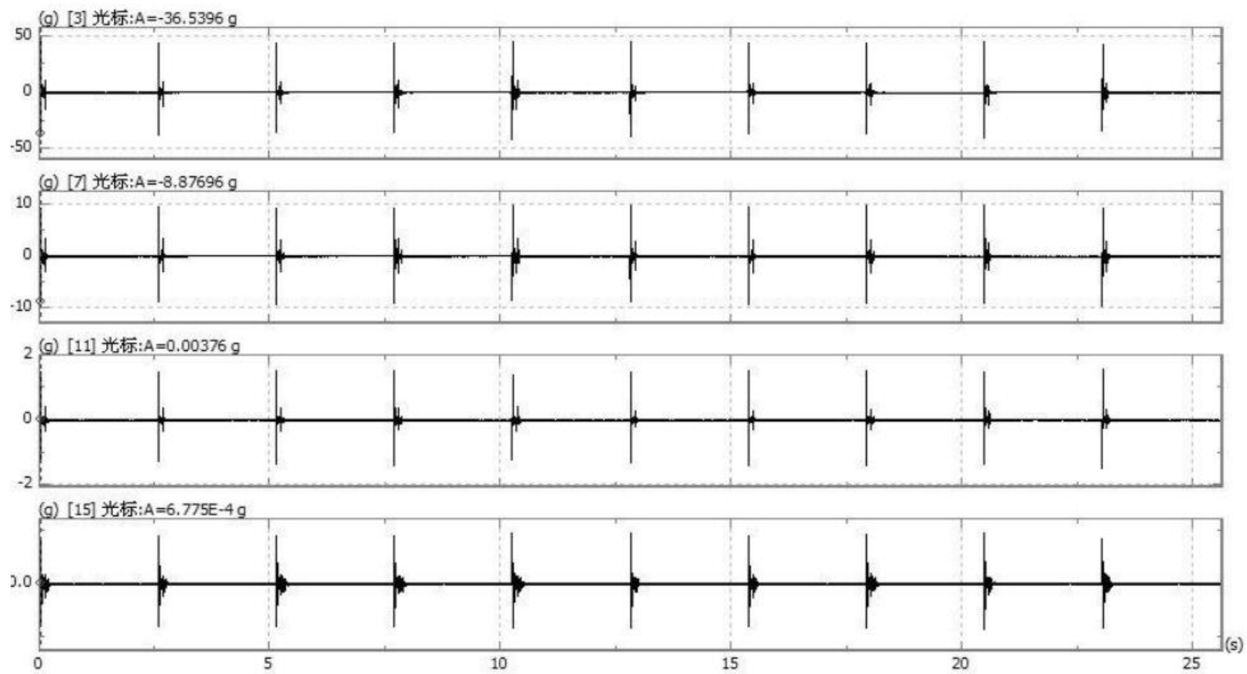


Figure3.16 Typical time history of Section (all four locations), at10 useful records

To study the effect of vibration reduction with track solution, a 3D FE model of ballasted ladder track is established and then train loads are calculated, which are applied on the 3D FE model with both Ballasted ladder track and conventional ballasted track. The results are compared in time domain as shown in figure 3.7 and 3.18. According to 3D finite element analysis, ballasted ladder track has better effect on vibration reduction than conventional ballasted track by considering the peak value of the time domain.

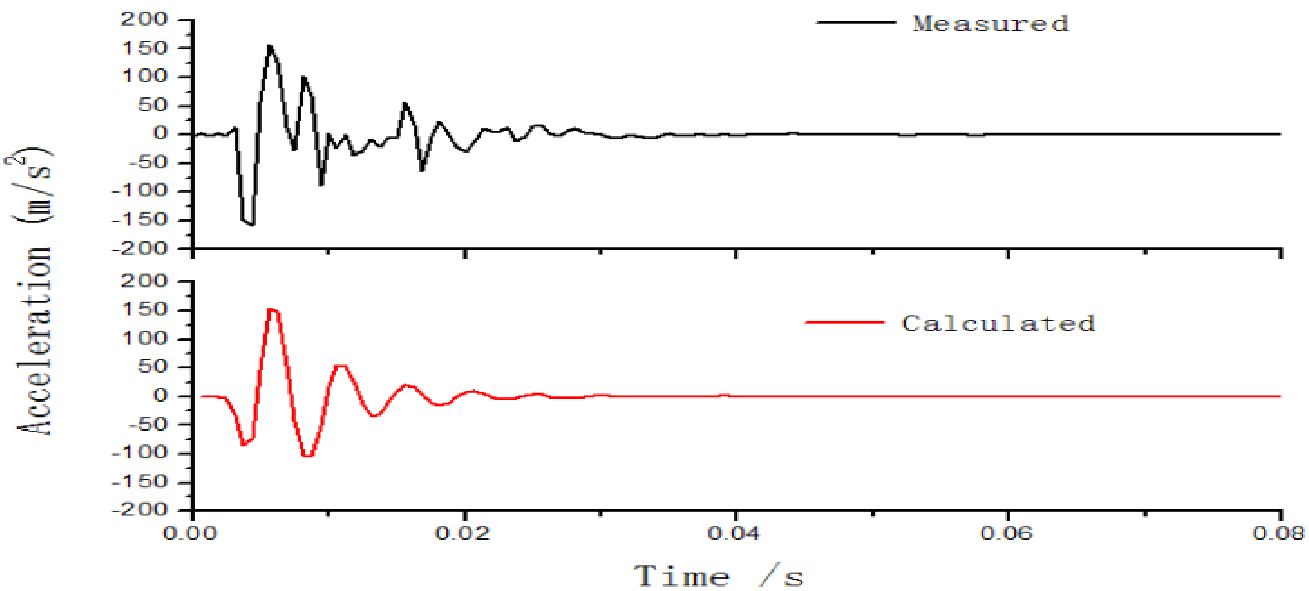


Figure3.17 Comparison of calculated and measured time history on ladder sleeper

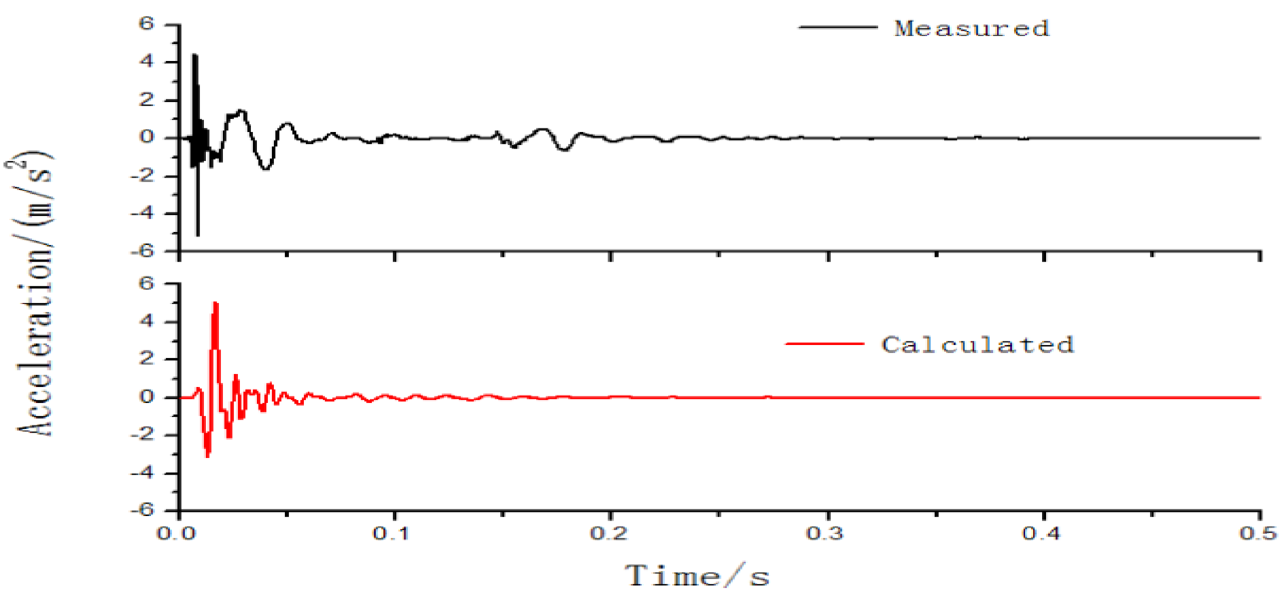


Figure3.18 Comparison of calculated and measured time history on the ground

CHAPTER FOUR

MODELING APPROACH

4. Fundamental Assumptions and Simplification

The following assumptions and simplification are made in establishing the model for dynamic analysis of the track.

- Track is modeled in 2D to minimize computational costs in 3D model
- Only vertical dynamic loads are considered in the model.
- Parameter of a track is linear and constant in geometry
- Ballast layer and railpads are represented by series of spring and damper.
- Rail is modeled as solid element
- No car body and track coupling system is used, only load is applied on center of rotating wheel; this is to know the effect of train speed on dynamic response of a track.
- The contact force between wheels and rail is ruled by nonlinear hertzian contact theory**.**

To compare accuracy of models, solid element and beam element is used for the simulation of the rails. The solid element model is more detailed than the beam element model. When using dynamic analysis, solid element increases the computational cost, because the time increment is based on the smallest element in the model.

In order to account for the dynamic behavior of the discretely supported track, a model of finite length (24m) based on the FE method is applied. Nonlinear-behavior is included in the model both for time model and frequency model simulation (see table4.1). The assumption of non-linear behavior for frequency domain simulation increase computational cost while it is preferable for time domain simulation

4.1 *Modeling of track*

Two categories of track that are most commonly used for dynamic behavior are (1) where the rail is assumed to be continuously supported or (2) where the rail is assumed to be discretely supported. This distinction is established by the discrete nature of sleepers along the track's direction. In both cases, the rail is treated as a flexible beam, which can be interpreted as infinite (the problem is solved in the frequency/wave number domain) or finite (more suitable for time domain simulation). One of the most straightforward approaches to rail modeling is to use a Euler beam. Although (Grassie SL, Gregory RW, Harrison D, Johnson KL., 1982) concluded that this model is deficient in several respects in the frequency range 50–1500Hz, the difference shown when advanced modeling is used (Timoshenko beam, including shear deflection and rotational inertia of the rail) is negligible for frequencies below 500Hz. Continuously supported models are intended to simulate the entire track and neglect the effect of sleepers. To overcome this problem, sleeper effects can be modelled with the use of a intermittent support, facilitating superior accuracy at higher frequencies. In this model ladder track is considered as continuous model. A discrete support has multiple layers representing rail pads, sleepers, ballast, sub ballast, and sub grade. Such models can be solved in both frequency and time domains, however, frequency domain techniques reached its limit if nonlinearities inside the track structure after certain frequency range. In discretely supporting model approach conventional ballasted track is considered. In this model rail and sleeper are considered as solid element and spring and damper between sleeper and rail, and also ballast layer are represented as elastic support of super structure of track while subgrade is represented by solid element as shown in figure 4.1, and figure 4.2.

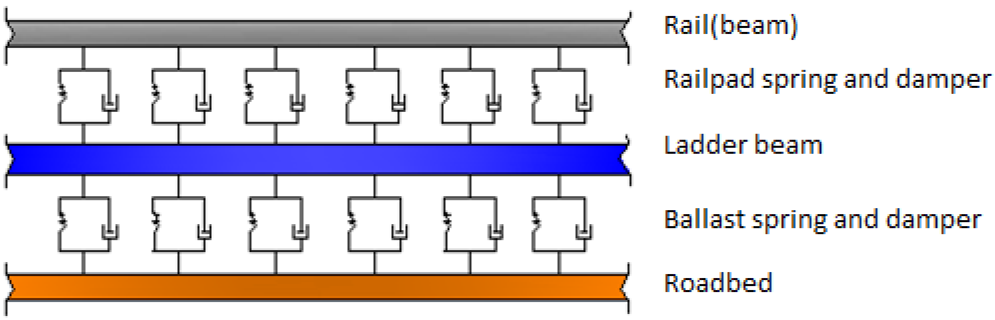


Figure4.1 Ladder track longitudinal cross section

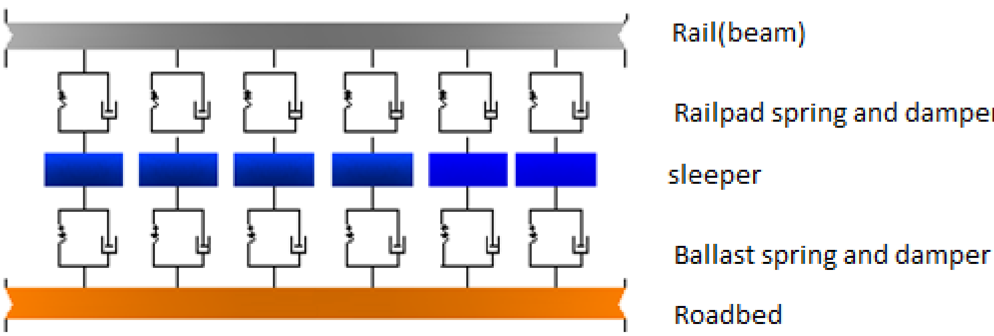


Figure4.2 Conventional Ballasted track longitudinal cross section

Table4.1 Material parameter for components of track (Feng, 2011)

Materials	Density(kg/m3)	Elasticity(GN/m2)	Poisson ratio	Thickness(m)
Rail	7800	210	0.3	
Ballast	1700	0.15	0.35	0.15
subgrade	2000	0.01	0.4	3.5
Concrete/sleeper	2400	35	0.25	0.25

Table4.2 spring and Dashpot, Elasto-plastic material parameter (Drucker pracker) (Shi, 2009)

Elasto-plastic material parameter (Drucker pracker hardening)	
Strain	**Stress (pa)**
0.0005	4,850
0.008	15,000
0.02	20,000
0.04	26,000
0.06	29,500
0.09	30,500
0.15	31,500
0.2	400,000

Layer	Stiffness (MN/m)	Damping (KNs/m)
Railpad	140	40
Ballast	250	40
Drucker Pracker Parameter		
Angle of friction	**Flow stress**	**Dilation angle**
45	1	25

The static axle load is set to 25 ton since it is the highest load allowed on standard tracks in different country. In the simulation since two dimensions is applied half of the axle load is considered. The dynamic load increase with increase of speed of train, the dynamic load factor is set to 1.5 since speeds below 200 km/h is assumed. Depending of level of service the speed of a vehicle allowed for conventional ballasted track and ladder track are not the same; since conventional ballasted track is not stable under higher vehicle speed in this thesis it is limited to upper speed up to 180 km/hr.

CHAPTER FIVE

5. RESULTS AND DISCUSSION

In this chapter the results of Finite element analysis of the tracks are provided in a time and a frequency domain .In the model three types of dynamic analysis are carried out: dynamic explicit, Eigen value analysis and steady state modal dynamic analysis. To have a clear understanding of the dynamic performance of both tracks the results are presented in acceleration, velocity and displacement versus time for each component of the track and results are highly filtered to briefly describe relative response of all components of track ; frequency analysis is also presented in stress, Acceleration and vibration amplitude versus frequency and mode number. The track response in frequency and mode number domain is obtained in the steady-state dynamic analysis by applying a harmonic load on the middle of the rail whereas response in time domain is obtained from dynamic explicit by applying amplified dynamic load on the center of rotating unsprung wheel mass.

5.1Time History Responses of Ballasted Ladder Track

All Abaqus outputs provided in figure are taken at middle of track for a rail and ladder beam, and also at 80cm depth from top of subgrade for subgrade layer. The main reason of taking the output at 80cm depth is because at this point most of the time from the contour we can observe relatively larger stress and also output indicated in all graphs are the vertical component of the response of the simulation. Relatively comparing rail, ladder beam and sub grade of ladder track as shown in figure 5.1, it has been seen that rail has more deformation than another components. The maximum displacement of the rail is around 2mm which is larger when compared to deflection of ladder beam (ladder sleeper) and subgrade ;this indicates that substructure of ladder track is slightly stable under moving load. Deformation of the track is affected by the track stiffness .Track with low stiffness significantly decrease the wheel-rail, sleeper-ballast and ballast-subgrade contacting force and increase track deflection. The major problem of the track stiffness is when it various along a track: that cause a variation of a vehicle-track interaction forces .This leads to differential settlement which interns damage the structure of the track.

