Lateral Dynamic Analysis of Rail Road Vehicle through Bond Graph Modeling

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Abstract

The railway train running on along a track is one of the most complex dynamical systems in engineering. In this paper lateral dynamic behaviour of the railroad vehicle is analyzed through bond graph modeling. The paper further deals with the effects of railway track imperfections on dynamic behaviour of vehicle through numerical simulation. The numerical simulation of the dynamic behaviour of a typical railroad vehicle will be done by developing a bond graph model for the vehicle and track coupling system, which includes the rail beam, sleeper and ballast masses.

A complete model of a railway vehicle is considered, which is assembled from wheel sets, car body and intermediate structure which are flexible, and which are connected by components such as springs and dampers. Similarly, the vehicle is considered to run on a track, which has a complex structure with elastic and dissipative properties. The track can be modeled as a continuous structure with moving interface at the point of contact, whereas the interaction between the wheel and the rail is dependent on the relative motion. In calculating the coupled vehicle and track dynamics, Hertzian contact theory is applied to calculate the normal force between the wheel and the rails. Symbols Shakti Software [1] is used for simulating the bond graph model of vehicle at different operating speeds.
Keywords: Lateral dynamics, Bond graph Modeling, Rail-track system

1 Introduction

The railway train running along a track is one of the most complex dynamical systems in engineering .It has many degrees of freedoms, the interaction between wheel and rail involves both complex geometry of wheel tread and rail head. The long history of railways engineering provides many practical examples of dynamical problems, which have degraded performance and safety. In a complete model of dynamics of a railway vehicle is considered to be assembled from wheel sets car body an intermediate structures which are flexible, and which are connected by components such as springs and dampers. Similarly, the vehicle is considered to run on a track, which has a complex structure with elastic properties. Each major component has six rigid body degree of freedom pulse addition of the component the track can be modeled of the structure with a moving interfaces at the point of contact, where the interaction between wheel and rail is dependent on the relative motion.

The ballast and sleeper at some section of high speed track are very significant and adversely affects the dynamics of the vehicle, such phenomenon is mainly due to the vibration at contact point of wheels and the rail due to the various irregularity of the track and the wheel set .The settlement of the ballast is a long term and slow process which needs several consideration to understand the dynamics. In the present work numerical simulation of the lateral dynamic behaviour of a typical railroad vehicle with sleepers will be done by modelling through bond graph technique. Dynamical behaviour with sleepers of the railroad vehicle will be analysed for a typical Indian railway vehicle. In this model the vehicle is modelled as a multi body system and the track is considered as a 3-layer model with rail vehicle sleepers and ballast masses later on each rails will also be modelled as a Timoshenko beam or Rayleigh beam.

Due to the unique dynamics that exist between the rail and wheel, rail vehicle dynamics are often difficult to model accurately. This velocity-dependent dynamics justify the importance of the track input to railcar modeling. In the physical system, the input comes from the actual track. In a model, a user-defined input is used to predict the actual track characteristics. The user-defined input can be created analytically or can be based on actual measurements. Measured track data are obtained by running a specialized railcar down the track. Analytic track data are created using mathematical shapes, such as cusps, bends, sines, to represent the track geometry [2].

There have been several studies, which are contributed by many researchers regarding the dynamic analysis and to enhance the ride comfort while travelling. Kumar and Sujata [3] presented the numerical simulation of the vertical dynamic behaviour of a railway vehicle and calculated Sperling ride index for comfort evaluation. They modelled a typical Indian railroad vehicle running on broad gauge for the analysis. Kumaran et al.[4] discussed the dynamic response of a typical prestressed concrete rail track-sleeper due to wheel-track interaction dynamics. Nielsen and Igeland [5] investigated the vertical dynamic behaviour for a railway bogie moving on a rail, which is discretely supported by sleepers resting on an elastic foundation. Effects of imperfections on the running surfaces of wheel and rail were studied by assigning irregularity functions to these surfaces. Bureika and Subacius [6] investigated the dynamics of vertical interaction between a moving rigid wheel and a flexible railway track. Gangadharan et al.[7] studied the influence of different track irregularities on dynamic response and coupling between vertical and lateral dynamics.

2 Modeling of Rail Road Vehicle

To analyze the dynamic behavior of railway vehicles, usually the vehicle (and if necessary the environment) is represented as a multi-body system. A multi-body system consists of rigid bodies, interconnected via mass less force elements and joints. Due to the relative motion of the system's bodies, the force elements generate applied forces and torques. Typical examples of such force elements are springs, dampers, and actuators combined in primary and secondary suspensions of railway vehicles.