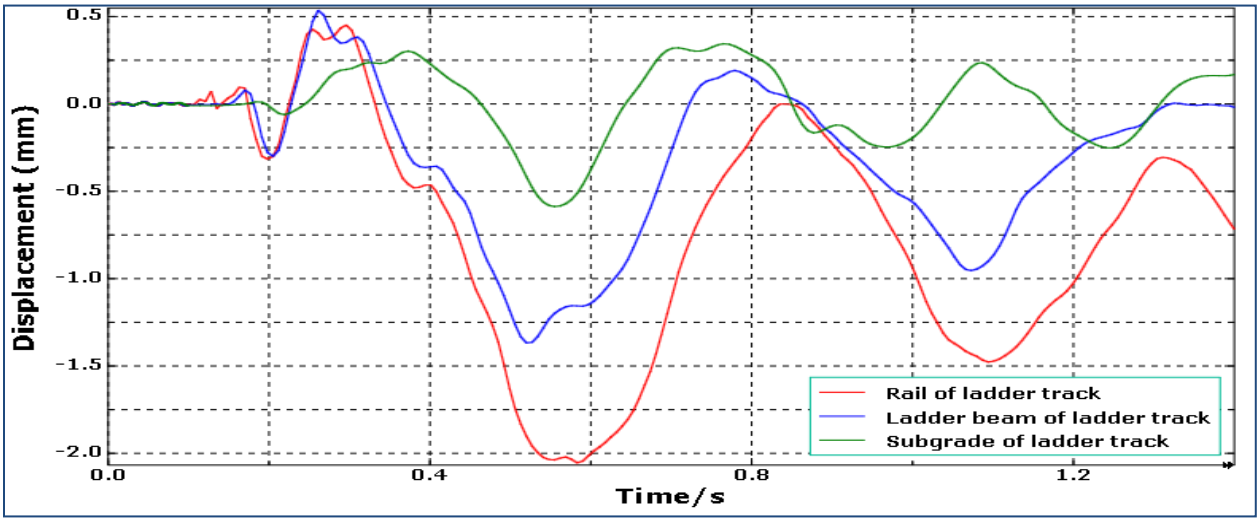


Figure5.1 Displacement of components of ladder track for train moving with speed of 120 km/hr. which is taken at the middle of the track

Relatively comparing the deformation of rail of ladder track for train moving at 40km/hr. and 120km/hr., maximum rail deformation at 40 km/hr. and 120 km/hr. is about 2.1mm and 2mm respectively. The displacement indicated in figure 5.2 is nearly close to the displacement indicated in figure 5.1. One of the reasons of closeness of the peak values are the analysis points on the two tracks are exactly not the same; it may varies with certain range. When train travels with low speed the displacement pattern of response of the track is becoming similar with graph of displacement under static force, Figure 5.2 also almost shows the behavior of static displacement.

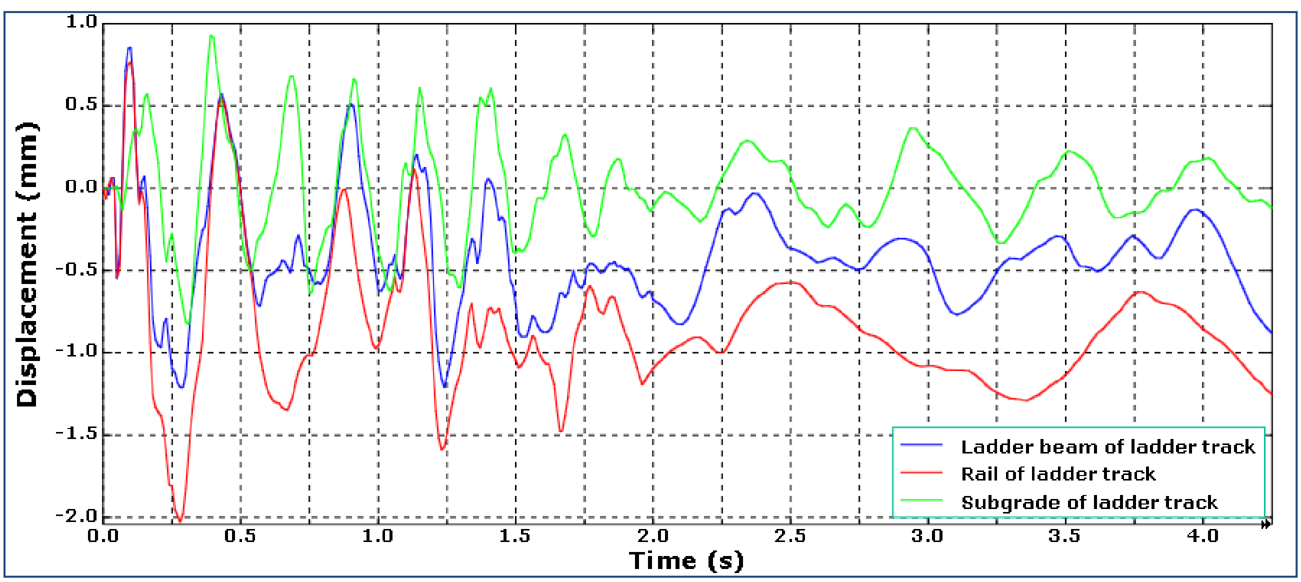


Figure5.2 Displacement of components of ladder track for train moving with 40km/hr. which is taken at the middle of the track

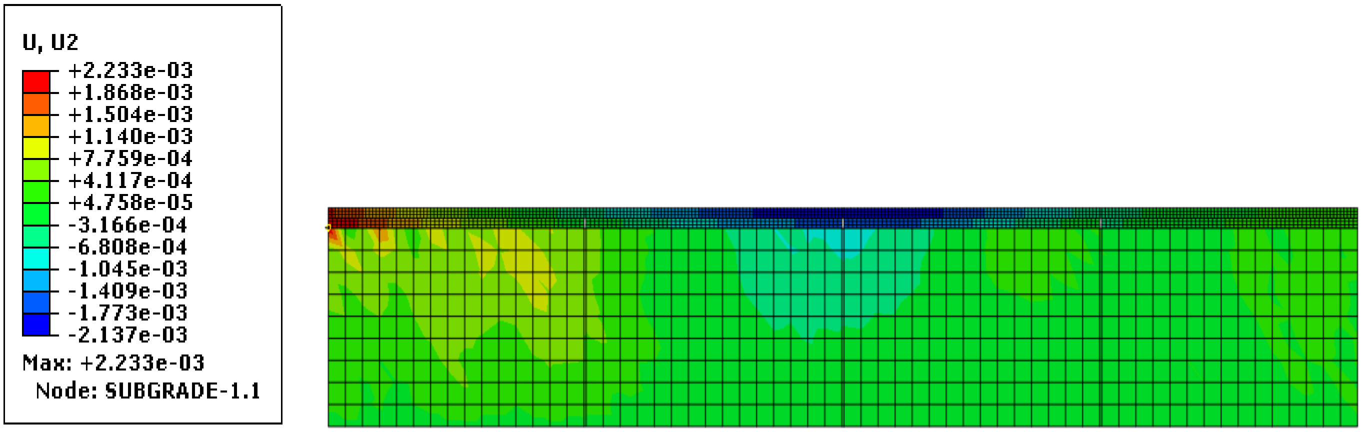


Figure5.3 Displacement contour of ballasted ladder track for train moving with speed of 120 km/hr

Figure 5.4-6 indicates that relatively ladder beam has high velocity and acceleration responses than rail and subgrade. Rail is continuously supported by ladder beam and almost all vertical vibration acceleration of the rail is absorbed and damped to zero by rail pad, and series of spring and dashpot of ballast but the ladder beam is supported only by series of the spring and dashpot of ballast. This leads the acceleration of ladder beam to be larger since the rail vibration acceleration is in addition damped by railpad (lorieux, 2008). Similarly the vertical acceleration of sleeper, ballast and bridge deck was analyzed by Louis Lorieux (lorieux, 2008) under analysis of train induced vibration on single span composite brigade the maximum acceleration of sleeper ($35m/s^2$) is greater than acceleration of ballast and rail (lorieux, 2008).

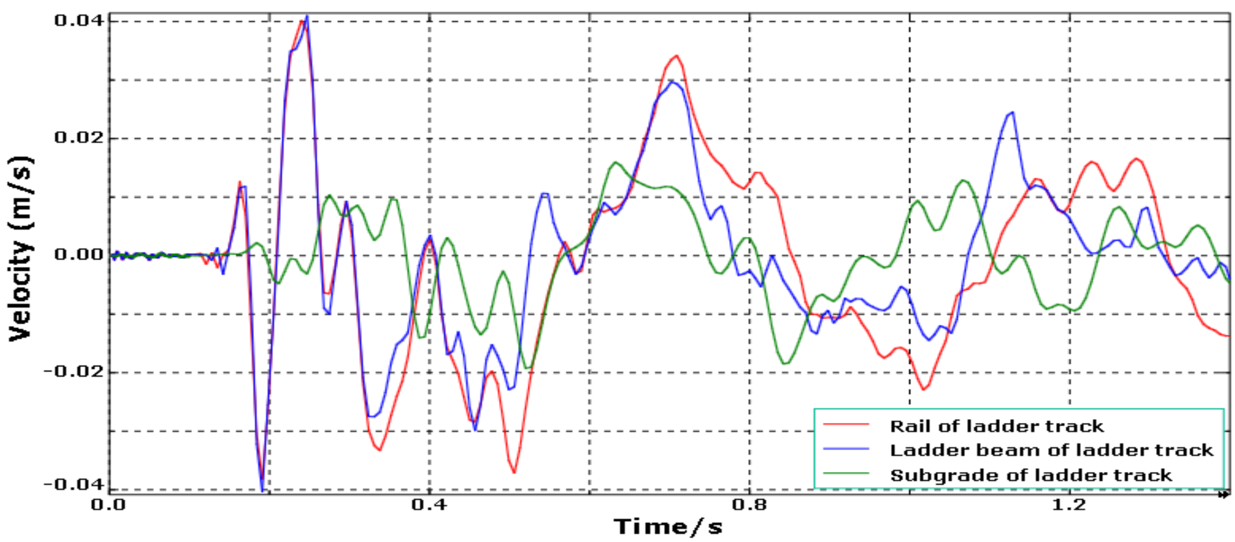


Figure5.4 Vertical velocity of component of ladder track for train moving with speed of 120 km/hr. which is taken at the mid of the track

In the figure 5.4 we can distinguish different peak velocity of a rail at different time. It is possible to take peaks at around 0.20 sec and 0.70 sec. which is about 0.04 m/s^2 and 0.03 m/s^2 respectively. These peak speeds also appears in this figure for ladder beam. This indicates that ladder beam vibrates with larger velocity initially and after certain time rail starts to oscillate with slightly higher velocity than other components.

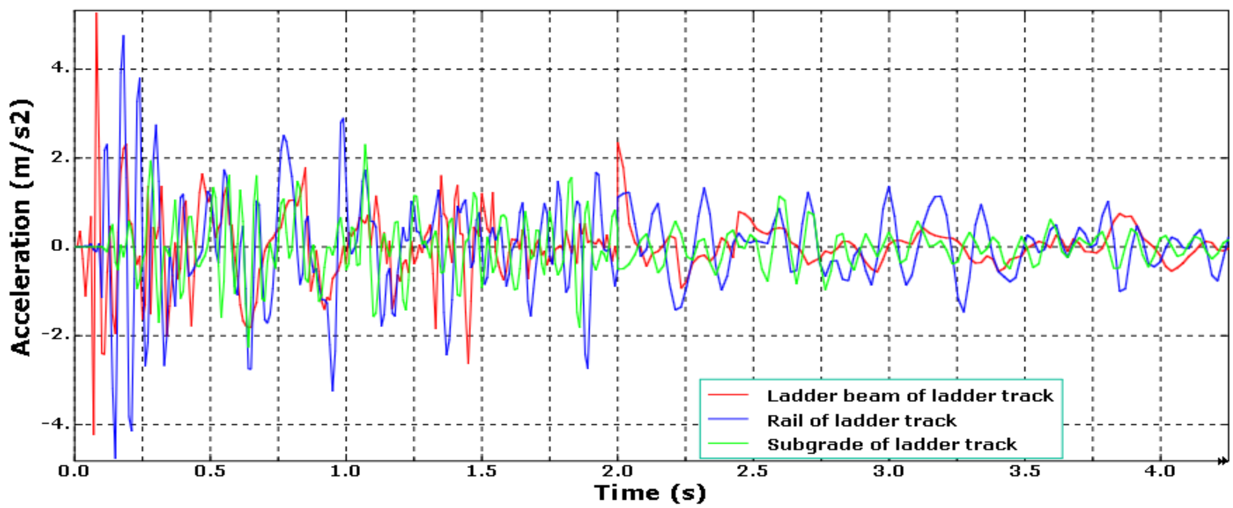


Figure5.5 Acceleration of component of ladder track for train moving with speed of 40 km/hr. which is taken at the middle of the track

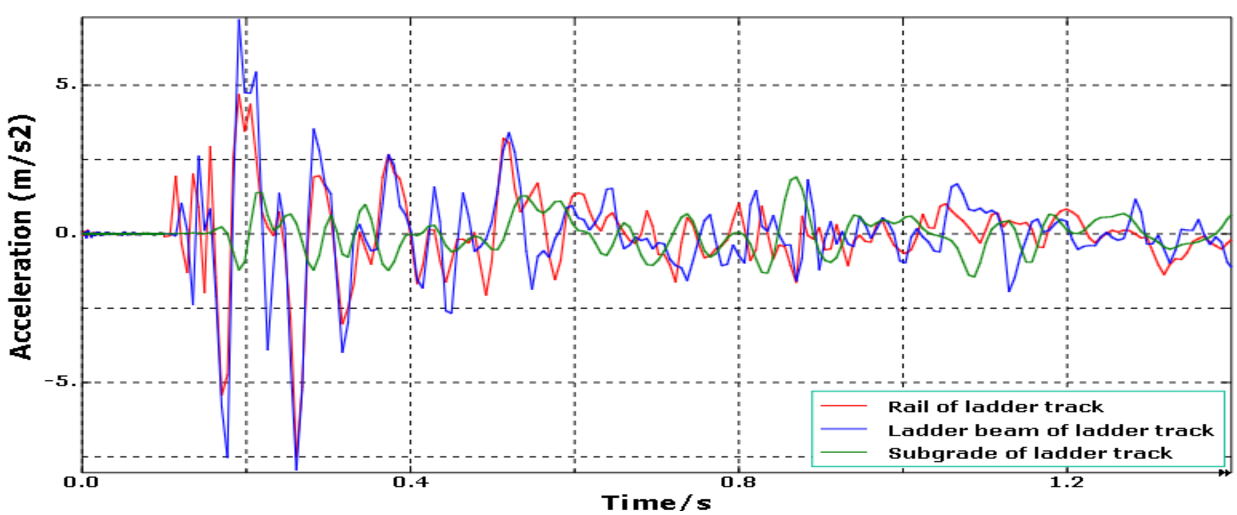


Figure5.6 Acceleration of component of ladder track for train moving with speed of 120 km/hr. which is taken at the mid of the track

The result from simulation presented in figure 5.5-7 can briefly show us the effect of different speed of train on component of the ladder track. When only focusing on peak response of ladder beam we can see that the acceleration of ladder track is greater than other components at all speed level. The main reason is that ladder beam acceleration is decreased by only series of spring and dashpot while acceleration of rail is decreased by both railpad, and spring and dashpot. It is also possible to observe the effect of speed on the response of sub-grade by focusing on the peak response of sub-grade of ladder track as shown in figure 5.5-7. As indicated in figure5.5-6 for train moving with speed of 40 km/hr, 120 km/hr the peak acceleration of sub-grade is about 2 m/s^2 and 1.5 km/hr. It is roughly possible to say that the acceleration response of sub-grade decrease as speed of train increase until critical soil speed reaches. The acceleration responses of sub-grade above critical speed need extensive research. From the simulation results indicated in figure 5.7 for train speed of 180 km/hr we can see different ladder track response patterns.

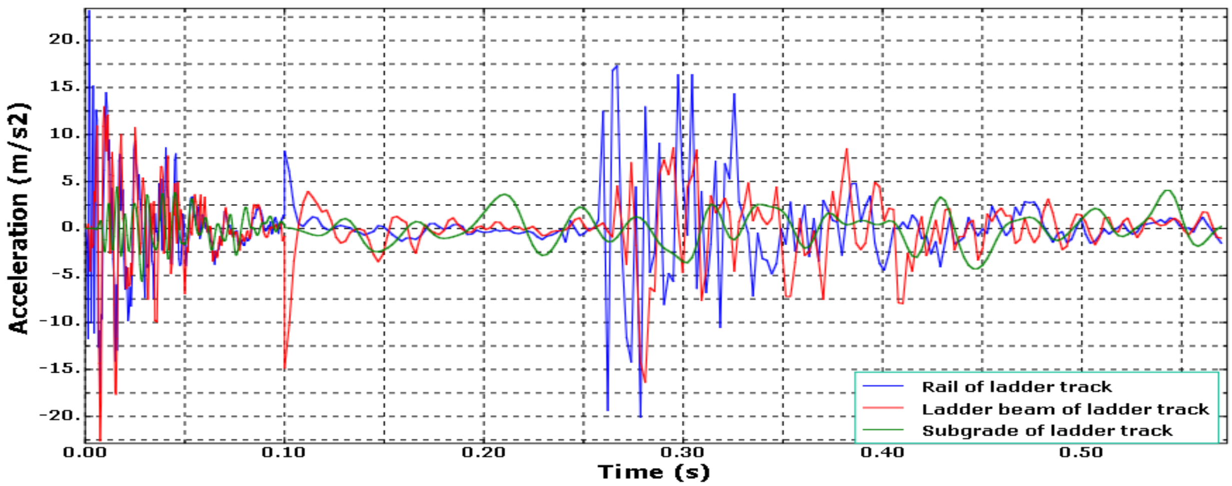


Figure5.7 Acceleration of component of ladder track for train moving with speed of 180 km/hr which is taken at the middle of the track

In figure 5.7 vertical acceleration of ladder track is plotted on the same graph so that we can clearly see the response pattern of a ladder track. The results show that the direction of vibration of ladder sleeper and rail is opposite in direction. The acceleration of rail and ladder sleeper are nearly equal at the beginning of the train movement and gradually ladder sleeper vibration exceeds the acceleration of rail and after certain time of seconds the vibration of rail and ladder sleeper increase dramatically and again gradually decrease. However the acceleration response pattern of sub-grade is totally different from other components. When train passes at the point of analysis the acceleration of both the rail and ladder sleeper indicate larger value than that of sub-grade and after certain time the acceleration of sub-grade starts to dominates the acceleration of both rail and ladder sleeper; this occur because of the load imposed on the rail transmitted under laying formation layer gradually not immediately.

5.2 Time History Response of Conventional Ballasted Track

Figure 5.8, 5.9 and 5.10 show the variation of dynamic response of conventional ballasted track for vehicle moving at speed of 180 km/hr and 120 km/hr respectively. When deflection of the rail and other component is relatively compared as shown in figure 5.8-9, rail has higher deformation than conventional sleeper and sub grade, however it has relatively less velocity and acceleration than sleeper does; this is due to presence of rail pad under the rail which isolate the vibration of rail not transferred to the sleeper and down to underlying structure. By looking at figure 5.12-14 (for train speed of 40 km/hr, 120 km/hr and 180 km/hr) at constant railpad stiffness, ballast stiffness and damping, sleeper acceleration dominates that of other components. This indeed due to the discrete support system of which concentrated axle load applied on the rail is transferred to the point sleeper which produce high acceleration in the sleepers. Not only this but also presence of series of spring and dashpot under sleeper has a great effect on acceleration of sleeper. As discussed in section 5.1 the acceleration of rail is decreased and damped both by railpad and series of spring and dashpot under sleeper, however the acceleration of the sleeper is decreased and damped by only series of spring and dashpot; this is one of the reason for the acceleration of sleeper becomes largest relative to another components. In general the analysis shows that in the deformation parameter the rail indicates larger deflection than other components under all speed studies, however under acceleration parameter sleeper shows dominance by considering peak value of the simulation output. Therefore the rail under operation needs to be checked for settlement periodically while sleeper should be inspected for lateral or longitudinal movement since it is subjected to high acceleration.

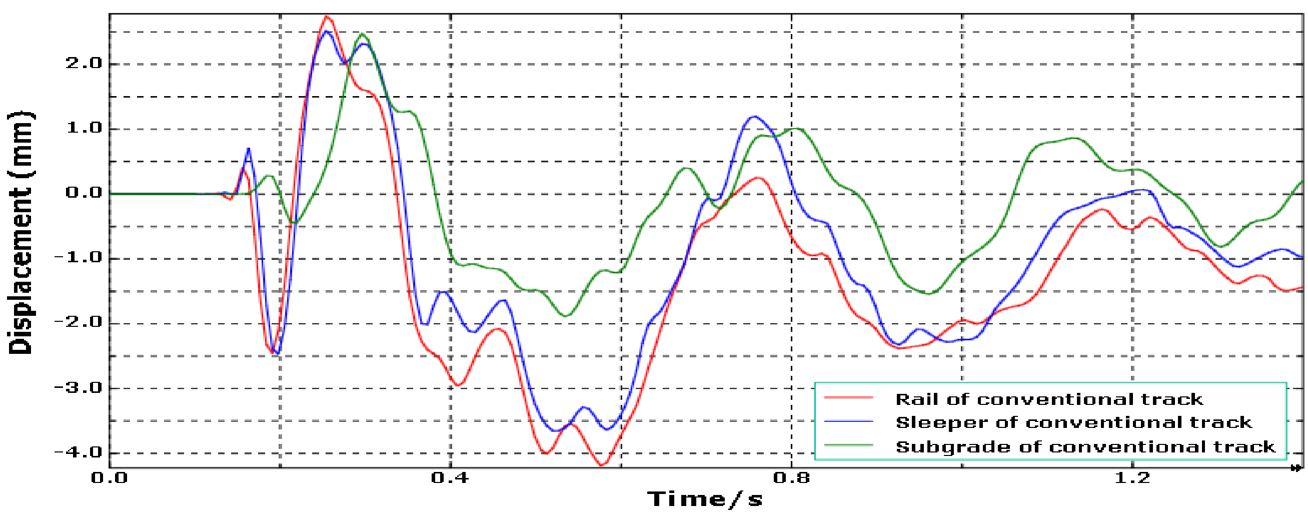


Figure5.8 Displacement of components of conventional ballasted track for train travelling with 120 km/hr which is taken at the mid of the track

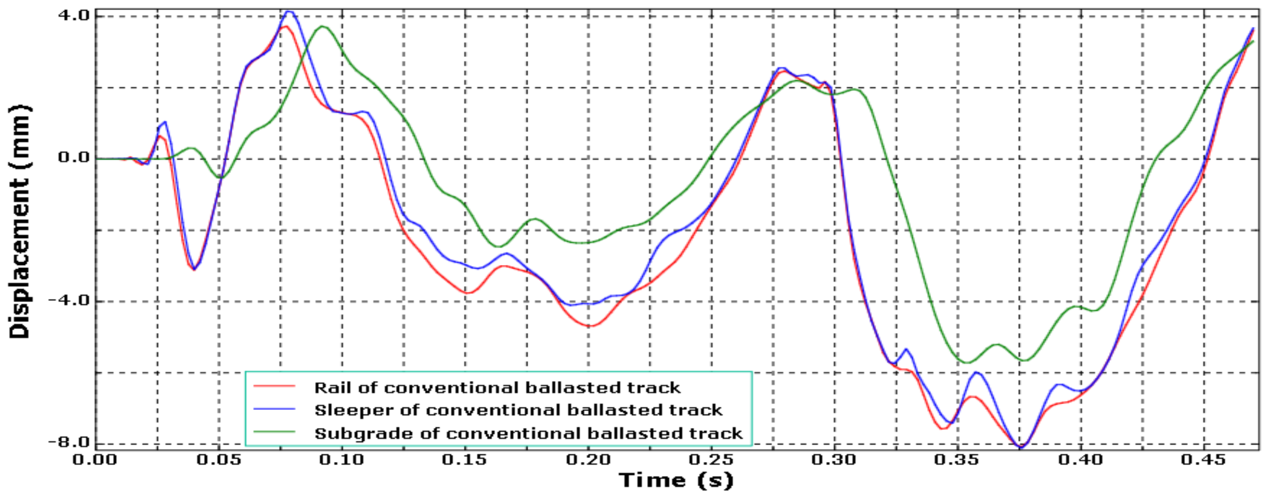


Figure5.9 Displacement of components of conventional ballasted track for train moving with speed of 180 km/hr which is taken at the mid of the track

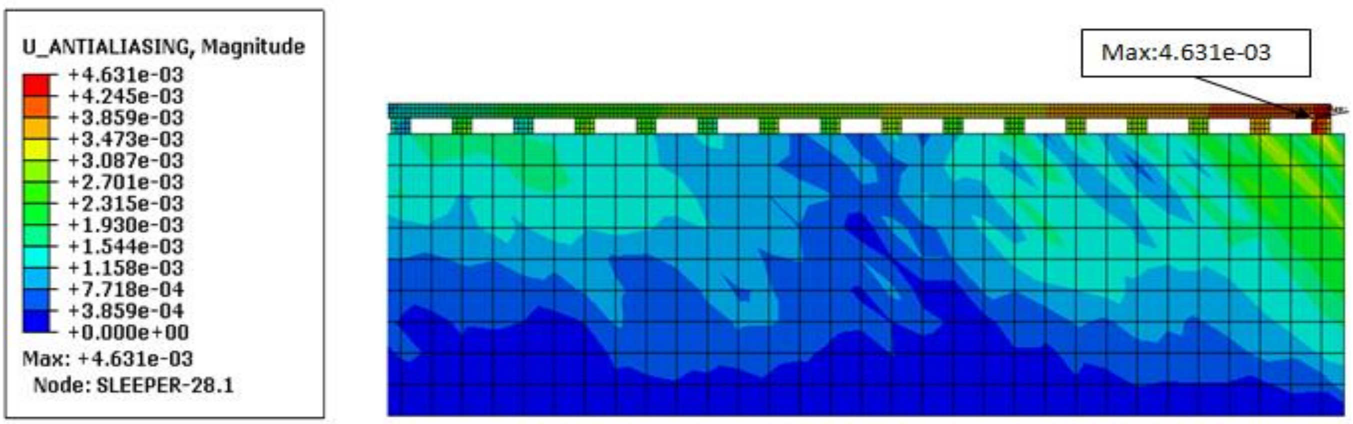


Figure5.10 Displacement contour of conventional ballasted track for train moving with speed of 120 km/hr

Figure 5.10 indicates the displacement contour of conventional ballasted track under train speed of 120 km/hr. The global maximum displacement (4.631e-03) occurs under sleeper of the end; however the maximum displacement of the components of track at the middle of track (analysis point) shows nearly equal rail displacement not exact value. This is the reason that the explicit dynamic analysis merely focus on relative response of the components of the track rather than absolute maximum value (analysis approach of the explicit dynamic analysis).

Relatively comparing the deformation of rail of ladder track for train moving at 120 km/hr and 180 km/hr, as shown in figure 5.8 and 5.9 the maximum rail deformations are about 4.1 mm and 8.0 mm respectively; which has very far difference. From those figure it is possible to understand that as speed of the train increase the deformation of rail of conventional ballasted track dramatically increases. This indicates that the rail is subjected to more deformation at higher speed which intern decrease serviceability of the track. Therefore conventional ballast track is unstable at higher speed, however it needs extensive research to investigate the speed level at which the conventional ballasted track is unstable.

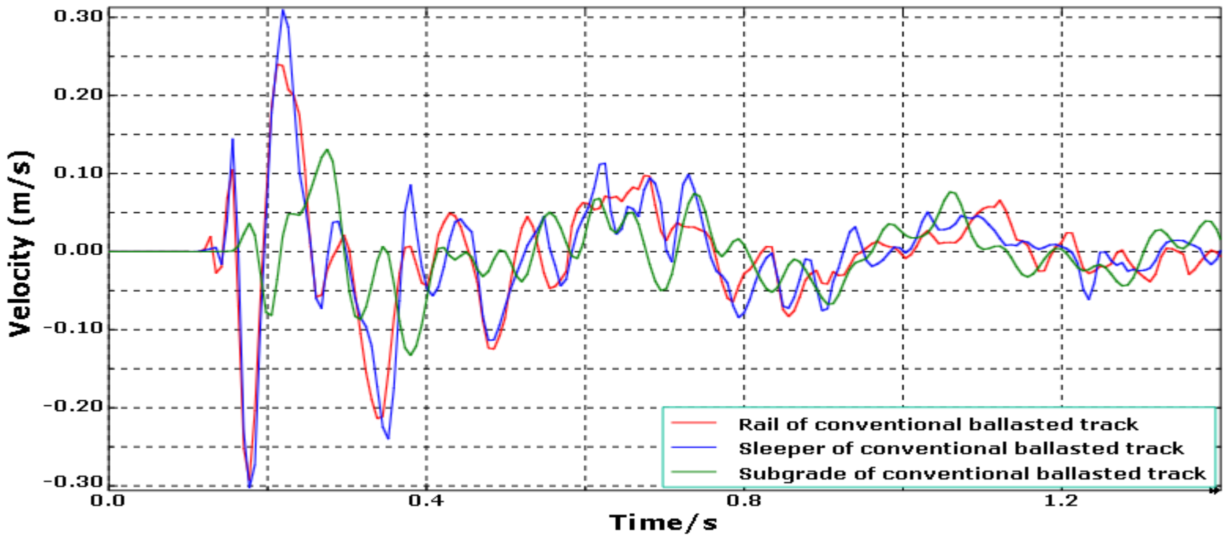


Figure5.11 Velocity of components of Conventional ballasted track for train travelling with speed of 120 km/hr which is taken at the mid of the track

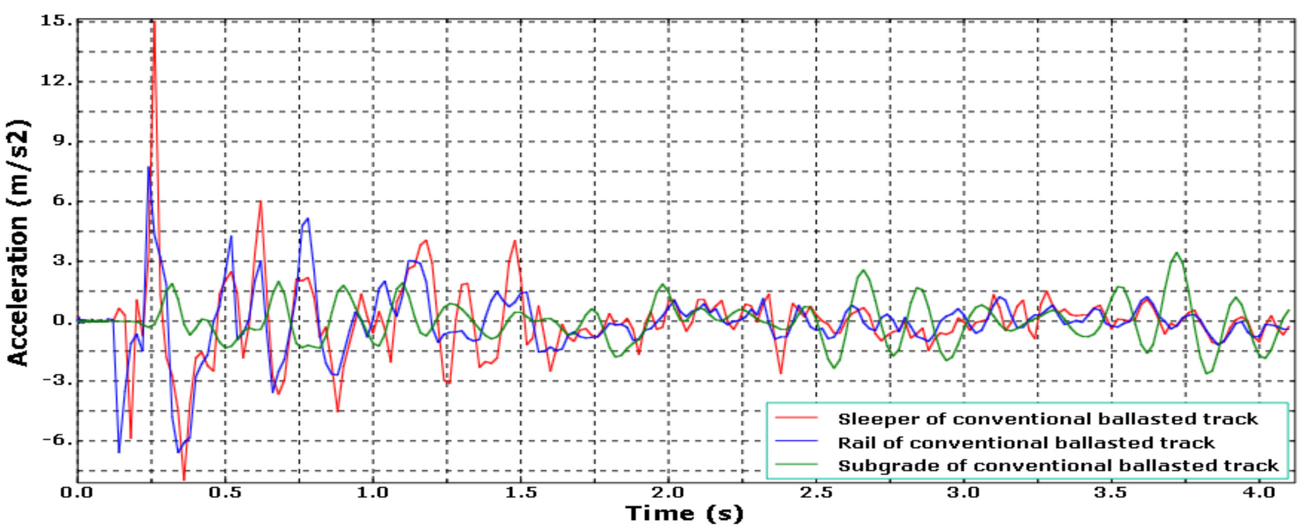


Figure5.12 Acceleration of component of conventional ballasted track for train travelling with speed of 40km/hr which is taken at the mid of the track