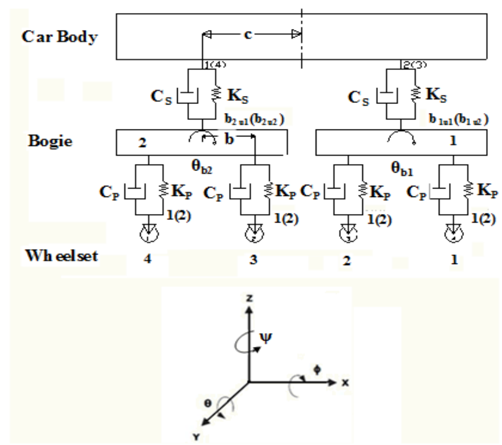
2.1 Modeling Assumption

The assumptions made in formulating the model are as follows:

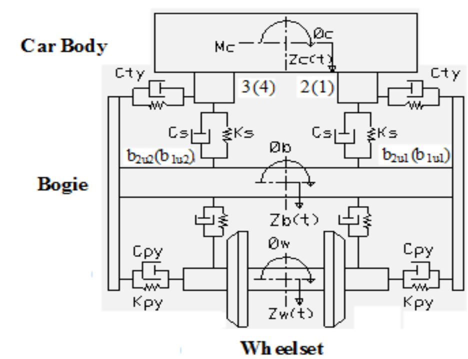
- Bogie and car body component masses are rigid.
- The springs and dampers of the suspension system elements have linear characteristics.
- The vehicle is moving with constant velocity on rigid and constant gauge.
- Straight track was assumed.
- A bump shape irregularity in vertical direction is considered only on one rail.

2.2 Rail road vehicle model

Fig.1 illustrates the train vehicle model. It consists of a vehicle body, two bogie frames and four wheel sets .Each bogie consist of the bogie frame ,the bolster, and two wheel sets. In this work, the car body and bogie frames as well as the wheel sets are treated as rigid bodies and are defined by their mass-inertia characteristics. The Car body is modeled as a rigid body having a mass M_C ;and having second moments of area Jcx , Jcy and Jcz about the transverse , longitudinal centroidal horizontal axes and yaw axes ,respectively. Each axle along with the wheel set has a mass M_B (M_{B1and} M_{B2}) With second moments of area J_{BX} , J_{BY} and J_{BZ} about the transverse and longitudinal centroidal horizontal axes ,yaw axes respectively. Each axle along with the wheelset has a mass M_w (for four axles M_{W1};M_{W2}; Mw_3 and M_{W4}).The Spring and the damper in the primary suspension for each axle is characterized by spring stiffness K_P and damping coefficient $C_{P;}$ and in lateral direction spring stiffness K_{TY} and damping Coefficient C_{TY} respectively. Likewise ,the secondary suspension is characterized by spring stiffness K_S and damping coefficient C_S and in lateral direction spring stiffness K_{PY} and damping coefficient C_{PY} respectively . The various displacements of the vehicle are described with respect to the equilibrium position. As the car body is assumed to be rigid, its motion may be described by the vertical displacement (bounce or Z_C) and rotations about the transverse horizontal axis (pitch or θc), about the longitudinal horizontal axis(roll or φ_c) and about the yaw vertical axis(yaw or ψ_c) similarly, the movements of the bogie units are described by degrees of freedoms Z_B ;θ_B ; φ_b and ψ_b. Each axle set is described by degree of freedom Z_W; and φ_w, about their centroids. Totally 35 degree of freedom has been considered. The detailed parameter regarding the moment of inertia and mass of different component is given in Table 1.



Front View



Left side view

Fig.1: Physical model of railway vehicle.

2.3 Bond Graph Model of a Rail Road Vehicle

A typical railroad vehicle system is composed of various components such as car body, springs, dampers, bogies, wheel-set, and so forth. When such dynamic systems are put together from these components, one must interconnect rotating and translating inertial elements with axial and rotational springs and dampers, and also appropriately account for the kinematics of the system structure. Bond graphs are well suited for this task. In deriving the bond graph models, the velocity in upward direction are assumed to be positive and springs and dampers are assumed positive in compression**.**

Kinematic constraints are always related with the flow variables [8]. To add the flow according to the constraints, 0-junctions are used. The transformers are used to convert the angular velocity into linear velocity components. The complete bond graph model for rail vehicle system is shown in Fig. 2.