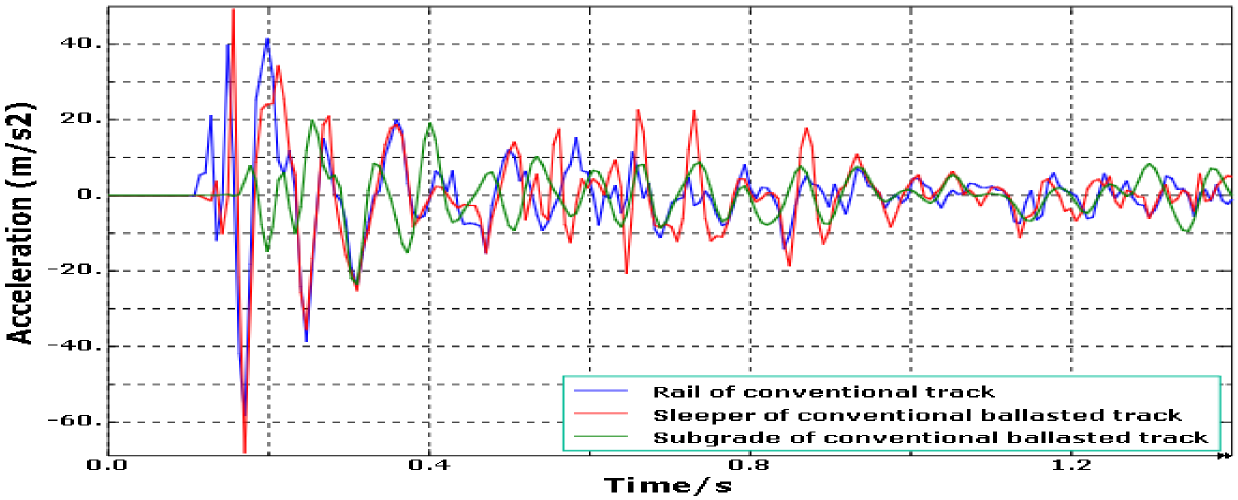


Figure5.13 Acceleration of component of conventional ballasted track for train travelling with speed of 120 km/hr which is taken at the mid of the track

As described for ladder track in section 5.1 similar acceleration pattern is observed in conventional ballasted track under train speed of 180 km/hr (see figure 5.14). The acceleration vibration of the components of conventional track at initial time is high and gently decreases upto 0.3 seconds and again it starts to accelerate more for fraction of secconds and redecrease. The response pattern of the track under train speed of 40 km/hr and 120 km/hr (see figure 5.13) are slightly similar with that of track under train speed of 180 km/hr until certain time range, however after certain time of vibration, acceleration of all components of the track will rise and again starts to decrease. This difference may arise from the influence of high speed of train on components of the track. To have enough reasonable reason for the difference of the resposnse pattern of track components under different speed studies, it needs to undergo detail investigation. In convetional ballasted track sleeper accelerates more than ather components at all speed studies by considering peak responses. Not only this but also the acceleration of sleeper increase as speed of the train increases.

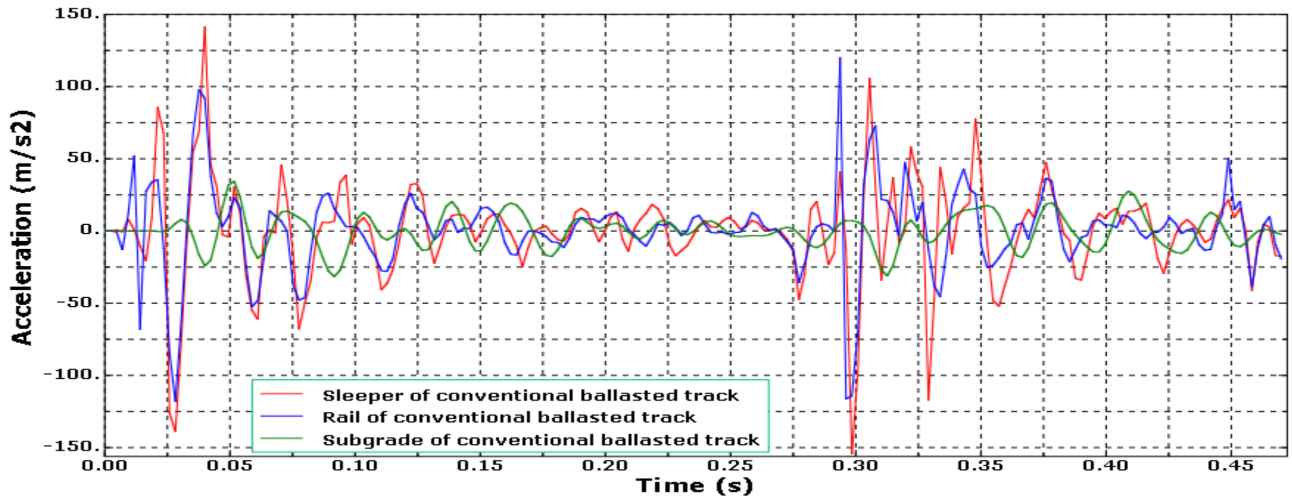


Figure5.14 Acceleration of component of conventional ballasted track for train moving with speed of 180km/hr which is taken at the middle of the track

5.3 Extraction of Natural Frequencies and Mode Shape

For modal analysis steady state dynamic modal analysis is used to determine the natural frequencies and mode shapes of components of the track. In this model sinusoidal load is applied directly on the rail and Lanczos Eigen solver is used to extract the mode shapes and corresponding natural frequencies**.** In structural dynamic analysis, the response is usually associated with the lower modes (Priest J. A., Powrie W., 2009). But to have a good description of dynamics of the track structure, enough modes should be extracted. To check whether sufficient number of Eigen modes is extracted or not it is possible to compare the total effective mass participating in each degree of freedom. In this model more than 95% of the effective mass is considered in extraction of modes of the track. Since sub-grade of track vibrates more at lower modes while rail and ladder sleeper and conventional sleeper are effective at higher mode it is necessary to consider all required mode number (see figure 5.16 and 5.19).

5.4 Ballasted Ladder Track Natural Frequency and Mode Shape

When the train moves a load from weight of train will move along with the train. The load will fluctuate due to differences at various parts of the train-track structure system, such as (i) irregularities on the surface of the rail and wheel, and (ii) variations in the support structure beneath the rail. Thus, vibrations are generated and propagate from the track into the surrounding ground. Depending on material properties of the track, components of ladder track have different range of frequency response (see figure 5.15)

As seen in figure 5.15 in the very lower frequency range (0-20Hz) the acceleration of the subgrade is slightly higher than ladder sleeper and rail. However at middle frequency range (40-200Hz) ladder sleeper and rail starts to accelerate more than whole components and at higher frequency range >200Hz ladder sleeper and sub-grade acceleration response decrease, Whereas rail starts to dominate with higher acceleration value. Sub-grade significantly damps the vibration of track at lower frequency (<40Hz) and its response at higher frequency range is almost negligible. It is possible to say that low frequency vibration problem of ladder track cannot be solved by conventional vibration control measure such as inserting resilient material under rail and ladder sleeper but at higher frequency range it can be controlled by railpad and ballast mats. This indicates that the best solution to reduce the low frequency vibration is working on geometry and material properties of the sub-grade. The low frequency dynamics of the track is mostly related with geotechnical and geodynamic issue. The same behavior of track under these frequency range is also studied by Blanco et al. (Blanco-Lorenzo J., Santamaria J., Vadillo E.G. & Oyarzabal O., 2011). When vehicle travels with low speed it induces low frequency and produce significant effect on the surrounding structure but at higher speed it induces higher frequency and does not have major effect on surrounding structure, however it is challenging for rail and fastener structure.

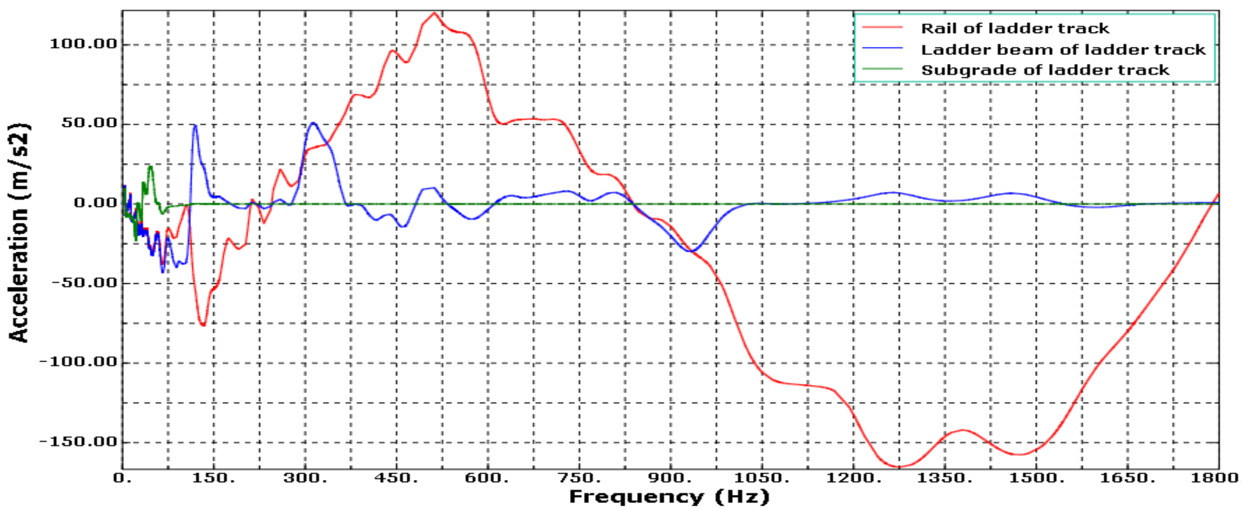


Figure5.15 Acceleration of ladder track component taken at the middle of track

It is indicated in the figure 5.16 the mode of the track is limited to 1000 for detail visualization of response pattern of all components of the ladder track. Adding mode does not change the pattern but it changes amplitude. As the number of the mode increase the amplitude of vibrating track also increases.

In the same way as described for acceleration response of the track, as shown in a figure 5.16, at lowest mode track structure vibrates in longitudinal direction and at higher mode the vibration of vertical direction of track dominates longitudinal vibration. Not only this but also at relative lower mode (<700) sub grade vibrates at higher amplitude and at mid mode (700-900) ladder sleeper vibrates more than rail and sub-grade, whereas at higher mode (>900) vibration amplitude of rail totally dominate the response of all components of the track.

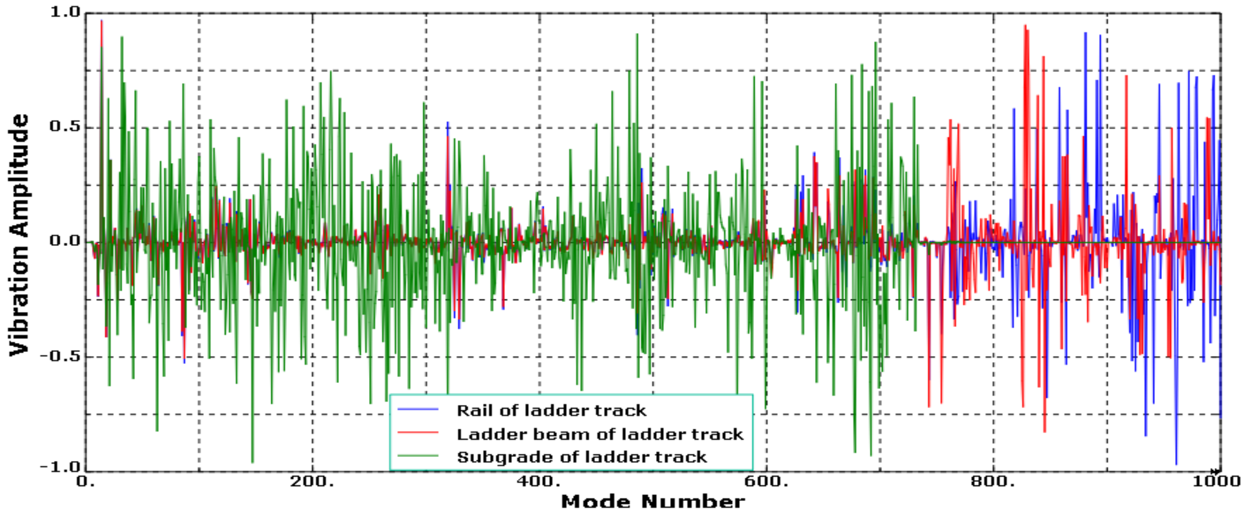


Figure5.16 Variation of vertical Vibration amplitude of ladder track components

It is shown in figure 5.17 as we go down from the super structure to substructure stress distribution decreases .This indicates that the load applied on the rail is distributed on larger area of ladder sleeper and finally to the sub-grade .The stress reaches the sub-grade is very small because the load is distributed on wide area. In the first 100 lower mode the imposed stress on the superstructure is as low as the stress imposed on substructure at higher mode .

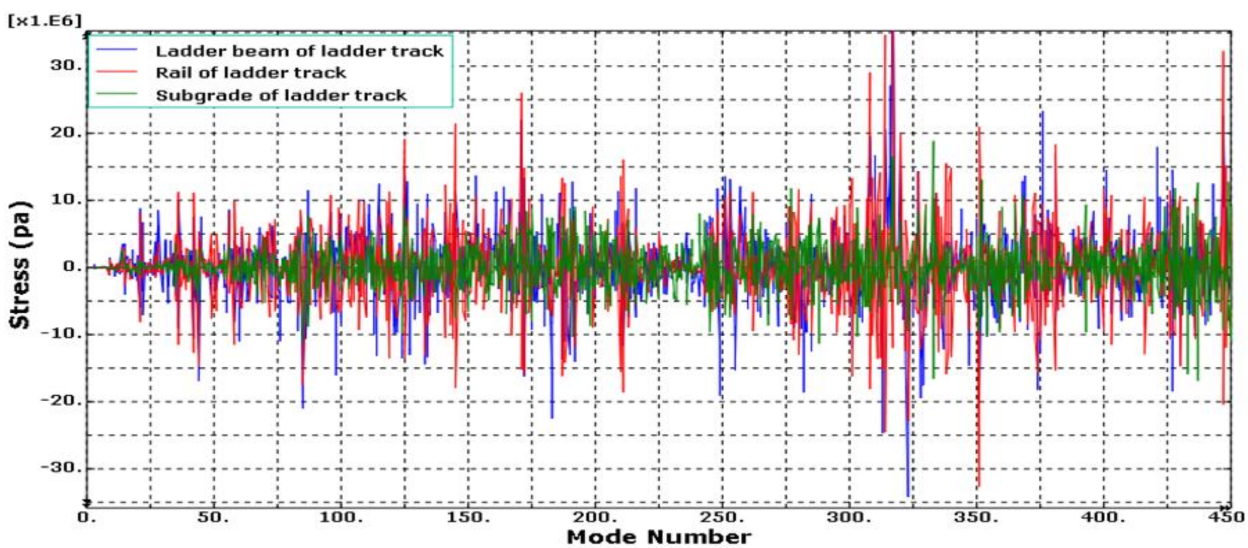


Figure5.17 Variation of vertical stress of ladder track

5.5 Conventional Ballasted Track Natural Frequency and Mode Shape

Similarly as Eigen frequency analysis presented for ladder track in section 5.4, vibration response of conventional ballasted track is also studied in this section, almost similar response pattern results have been obtained when relatively compared to vibration response of ladder track. In figure 5.18 it is demonstrated that the acceleration of components of ballasted track responds differently at all frequency ranges. In very low frequency range (0-20Hz) sub-grade acceleration is seen largest; however at mid-frequency range (40-600Hz) sleeper acceleration dominates that of rail and sub-grade while frequency range above 600Hz rail acceleration vibration takes its global dominance.