Table1: Details of the elements of the rail –road vehicle

S.No.	**Name of the element of the rail-road vehicle**	**Mass (Kg)**	**Moment of inertia(Kg-m^2)**		
			Ixx	Iyy	Izz
1.	Car Body	48200	8.167×10^5	2.99×10^6	4.5×10^6
2.	Bogie-I	3086	2.312×10^3	4.73×10^6	4.73×10^3
3.	Bogie-II	3086	2.312×10^3	4.73×10^6	4.73×10^3
4.	Wheel set-I	1675	9.0×10^2	1.08×10^2	9.0×10^2
5.	Wheel set-II	1675	9.0×10^2	1.08×10^2	9.0×10^2
6.	Wheel set-III	1675	9.0×10^2	1.08×10^2	9.0×10^2
7.	Wheel set-IV	1675	9.0×10^2	1.08×10^2	9.0×10^2

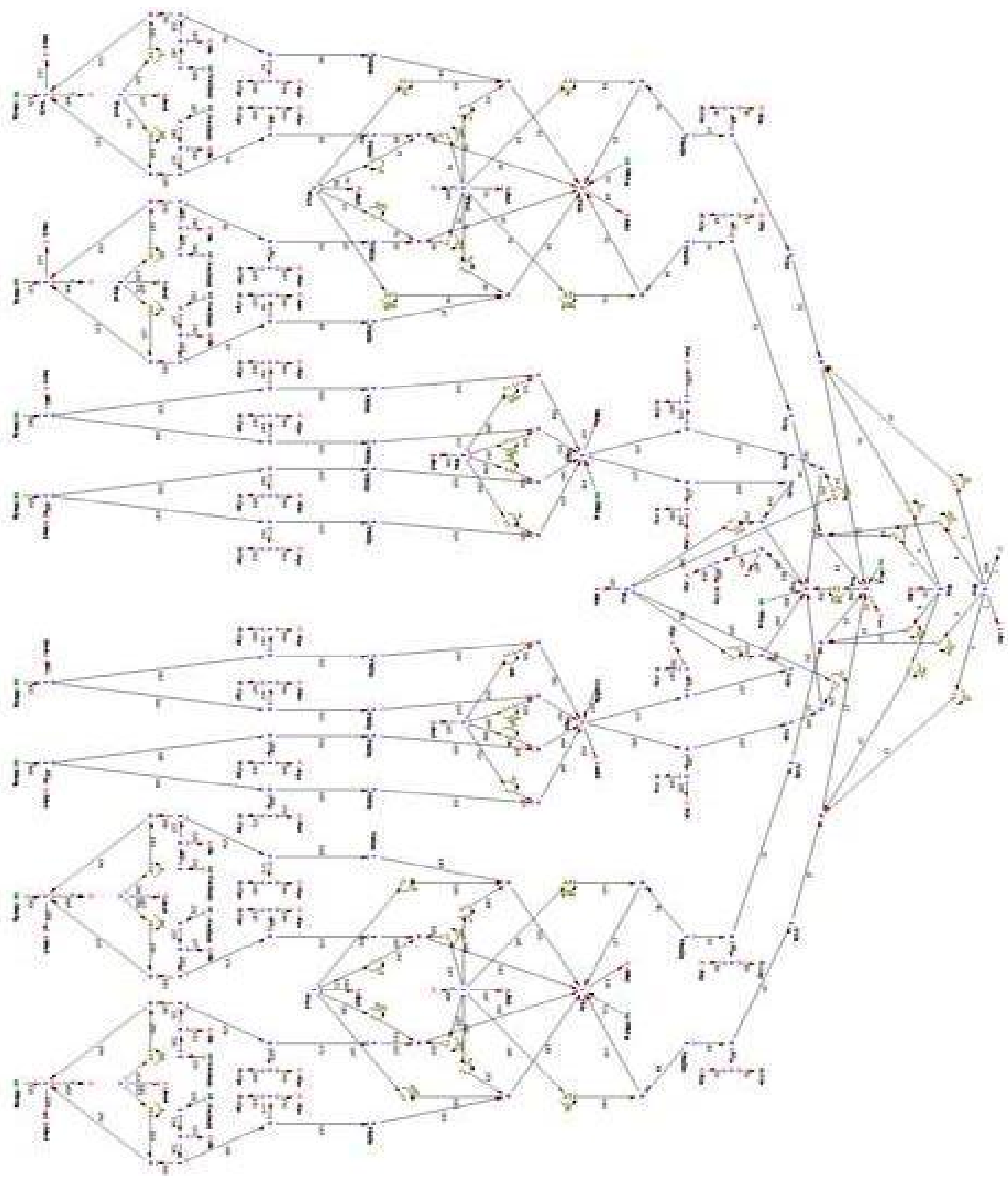


Fig. 2: Bond graph Model

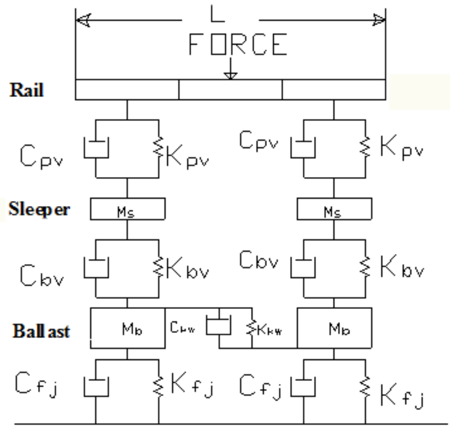


Fig.3: Model of rail track

3.3 Bond Graph Model of Rail Track

In deriving the bond graph models, the velocities in upward direction are assumed to be positive and springs and dampers are assumed positive in compression.

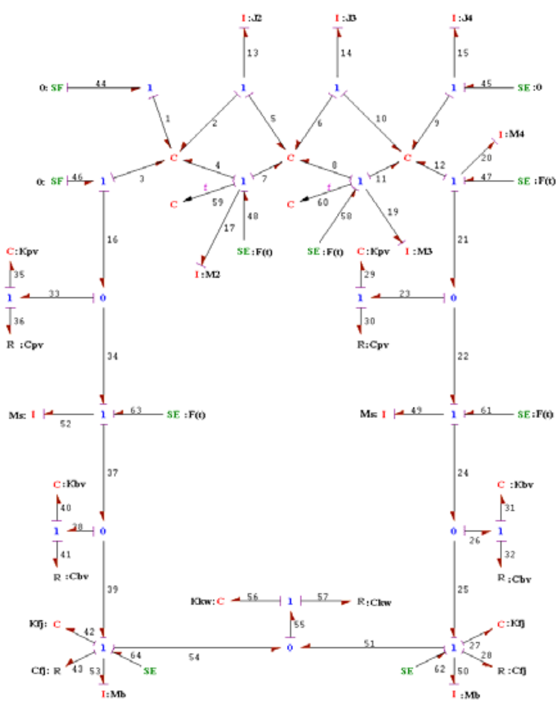


Fig.4: Bond graph model of rail track

4 Track inputs to railroad vehicle

The dynamic wheel loads generated by a moving train are mainly due to various wheel/track imperfections. These imperfections are considered as the primary source of dynamic track input to the railroad vehicles. Normally, the imperfections that exist in the rail-track structure are associated with the vertical track profile, cross level, rail joint, wheel flatness, wheel/rail surface corrugations and sometimes uneven support of the sleepers.

In actual practice different type of periodic, aperiodic or random track irregularities may exist on the track, but in the present study bump type of irregularity is considered as shown in Fig.5 [2]. The shape of irregularity is assumed to be opposite on left and right rail.

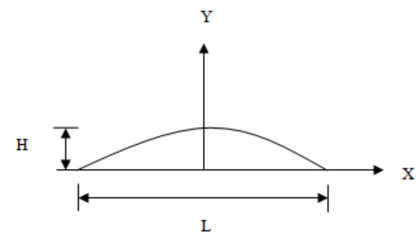


Fig. 5: Model of track irregularity

The bump excitation of the front wheel of leading bogie is

$$y = H \times \sin\left(\pi \times \frac{V}{L} \times t\right) \qquad \text{for } 0 \le t \le \frac{L}{V}$$

$$= 0 \qquad \text{for } t > \frac{L}{V}$$

The bump excitation of the rear wheel of leading bogie is

$$y = H \times \sin\left(\pi \times \frac{V}{L} \times \left(t - \frac{A_1}{V}\right)\right) \quad \text{for} \quad \frac{A_1}{V} \le t \le \frac{A_1+L}{V}$$

$$= 0 \quad = 0 \qquad \text{for} \quad t > \frac{A_1+L}{V}$$

where, A_1 is the distance between the front and the rear axle. Similarly the expressions for other wheels are obtained. Thus, the expressions for flow variables are obtained by differentiating above expressions w.r.t. time.