The dynamic behavior of ballasted track contains several resonant frequencies .The full track resonant frequency of the ballasted track at the mid span or at the support is the lowest frequency while pinned-pinned resonant frequency of a rail is the largest frequency response of the track. Relatively speaking, the mid-span response frequency is higher than on support frequency when it is out of full track resonance.

As indicated in figure 5.18 in a frequency range (0-40Hz) the response of the sub-grade of the conventional ballasted track is high when compared to other components .This is also studied by Oscarsson (oscarsson, 1999): the resonance when track is built on soft ground and where a great deal of substructure vibrate and upper track structures have minor role at this frequency range (Priest J. A., Powrie W., 2009).

Second frequency range that is seen in the figure 5.18 is (40-600Hz) which rails and sleepers vibrate on the ballast bed. In this range rails and sleepers provide a mass and ballast provide the spring for resonance vibration.

The third frequency range is 600-1250 Hz; the rail bouncing on the railpad and ballast used as damper .The fourth and the last frequency range is above 1250Hz and it is called pinned –pinned resonance frequency. This occurs when the wave length of the bending waves of the rail is twice the sleeper spacing. The pinned-pinned resonance frequency is so lightly damped; mainly the steel material itself (propagating waves along the rail) is involved in damping this vibration and very little vibration energy is transmitted to the surroundings (sub-grade). As studied by Krus and popp (Kruse, H. and Popp,K., 2000) damages to sleepers and ballast settlement problems are mainly attributed to vibration in the range of 50-500 Hz. This ranges corresponding to the mid-frequency range in which the ballast and sleeper vibrate with higher acceleration value. For noise problems the upper vibration limit is about 2000 Hz, at this frequency range the wheels begin to dominate the noise or vibration radiation at higher frequency (2000 Hz) (D.J.Thompson, 1988). In the figure 5.18 we can see the pinned-pinned resonance frequency of rail at 800-1000 Hz which corresponding to the first bending resonant frequency of rail segment between two sleepers. Similarly Knothe and Grassie (Knothe, Ki and Grassie, 1993) explained the occurrence of pinned-pinned resonance frequency at 800-1000 Hz.

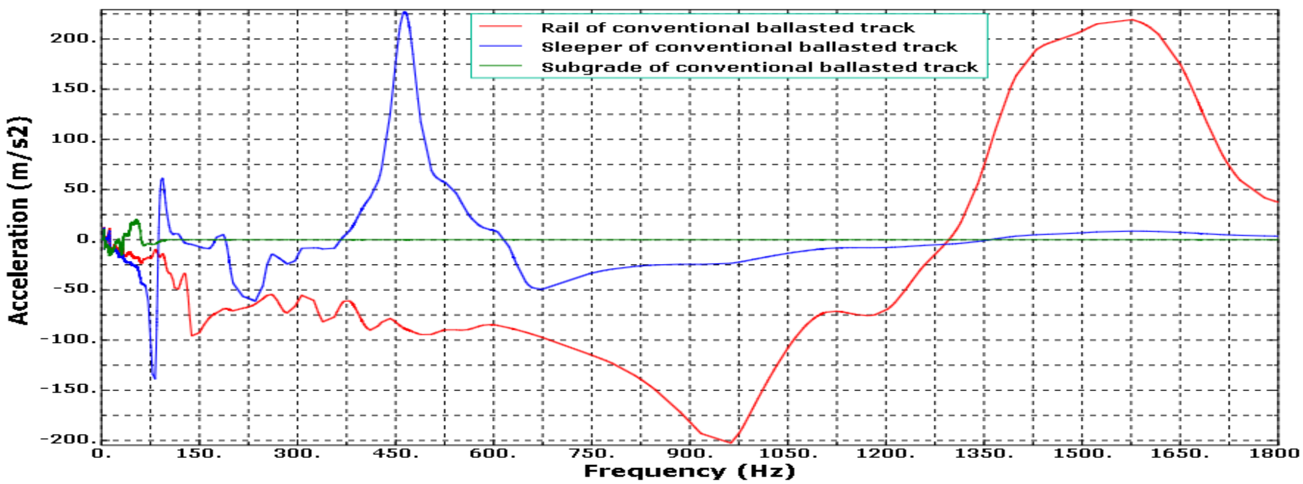


Figure 5.18 Acceleration of conventional ballasted track components taken at the middle of the track

The result of the simulation also shows the vibration response of sleeper at different frequency ranges. There are several resonance frequency peaks around 75Hz and 450Hz. At around 450 Hz sleepers shows largest acceleration which is almost equal with the peak resonance of the rail.

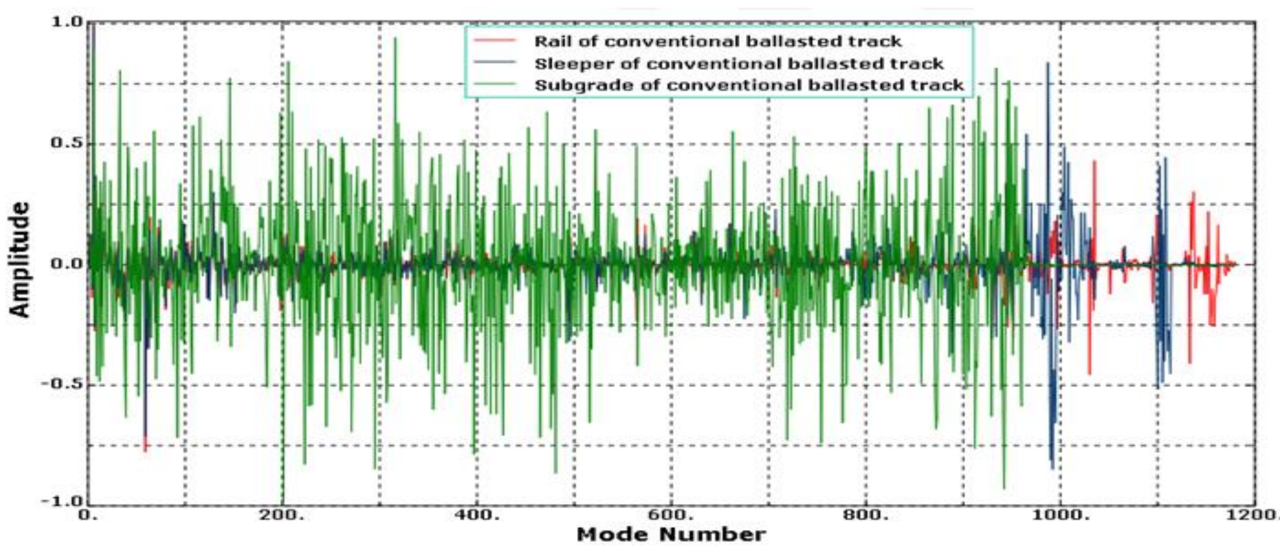


Figure 5.19 Variation of vertical Vibration amplitude of conventional ballasted track

In the same way as described for Ladder track as shown in a figure 5.19, at lower mode sub grade vibrates at higher amplitude and at relative mid-mode (970-1150) conventional sleeper vibration response is higher until it transfer its vibration role to the rail, whereas at higher mode (>1150) rail vibration response totally dominate the response of components of the track.

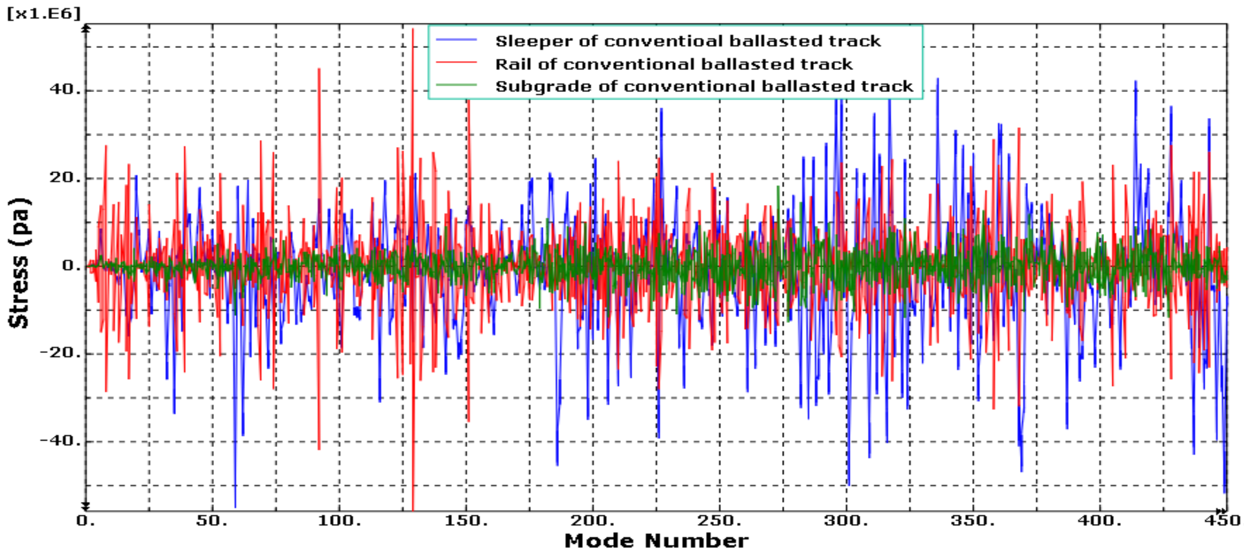


Figure 5.20 Variation of vertical stress of conventional ballasted track

As indicated in figure5.20 by overall visualization the stress transmission from top structure to down structure decreases. Mode has its own effect on the stress distribution on the structure of ballasted track; it is shown in figure 5.20, at lower mode (<170) the stress level of the rail is seen to be higher than all components while at higher mode the sleeper is stressed more than rail. At very lower mode (<5) the stress level that subgrade or ballast bed subjected to is less than 0.5Mpa. The maximum induced stress to sub-grade has limited to 0.5Mpa to keep stability and safety of the formation layer (Esveld C. , Modern railway technology, 2001).

5.6 Dynamic comparison of ballasted ladder track versus conventional ballasted track

The dynamic responses of both conventional ballasted track and ballasted ladder track are studied in previous section 5.4 and5.5. But in this section dynamic performance of both track will be compared in response of both time and frequency domain. As shown in figure 5.21 the sub-grade of conventional ballasted track deforms almost about 2.5mm while that of ladder track deforms about 0.5mm by taking global maximum value. The deformation of ladder track is very small compared to conventional ballasted track. It indicates that conventional ballasted track deforms five times of ladder track do. It is possible to say that ladder track has great advantages in reducing the deformation of sub-grade of the track and intern decrease deterioration of formation layer.

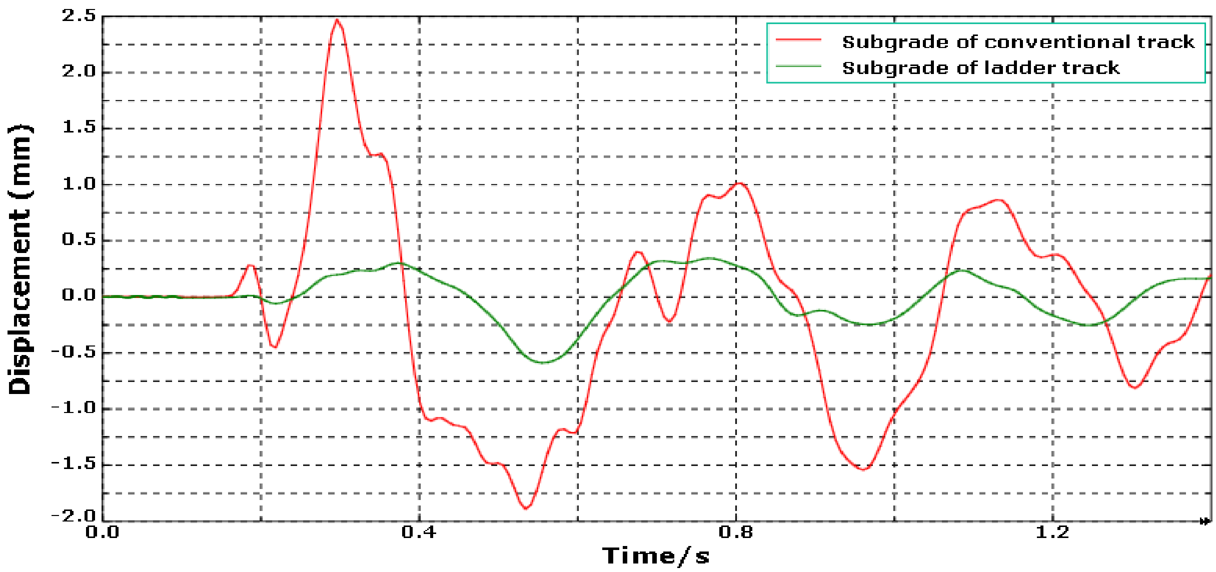


Figure 5.21 Displacement of sub-grade of ballasted ladder track versus sub-grade of conventional ballasted track taken at the middle of the track (under train speed of 120km/hr)

From figure 5.22 it is possible to understand that rail of Ladder track accelerates almost $5m/s^2$ while that of conventional ballasted track accelerates about $60m/s^2$ by taking maximum value. Ladder track reduces acceleration of a rail almost by 92%. Similarly figure 5.25 indicate that acceleration comparison of sleeper and ladder beam of both ladder and ballasted track; ladder beam also decrease acceleration by 93%. Therefore ballasted ladder track is effective in decreasing acceleration of components of the track and it can be used for modern railway which is used for rapid train.

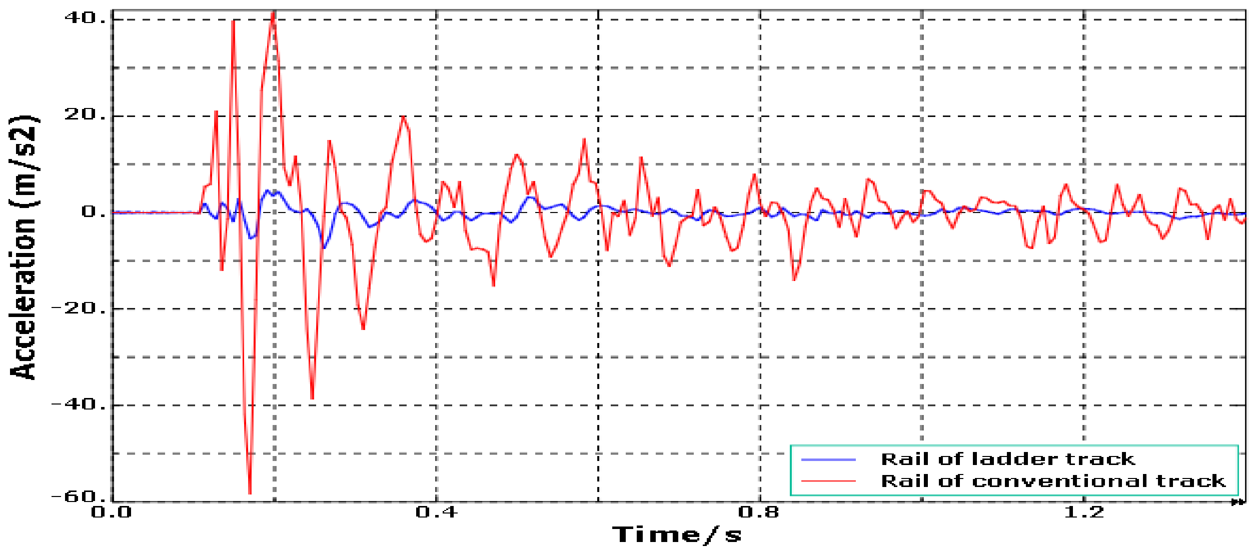


Figure 5.22 Acceleration of rail of conventional ballasted track versus rail of ballasted ladder track taken at the middle of the track (under train speed of 120km/hr)