5 Simulation Study

The Simulator of Symbols Shakti, which is the base post-processing module of SYMBOLS Shakti, is used for the simulation of the rail vehicle.

Simulation was carried out at different speed of 15m/s, 30m/s, 45m/s and 60 m/s. The following output parameters are monitored:

- Vertical acceleration at the floor of the car-body center of mass.
- Lateral acceleration at the floor the car -body center of mass.
- Pitching acceleration of car body
- Rolling acceleration of car body
- Deflection of rail track

Vertical acceleration at the floor of the car-body centre of mass.

The acceleration response of the car body for speed of 15m/s, 30m/s, 45m/s 60m/s are shown in Fig 6-9. The plots show that initially the value of acceleration is nearly -9.8 m/s^2, which is mainly the acceleration due to the gravity. Finally it goes to zero when the vibration of car body ceases and it stabilizes. The acceleration is generally within acceptable range and does not show any instability**.**

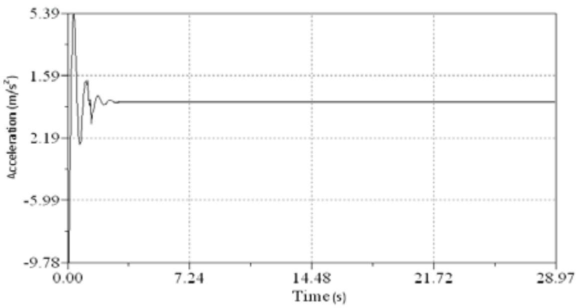


Fig.:6 Vertical acceleration at the floor of the car –body C.G for vehicle velocity of 15 m/s^2

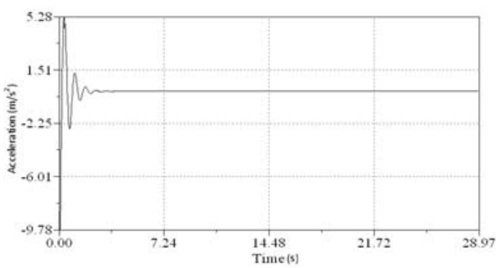


Fig.: 7 Vertical acceleration at the floor of car –body C.G for vehicle velocity of 30m/s^2

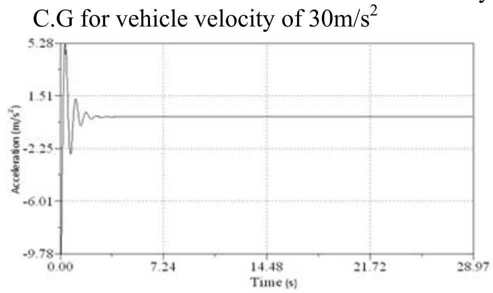


Fig.:8 Vertical acceleration at the floor of the car –body C.G for vehicle velocity of 45 m/s^2

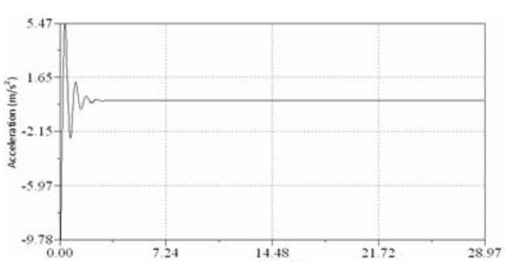


Fig.: 9 Vertical acceleration at the floor of car –body C.G for vehicle velocity of 60m/s^2

Lateral acceleration at the floor the car -body center of mass

The acceleration responses of the car –body in lateral direction for vehicle speed of 15m/s, 30m/s, 45m/s and 60m/s are shown in fig. 10-13. The plots shows that initially the value of acceleration is nearly equal to -.0036 m/s^2, which is mainly the acceleration due to input lateral forces. Finally it goes to zero, when the vibration of the car body ceases and it stabilizes. The acceleration is generally within acceptable range and does not show any instability.

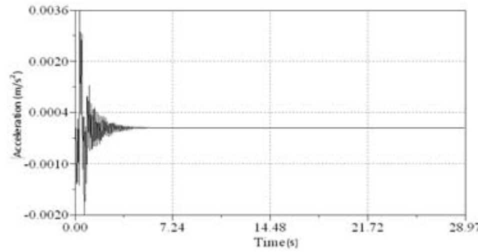


Fig.: 10 Lateral acceleration at the floor of car -body C.G for vehicle velocity of 15m/s^2.

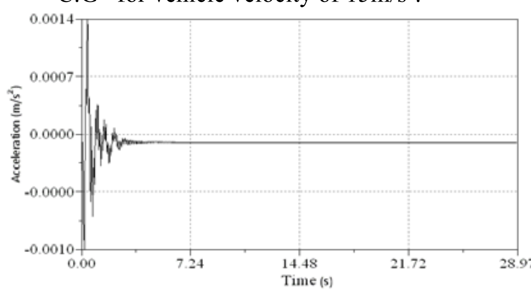


Fig.: 11 Lateral acceleration at the floor of car -body C.G for vehicle velocity of 30m/s^2.

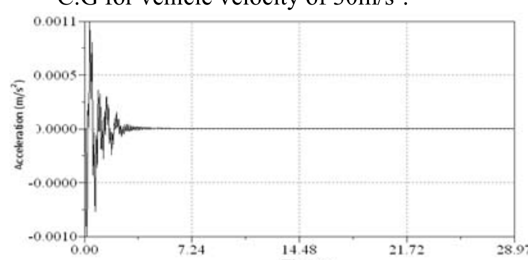


Fig.: 12 Lateral acceleration at the floor of car -body C.G for vehicle velocity of 45m/s^2.

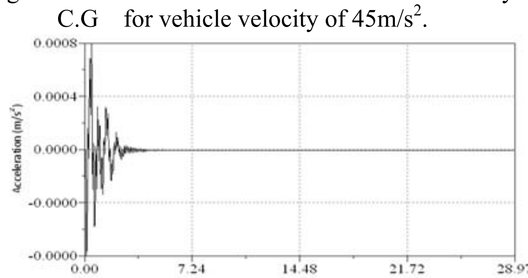


Fig.: 13 Lateral acceleration at the floor of car -body C.G for vehicle velocity of 60m/s^2.

Pitching acceleration of car body

Figures 14-17 shows the pitching motion of car body for vehicle speed of 15m/s, 30m/s, 45m/s and 60 m/s. It is clear from the study of the plots that the amplitude of vibration decreases with time and finally, it approaches to almost zero value.

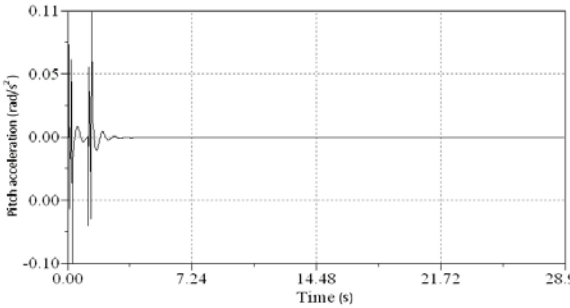


Fig. 14: Pitch acceleration of the car body for vehicle speed of 15 m/s.

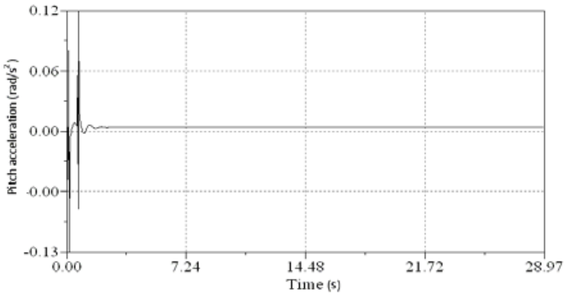


Fig. 15: Pitch acceleration of the car body for vehicle speed of 30 m/s.

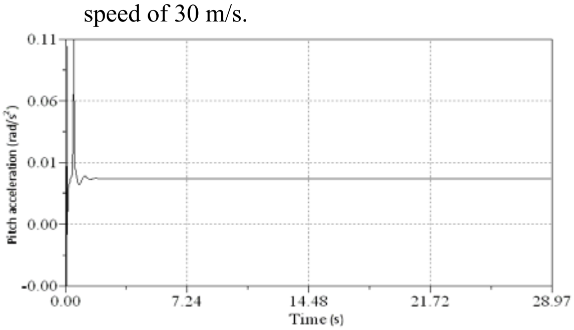


Fig. 16: Pitch acceleration of the car body for vehicle speed of 45 m/s.