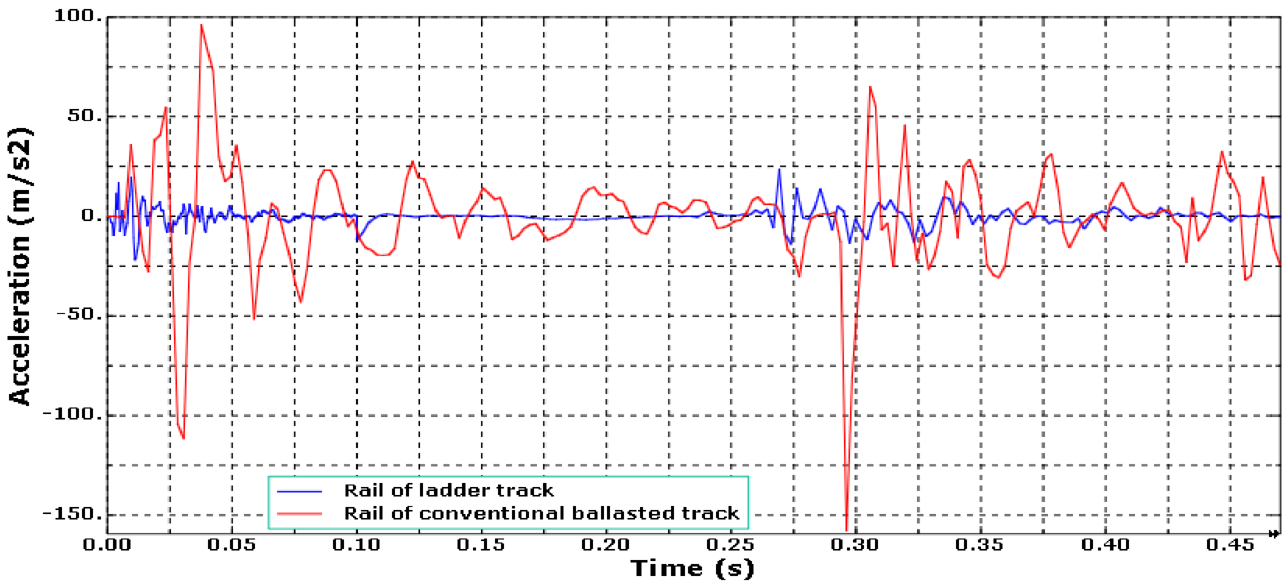


Figure 5.23 Acceleration of rail of conventional ballasted track versus rail of ballasted ladder track which is taken at the middle of the track (under train speed of 180 km/hr)

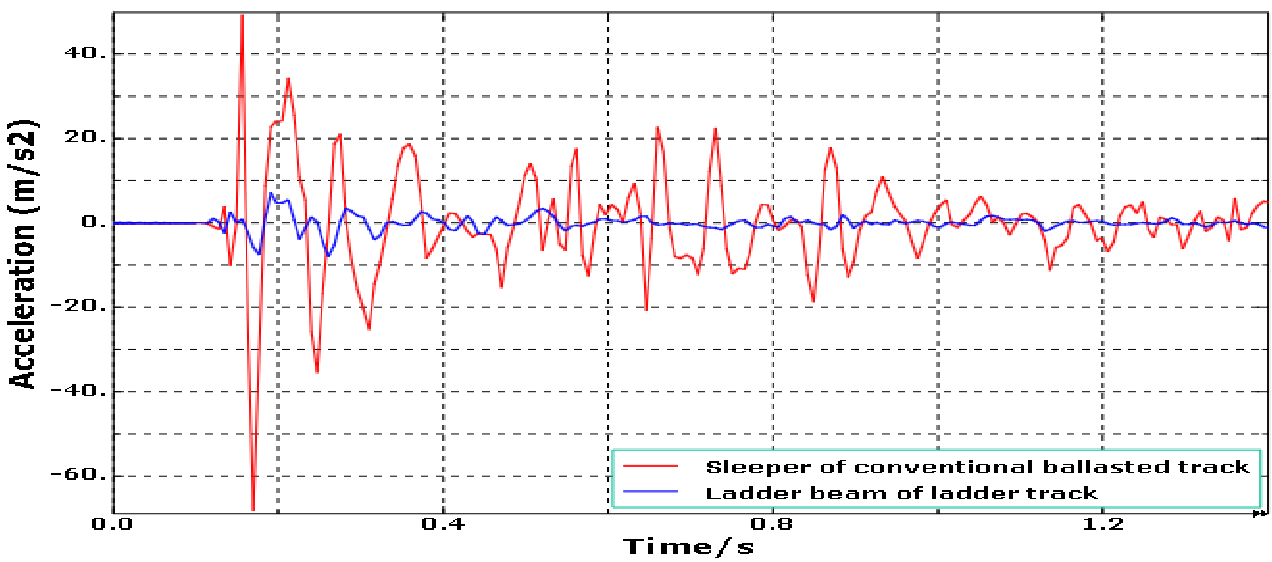


Figure 5.24 Acceleration of sleeper of conventional ballasted track versus ladder sleeper of ballasted ladder track taken at the middle of the track (under train speed of 120km/hr)

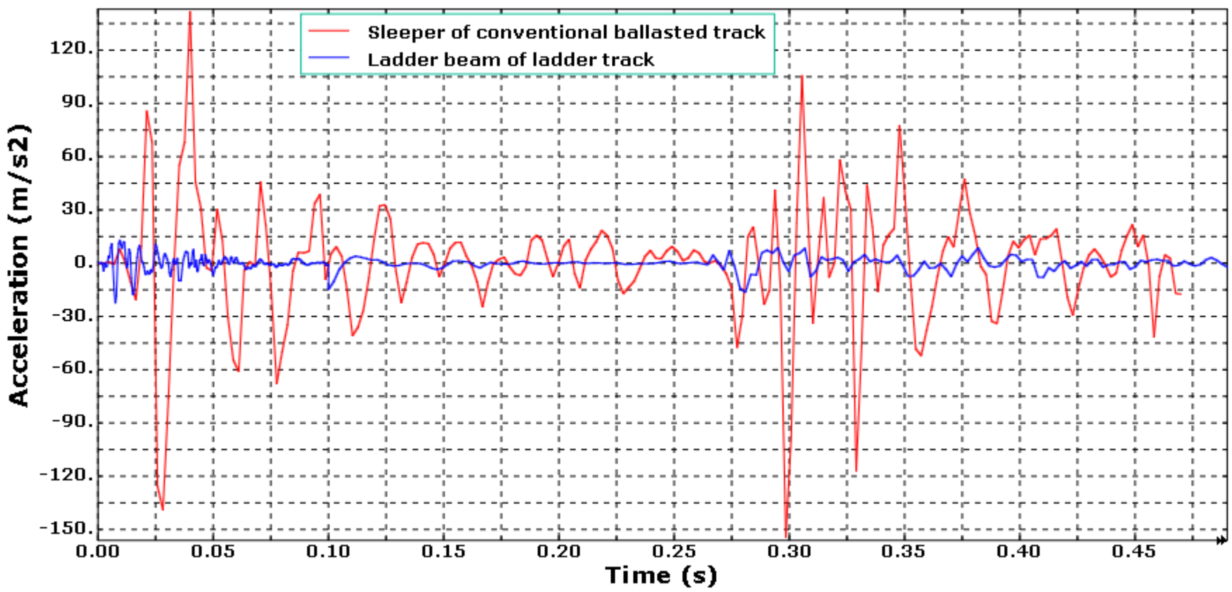


Figure 5.25 Acceleration of sleeper of conventional ballasted track versus ladder sleeper of ballasted ladder track which is taken at the middle of the track (under train speed of 180km/hr)

Figure 4.23 precisely indicates the influence of speed on acceleration response of discretely supported and continuously supported of rail. Maximum acceleration of the rail of conventional ballasted track and rail of ladder track under train speed 180 km/hr is about 150 m/s^2 and 15m/s^2 respectively. This indicates that at very high speed of train, rail of conventional ballasted track accelerates higher than rail of ballasted ladder track; this indicates that rail of conventional ballasted track becomes unstable under higher train speed. Therefore usage of conventional ballasted track for speed of train above 180km/hr is as much not economical since ballast layer is becoming unstable and it is subjected to more repeated maintenance.

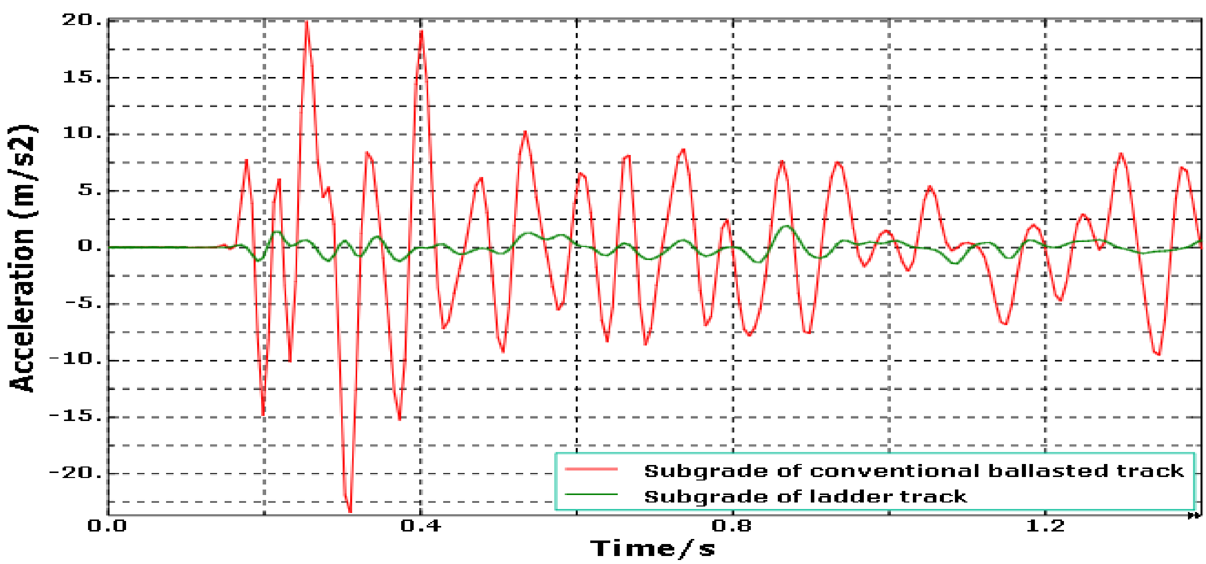


Figure 5.26 Acceleration of sub-grade of conventional ballasted track versus sub-grade of ballasted ladder track which is taken at the middle of the track (under train speed of 120km/hr)

It is obvious that dynamic response that is obtained in time domain is difficult to absolutely characterize (define) dynamic behavior of track; therefore it is necessary to enhance the study by considering all frequency range. As seen in figure 5.27, in the relative low-frequency range (0-150Hz) the vibration acceleration of the rail of ladder track is slightly higher than rail of conventional ballasted track. However at higher-frequency range rail of conventional ballasted track accelerates more than that of acceleration of rail of ballasted ladder track. Rail of ballasted ladder track reaches peak acceleration at three points around 150Hz, 500Hz and 1250Hz. Among these points global peak acceleration (175m/s) occur at 1250Hz. But rail of conventional ballasted track shifts its global peak acceleration(225m/s2) to higher frequency (1575Hz) and other peaks are attained at 150Hz and 975Hz.

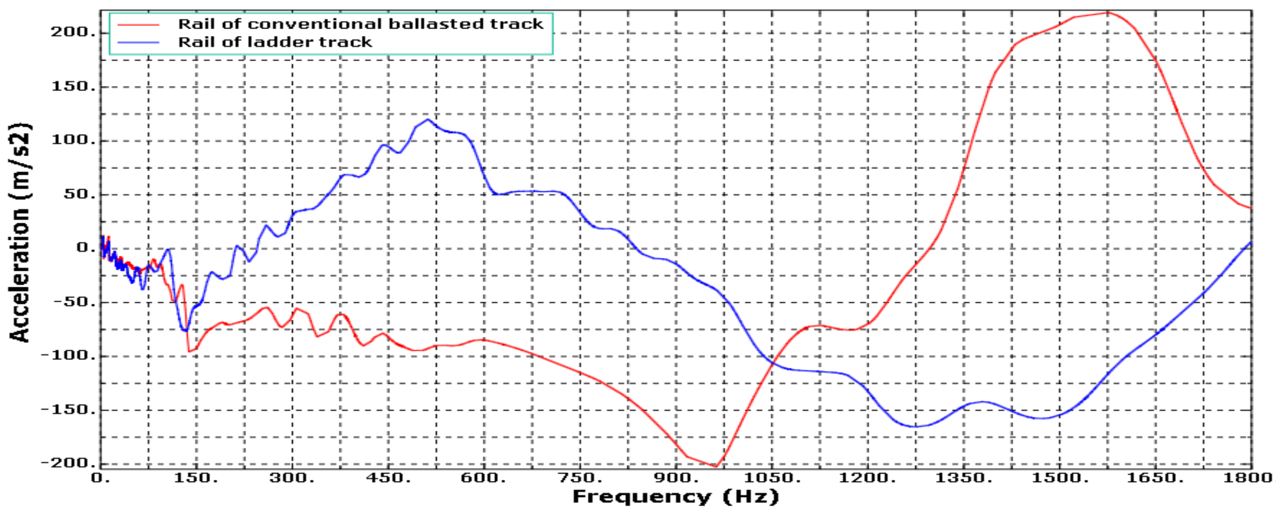


Figure 5.27 Acceleration of rail of conventional ballasted track versus rail of ladder track taken at the middle of the track

Knothe et al. also obtained the same result by considering vibration of rail between two sleepers. The first pin-pin resonant frequency occurs between 400-1200 Hz and second one occurs at higher frequency around 1500 Hz. Similarly figure 5.27 show that vibration of rail of ballasted ladder track forms pin-pin resonant frequency at frequency range of 300-700 Hz whereas the second one occurs between 800-1600 Hz.

In general it indicates that Ballasted Ladder track is effective in reducing acceleration of the rail at higher frequency range. It is very effective for high speed train which rail vibration is becoming a great issue in high speed railway line.

The detail relative dynamic response of sleeper and ladder beam indicated in figure 5.28. At different frequency range, both of the tracks have different responses. Ladder beam of ballasted ladder track shows high acceleration at low frequency (0-40Hz) but at middle frequency (40-350Hz) both structure accelerates with slight difference. In frequency range (350-1000Hz) conventional sleeper absolutely dominates the ladder beam; however at higher frequency, acceleration level of both structure decrease and becomes almost equal. In general the vibration reduction of both sleeper and ladder beam depends on frequency range and ladder beam is less effective in lower frequency range while sleeper do at middle frequency range. However by overall visualization ladder beam is relatively effective in all frequency range in reducing acceleration vibration of the track.

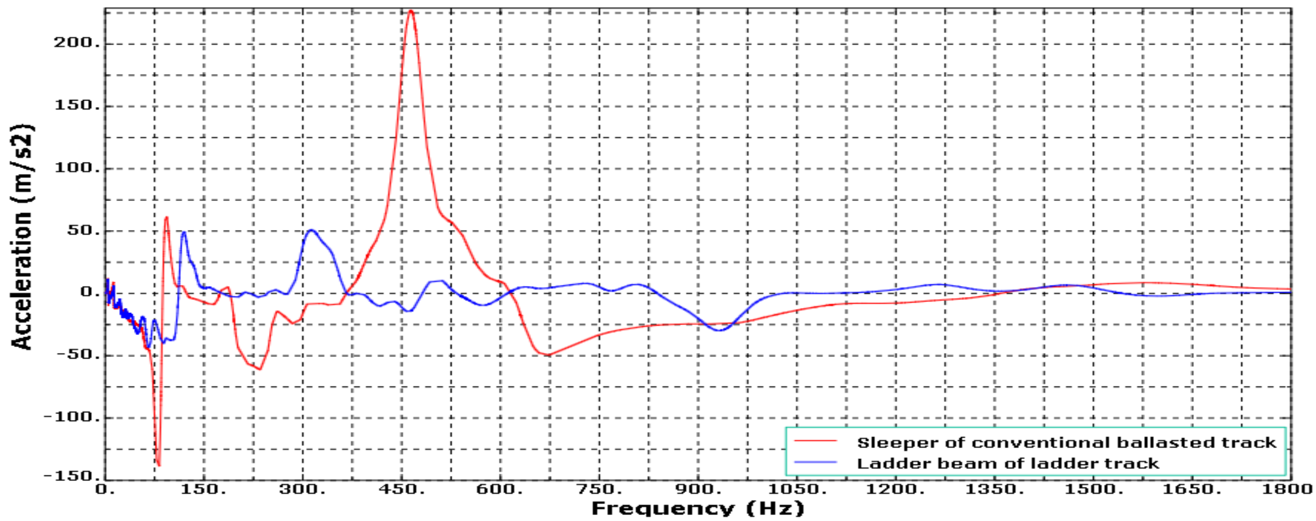


Figure 5.28 Acceleration of sleeper of conventional ballasted track versus ladder beam of ballasted ladder track which is taken at the middle of the track

It is indicated in figure 5.29 at lower mode rail of Ballasted ladder rack vibrates at higher amplitude whereas at higher mode vibration amplitude of rail of conventional ballasted track dominates.