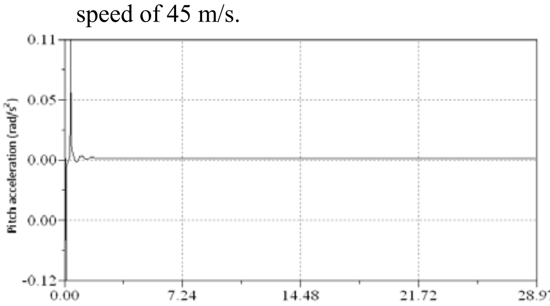


Fig. 17: Pitch acceleration of the car body for vehicle speed of 60 m/s.

Roll acceleration of car body

Figures 18-21 shows the rolling motion of the car body for vehicle speed of 15m/s, 30m/s, 45m/s and 60m/s.

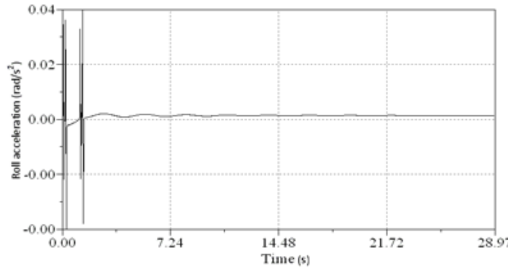


Figure 18: Roll acceleration of car body for vehicle speed of 15m/s.

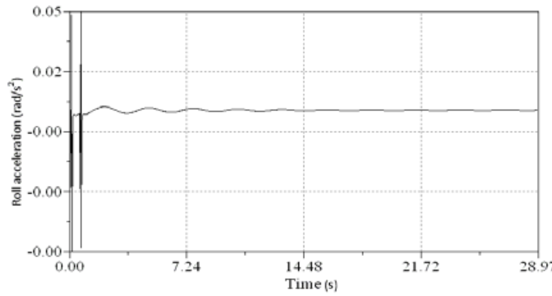


Fig. 19: Roll acceleration of car body for vehicle speed of 30m/s.

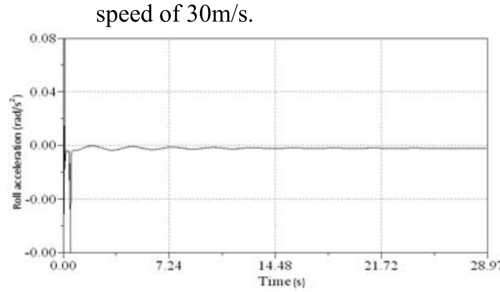


Fig. 20: Roll acceleration of car body for vehicle speed of 45m/s.

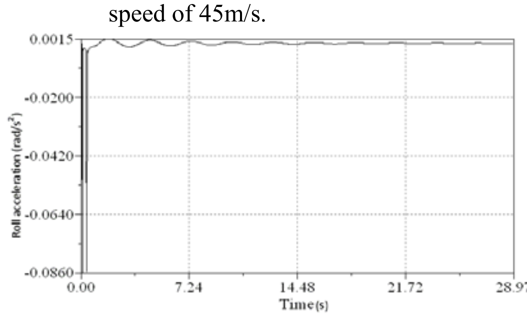


Fig. 21: Roll acceleration of car body for vehicle speed of 60m/s.

Deflection of rail track

Figure 26-29 shows the response of rail track for vehicle speed of 15m/s, 30m/s, 45m/s and 60m/s .The maximum value of deflection is nearly 1.5mm and is obtained at vehicle speed of 15m/s.

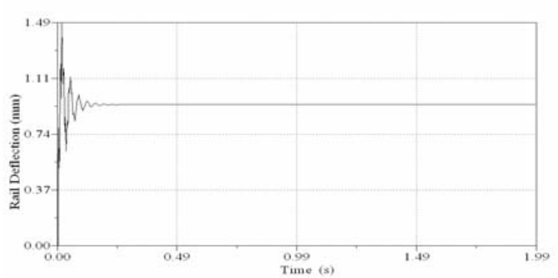


Fig. 26: Deflection of rail for vehicle speed of 15 m/s.

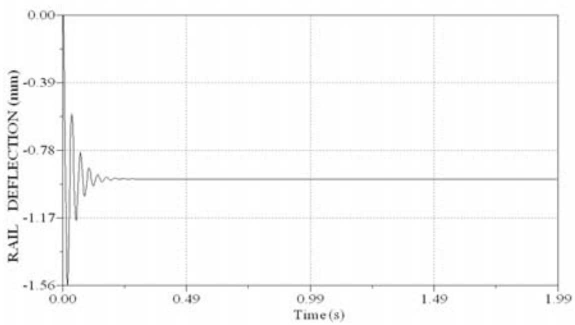


Fig. 27: Deflection of rail for vehicle speed of 30 m/s.