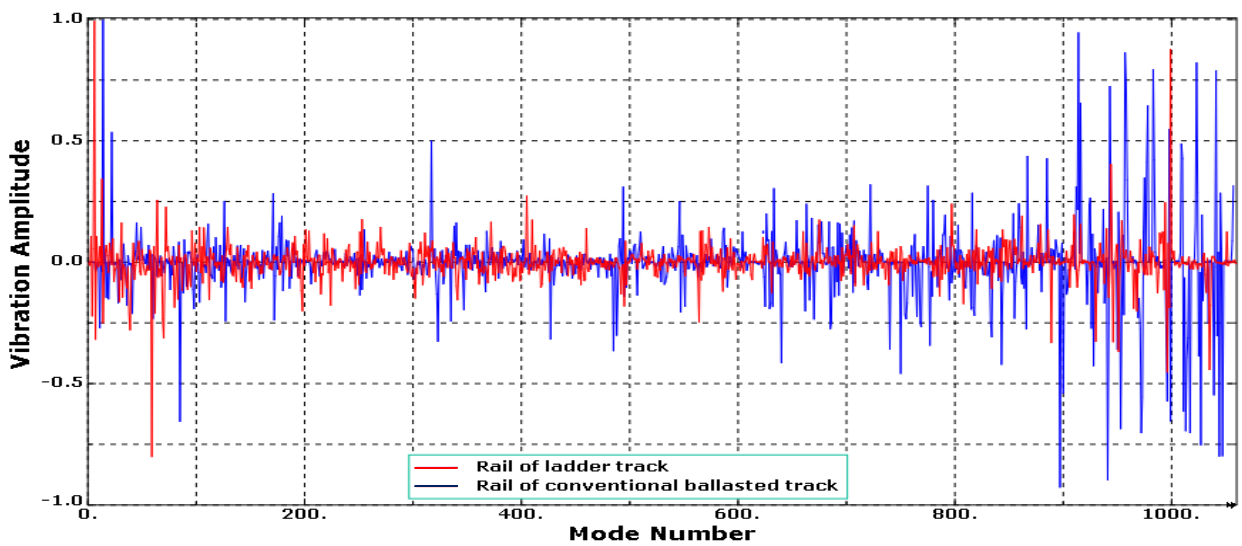


Figure 5.29 vertical Vibration amplitude of rail of conventional ballasted versus rail of Ballasted ladder track

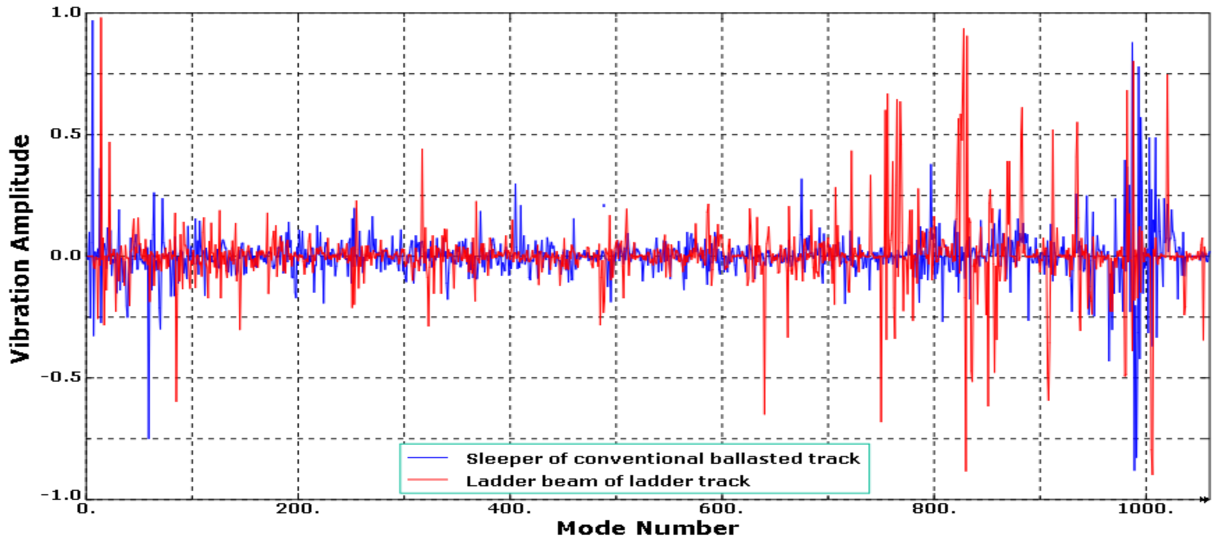


Figure 5.30 Vertical Vibration amplitude of sleeper of conventional ballasted track versus ladder beam of ballasted ladder track

The vertical stresses on the ballast bed and on the formation which are due to wheel loads will be considered as the determining stresses for the load-bearing capacity of the layer system. Overloading of the ballast bed causes rapid deterioration of the quality of the track geometry. As shown in a figure 4.32, at lower mode (<150) the Rail of conventional track is subjected to high stress relative to rail of ladder track ,however at higher mode the stress level of both tracks is almost close to each other.

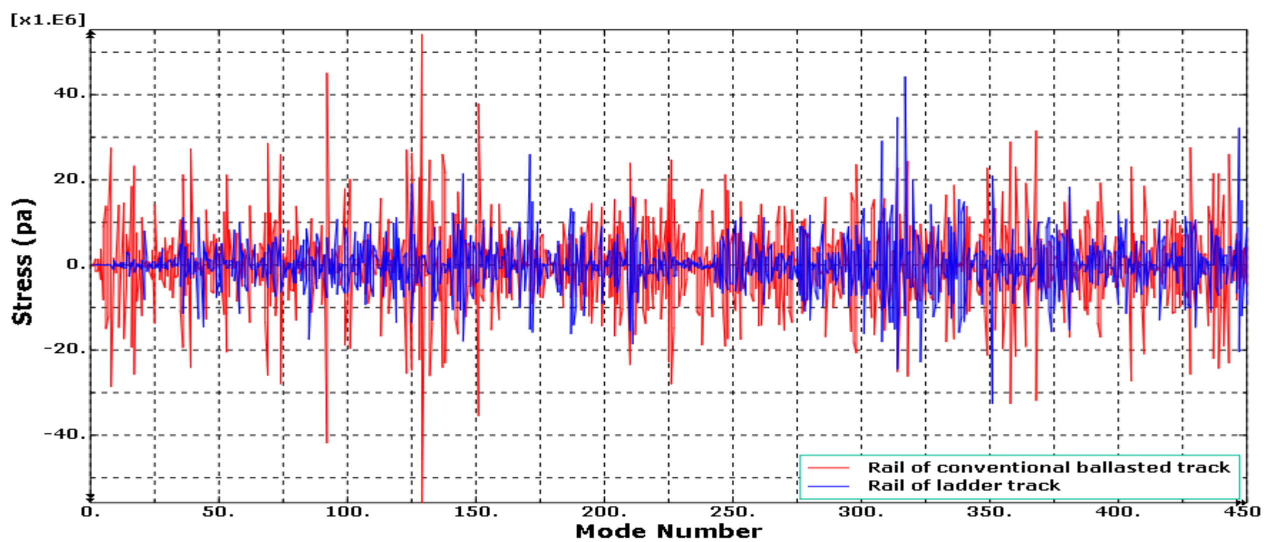


Figure 5.31 Variation of vertical stress of conventional sleeper versus ladder beam (at lower mode)

5.7 CPU Time Cost Comparison for Eigen Value Analysis

The time for extracting enough Eigen frequency and corresponding mode shape depends on Eigen solver .In this research Lonczos Eigen solver which effective for higher frequency is applied. The time for processing Eigen frequency for both conventional ballasted track and ballasted ladder track is indicated in table 4.2.

The analysis has been performed with a Intel Core I-3 CPU (2.2GHz) with 6 GB of random access memory (RAM).

Table5.1 CPU time cost for Eigen value analysis

Eigen Value Analysis			
Model	DoF	No.modes	CPU time (s)
Conventional ballasted track	8127	4000	4750
Ballasted ladder track	3510	3200	89

5.8 The Rail and Sleeper Modeling Using Solid and Beam Element

The railway track components are modeled in different element depends on the required frequency range .Sleeper can be modeled as rigid mass when the response is required under low frequency range 0-100 Hz but at middle frequency range (100-400Hz) Euler Bernoulli beam is effective while at very higher frequency range (>400 Hz) it is modeled using Rayleigh Timoshenko beam where sufficient accuracy is required. The same is true for rail also, but at higher frequency (>2500) the Rayleigh Timoshenko beam is also begin to be inadequate. Therefore it is necessary to extend to nonlinear, and high frequency statistical method (Knothe, Ki and Grassie, 1993).

This indicates that modeling the rail and sleeper blindly by selecting one of beam theory results inaccurate responses. Solid element approach can efficiently represent sleeper and rail in almost all models at any frequency range even if dynamic analysis using solid rail radically increases the computational cost, because the time increment is based on the smallest element. In the different previous research it is mentioned to check the accuracy level of solid rail in their future study recommendation. Huan feng (Feng, 2011) also tried to use the solid rail to analyze the Receptance of track .He has analyzed that below the frequency 500Hz both the solid rail and rail beam responds similarly, However at higher frequency, receptance function for solid element become significantly undulate. The reason for this might be due to the deformation of the solid rail profile, which has not been taken into account for the beam element. Another obvious difference is that the pin-pin resonance around 1000 Hz is missing for the solid element models. Finally he concluded that the reason for this is complicated and deserves further research.

In this research it is investigated that the response of the conventional ballasted track when modeled by solid rail and beam rail; as shown in figure 4.33 and figure 4.34 the acceleration response pattern is nearly similar but their peak value is slightly different.

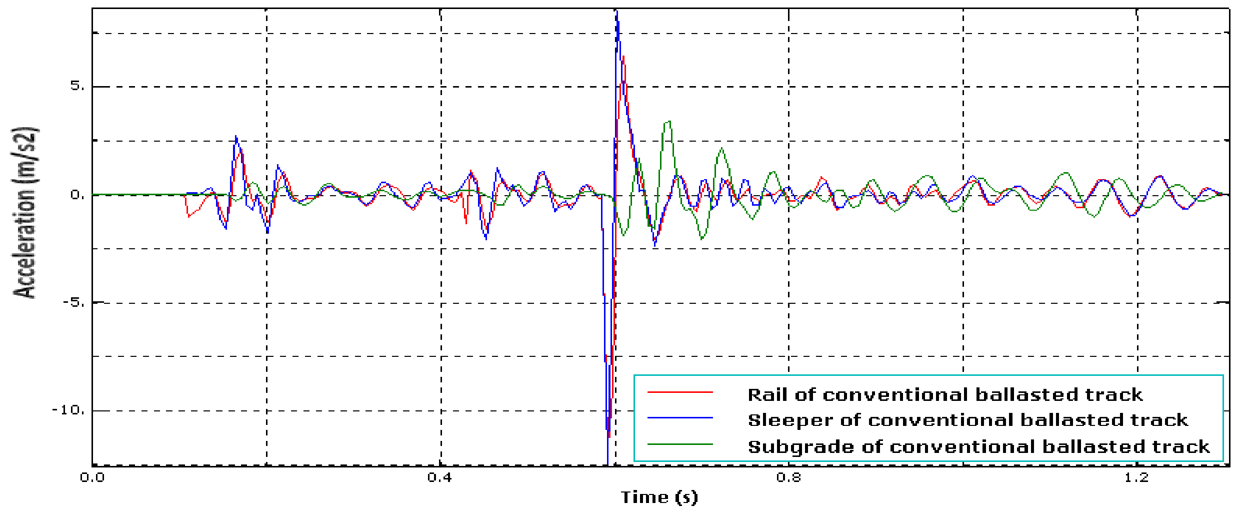


Figure 5.33 Acceleration of component of conventional ballasted track for speed of 40km/hr which is taken at the mid of the track when rail is modeled as Timoshenko beam

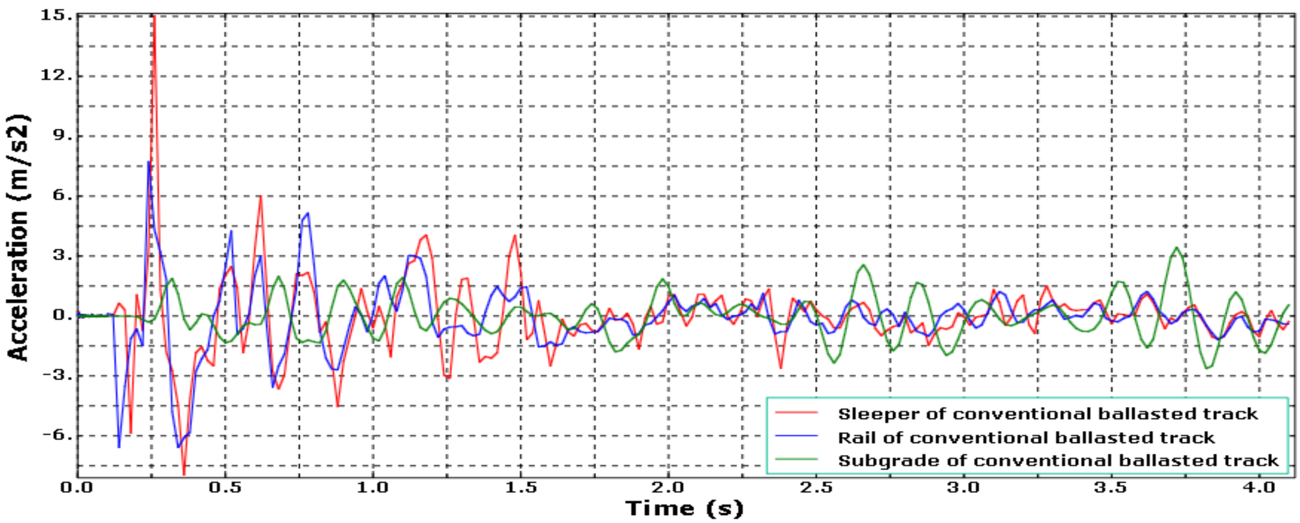


Figure 5.34 Acceleration of component of conventional ballasted track for train travelling with speed of 40km/hr which is taken at the mid of the track when rail is modeled as solid element.

CHAPTER SIX

CONCLUSION AND FUTURE STUDIES

6.1 CONCLUSION

This thesis attempts to study dynamic performance of a conventional ballasted track and ballasted ladder track by modeling both tracks in Abaqus finite element software. Rail is modeled as solid element on continuously supported and discretely supported in ladder and conventional track respectively. Rail pads and ballast are modeled as spring and dashpot. Finally Abaqus results deformation, velocity and acceleration response of track in time and frequency domain and they are used to analyze dynamic performance of both tracks. The model output is validated by comparing with experimental test result from some previous Researches. The result is relatively good even if it is modeled in 2D element. From the analysis the following conclusion is made;

- First the result of time domain analysis indicates that the deflection, velocity and acceleration response of components of ladder track are far less than that of conventional ballasted track. This is due to the continuous ladder supporting system in which all wheel load applied on the rail is distributed to larger area and the influence of the load that is received by under lying structure is very small.
- Second from frequency domain it is possible to understand that vibration acceleration and deformation response of component of ballasted ladder track is smaller than that of conventional ballasted track. The frequency ranges and vibration modes indicates that ballasted ladder track can with stand high vibration at higher frequency ranges where as conventional ballasted track effective at low frequency range. This is due to existence of continuous support elastic railpad and additional damping effect of formation layer. Ballasted ladder track can be used for high speed rail way line since it significantly reduce the vibration induced to track by high speed train. At very high speed of train, rail of conventional ballasted track accelerates higher than rail of ballasted ladder track; rail of conventional ballasted track becomes unstable. Therefore usage of conventional ballasted track for speed of train above 180 km/hr is not economical since formation layer is unstable and it is subjected to more repeated maintenance.

In general according to the 2D Finite element analysis, ballasted ladder track has better performance on vibration reduction than conventional ballasted track by considering the peak value in the time and frequency domain.

6.2 Future study

In this study tracks are modeled in 2D finite element Abaqus software; dynamic behavior of both tracks is analyzed and relatively compared with each other. From the model it is concluded that ballasted ladder track has good dynamic performance than conventional ballasted track .However to have advanced study the following suggestion is forwarded.

In these model two dimensional elements is used to decrease a time cost .However there is small discrepancy in accuracy of result between two dimensional elements and three dimensional elements. Therefore it is suggested to model the tracks using three dimensional elements.

Instead of modeling the tracks using spring and dashpot element in place of ballast, by inserting ballast mass between sleeper and subgrade (which represent real track); it is possible to compare the dynamic response of ballast layer for both track.

The length of the ladder sleeper that is used to model ballasted ladder track is 6m.At different railway track line different ladder sleeper length is used. However it is necessary to study the dynamic response of various lengths of ladder sleeper and optimizing its length to effectively reduce vibration of the track.

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Li M.X.D., Berggren E.G., and Berg M. (2009). Assessment of vertical track geometry quality based on simulations of dynamic track-vehicle interaction. *Proceedings of the Institution of Mechanical Engineers. 223*, pp. 131-139. Part F: Journal of Rail.

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Appendix A

Table A. 1 Mode shape and frequency of rail and ladder beam of conventional ballasted track and ballasted ladder track

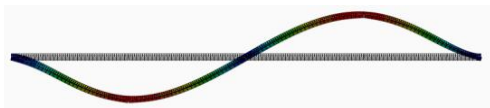
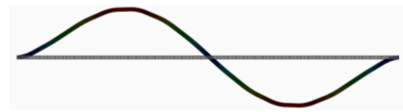
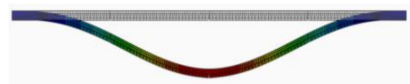
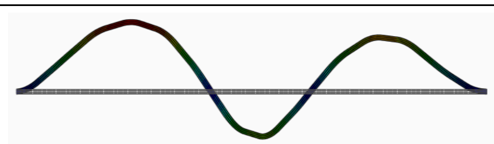
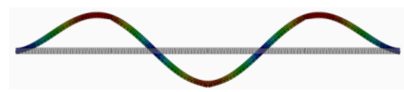
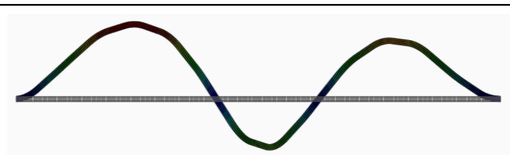
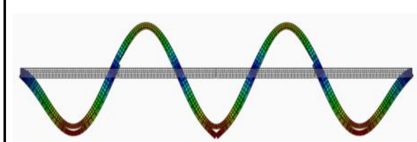
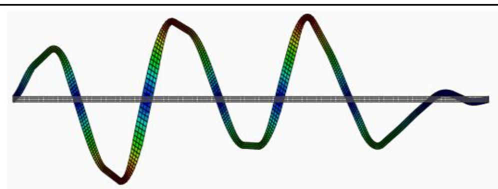
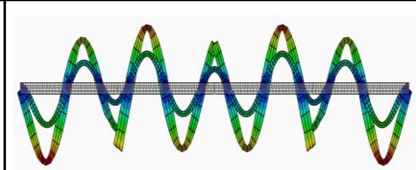
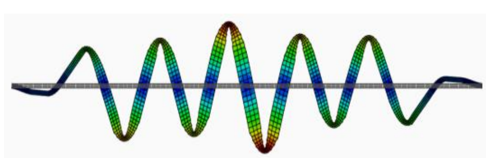
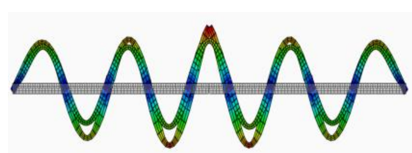
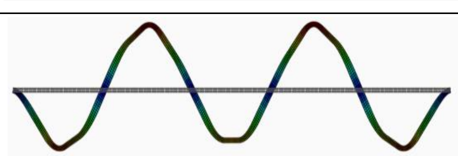
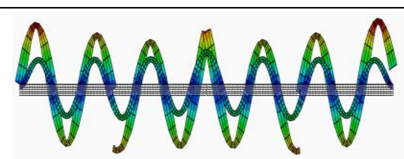
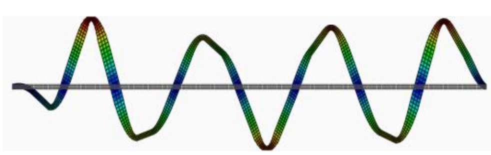
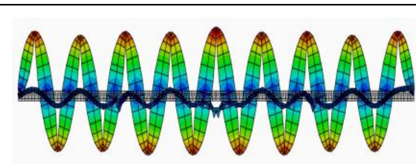
mode No	Frequency (Hz)	Shape		Frequency (Hz)	Mode No
		Ballasted	ladder track		
5	5.5425			3.362	5
6	5.705			4.2017	6
17	8.7853			6.6078	17
24	9.3551			8.1618	24
338	24.982			25.28	338
573	33.707			38.417	573
716	42.826			83.848	716
778	46.336			191.22	778

Table A.1 indicates that below frequency 0.0449Hz in both tracks longitudinal vibration exceeds vertical vibration; however above 3.362Hz the vertical vibration dominates lateral vibration. The response pattern of rail and ladder beam of ladder track above frequency 10 Hz is slightly different while at lower mode it is almost similar.

Appendix B

Abaqus simulation outputs

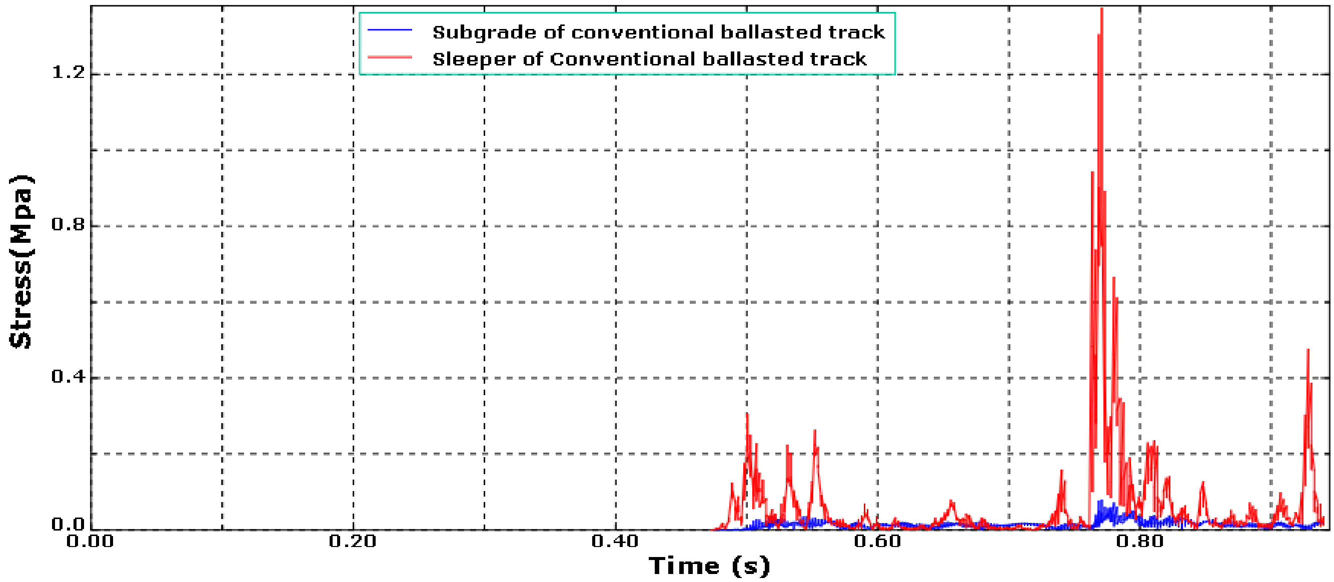


Figure B. 1 vertical Stress of conventional ballasted track

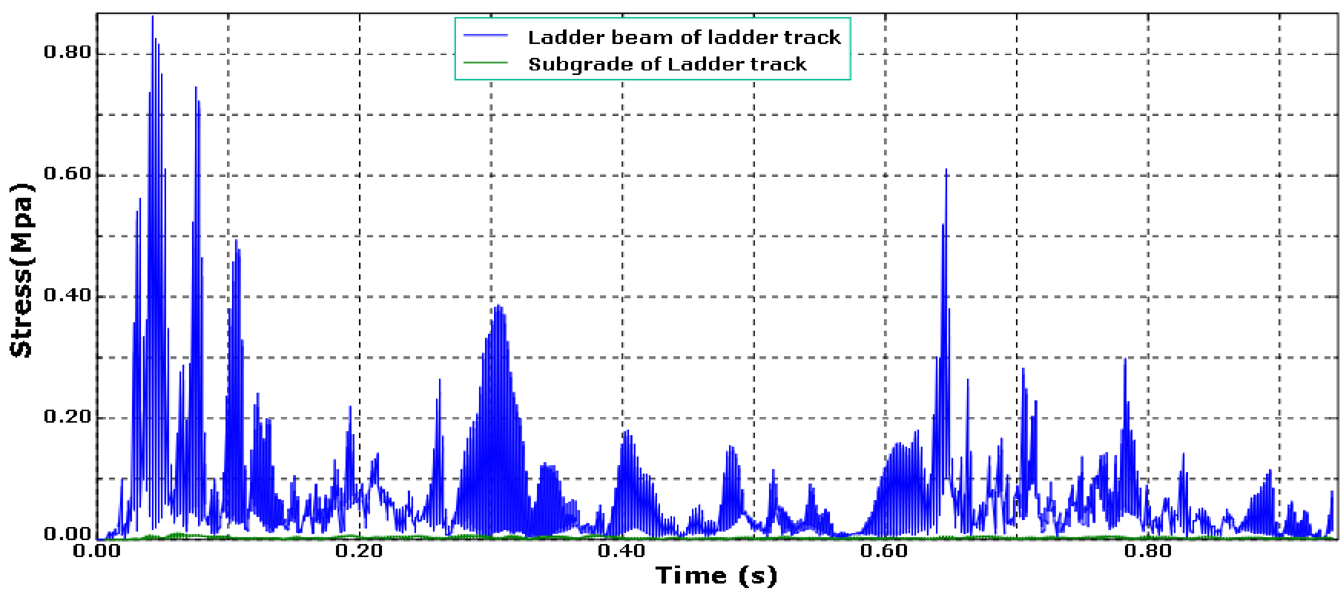


Figure B.2 Vertical stress of ballasted ladder track

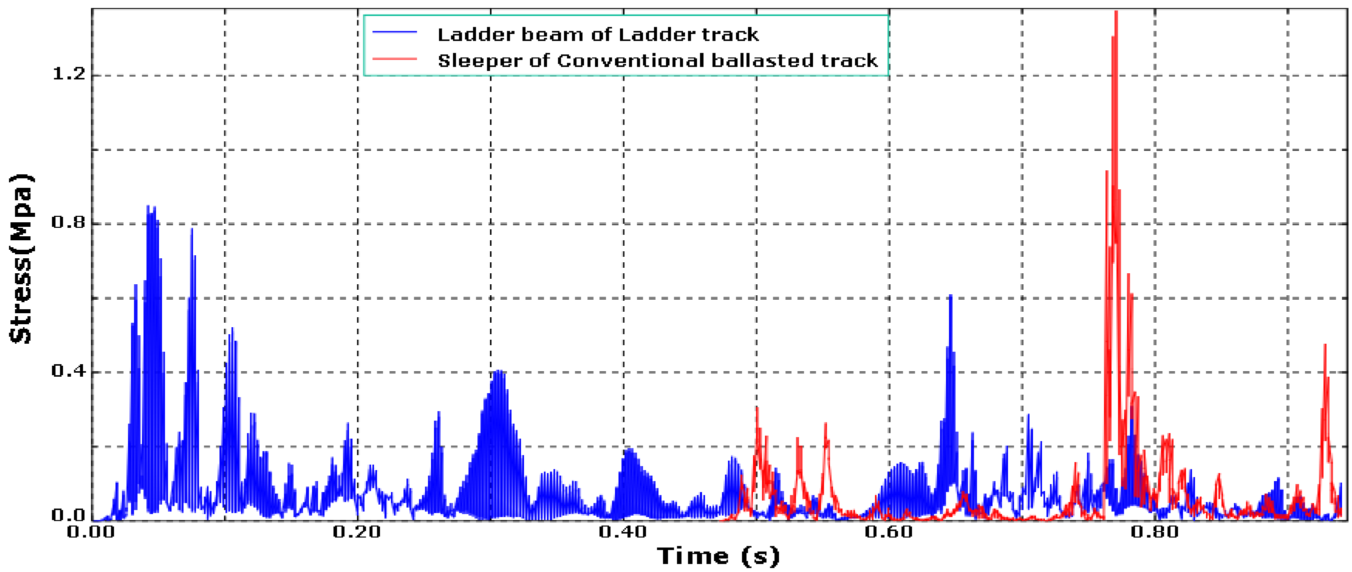
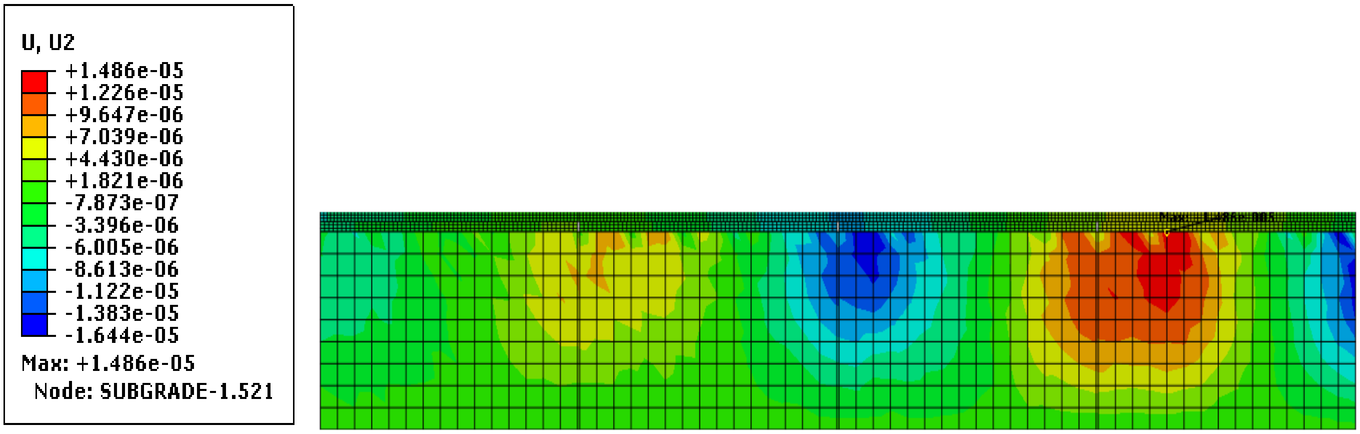


Figure B.3 Comparison of Vertical stress of conventional sleeper and ladder sleeper

Appendix C

List of Input Parameter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+1.226e-05
+9.647e-06
+7.039e-06
+4.430e-06
+1.821e-06
-7.873e-07
-3.396e-06
-6.005e-06
-8.613e-06
-1.122e-05
-1.383e-05
-1.644e-05
Max: +1.486e-05
Node: SUBGRADE-1.521

subgrade