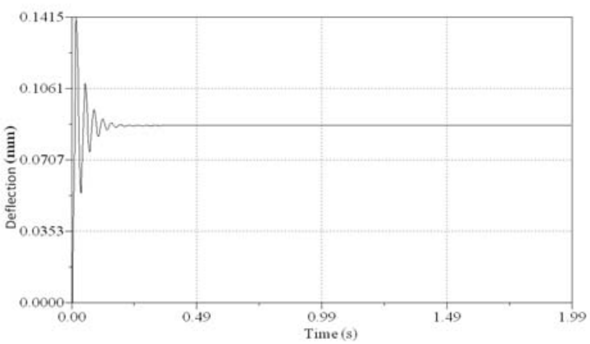


Fig. 28: Deflection of rail for vehicle speed of 45 m/s.

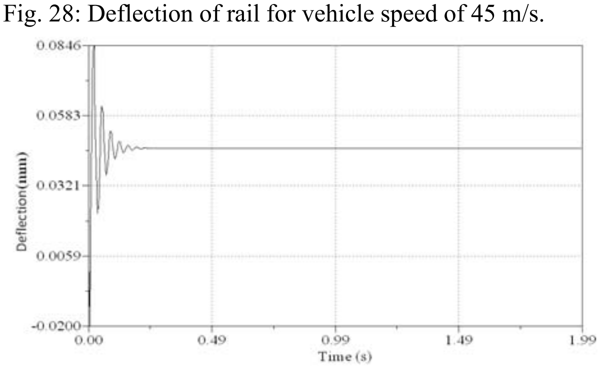


Fig. 29: Deflection of rail for vehicle speed of 60 m/s.

6 Conclusions

The present work was an attempt to investigate the dynamic behavior of a railroad vehicle including track structure through bond graph technique. Lateral and vertical dynamic analysis has been carried out for a railway vehicle running on broad gauge. A model, including the vehicle with 35 degrees of freedom and track structure has been investigated, considering vehicle suspension system, speed, rail irregularity and elastic properties of the sleeper and ballast-sub grade. The bump shape irregularity on left track has been considered to give the dynamic input to the railroad vehicle. The damping characteristics of the track and the railway vehicle have also been considered. The results of the interactive analysis give responses in the form of reaction time histories.

The dynamic analysis has been performed of the typical railroad vehicle running on broad gauge to obtain the vertical and lateral acceleration of the various components of the rail vehicle system for speed ranging from 15m/s to 60 m/s. The results obtained through simulation study revealed a great deal of actual behaviors of the railroad vehicles in various operating speeds.

The results obtained through simulation of the bond graph model of railway vehicle and track structure have been validated by comparing with railways standards and other available literature, which showed a good agreement between them.

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Simulation Parameters

Parameters	**Nomenclature**	**Values**
Primary spring stiffness	K_{py}	2.984×10^6 N/m
Secondary spring stiffness	K_s	8.788×10^6 N/m
Primary damping coefficient	C_{py}	0.0Ns/m
Secondary damping coefficient	C_s	0.0Ns/m
Primary lateral spring stiffness	K_t	4.500×10^6 N/m
Secondary lateral spring stiffness	C_t	0.0Ns/m
Primary lateral damping coefficient	K_{ty}	8.465×10^5 N/m
Secondary lateral damping coefficient	C_{ty}	3.0×10^4 Ns/m
Half of primary suspension spacing	b	1.448m
Half of distance between bogie centers	c	7.315m
Half of secondary suspension lateral spacing	d	0.794m
Same gauge length	e	0.864m
Half of primary suspension lateral spacing	f	1.127m
Mass of Rail	m_r	60 Kg/m
Mass of Sleeper	m_s	349 Kg
Mass of Ballast	m_b	466 Kg
Rail stiffness Coefficient	K_{pv}	7.8 x 10^7 N/m
Rail Daming Coefficient	C_{pv}	5 x10^4Ns/m
Sleeper Stiffness Coefficient	K_{bv}	2.947×10^7 N/m
Ballast Stiffness Coefficient	K_{fj}	7×10^5 N/m
Sleeper damping coefficient	C_{bv}	5×10^4 Ns/m
Ballast damping coefficient	K_{fj}	5×10^4 Ns/m