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A Review on Dynamic Analysis of Rail Vehicle Coach

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ABSTRACT:

Railway vehicle is one of the rigorously developing passenger and goods carrier in the past few centuries. Dynamic behaviour of the railway coach is a vital aspect in its design and also in terms of passenger safety and ride comfort. Dynamic response includes both deterministic and probabilistic analyses. Modal, harmonic and transient dynamic analysis is part of deterministic analyses, whereas random response using spectrum methods and power spectral density (PSD) is a probabilistic approach. This paper is an attempt to cover various modelling and simulation methods of the railway bogie and coach adopted by various researchers to understand the dynamic behaviour of the railway coach. Further, the research findings of various dynamic parameters obtained theoretically and practically against different inputs like sinusoidal and random inputs to the car body have been discussed. This forms a basis in understanding the development of railway coach design when one is interested in carrying out free and forced vibration analysis on the coach, as well as assists to optimize various design parameters of components like bogie, car body and suspension elements in terms of vehicle dynamics.

KEYWORDS:

Railway coach; Review; Dynamic analysis; Modelling; Simulation; Wheel-rail system

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1. Introduction

Railway vehicle is used for transport of commuters and freight via vehicles moving on railway tracks with tapered profile wheels. While roadway vehicles merely run on a prepared surface, locomotives are directionally guarded, governed or dragged along the rail surface. A rail vehicle moving on the track is one of the most complex systems in vehicle dynamics. It consists of so many components and each component has multiple degrees of freedom (DoF). Rigid body assumption of those components may not lead to a realistic system always. These components may be attached together in several ways. The suspension system attaching these components may be modelled as linear, non-linear or piecewise linear. A complex non-linear geometry and dynamical analysis is involved at the wheel-rail interface. The non-linear creep forces are generated near the contact point due to difference of strain rate for the rail and wheel [1].

Historically, the rail-wheel contact area is being assessed through theoretical, mathematical and software tools and methods developed to study vehicle and track dynamics. Multi body systems (MBS) and numerous commercial packages like Simpack, Vampire, Gensys, ADAMS/Rail, Nucars and ABAQUS have been successful in representing dynamic behaviour of the rail vehicle. While multi body dynamics have mostly been used to study railway vehicles, track models have been usually developed based on the FEM and BEM by researchers. ANSYS, NASTRAN, ABAQUS have gained importance in applying different algorithms to perform dynamic analyses and extract the free and forced vibration characteristics of track as well as vehicle as a part of various researches and investigations. Amendments in the physical, geometric and suspension design of the vehicle are feasible; however any modification in the track is not that frequently achievable. Hence rail vehicle dynamic studies are very important in terms of vehicle stability and passenger safety. This present paper aims to describe various modelling and simulation methods in the field of railway vehicle dynamics adapted by researchers worldwide and provides insights to choose suitable tool based on the type of dynamic response expected by upcoming researchers. It also highlights the limitations and assumptions of various coach dynamic studies.

2. Modelling/Simulation of Railway Coach

Design plays a prominent role in extracting the dynamic response of the railway coach. Typically, any railway coach comprises of the car body, bolsters, two bogies, side bearers and central pivot to connect the bolster with the bogie frames, two wheelsets each for one bogie and the primary and secondary suspension elements. Modelling of these components is vital for the dynamic studies along with the appropriate assumptions. Several reviews exist in this field and this article does not intend to duplicate these, but the main methodologies of the studies carried out on the railway coach earlier along with capabilities and limitations are discussed here. Due to the rising computer hardware capabilities and a constant drive from the software industry to integrate together the existing engineering analysis tools i.e. MBS and FEM, the limitations between the two categories become less distinct. Few such analysis tools like ADAMS, ABAQUS and SIMPACK apply both multi body dynamics and finite element (FE) formulations.

2.1. Coach & bogie mathematical modelling

In order to study the dynamic behaviour of railway coach it is important to develop a suitable mathematical model. The developed mathematical model can be used to write the equations of motion which are used in calculating various dynamic responses based on different input conditions. A fourteen DoF railway bogie model was considered by Broersen [2] assuming that the structural elements of the bogie are rigid and joined together by frictionless suspension components. The bogie model was taken to be resting on 4 contact points and the DoF are taken as 6 DoF for bogie frame and 4 DoF each for the two wheelsets. Mathematical model of the 14 DoF railway bogie described the random lateral motions of the railway vehicle, where creep coefficients, equivalent conicity and gravitational stiffness parameters were considered in the equations of motion relating wheel-rail forces. The above parameters derived after simulation, found to be in reasonable conformity with the experimental results.

Two theoretical models of the railway bogie were described by Hans and Jens [3], wherein first model called the Cooperrider bogie assumed the nonlinearities to be purely dynamic. One of the nonlinearities was modelled as stress- strain relation in the wheel-rail contact zone and the other nonlinearity aroused due to the modelling of flange with high stiffness with dead band. In the second model, a wheel running on a rail with realistic profiles was considered. The flange contact takes place naturally as a consequence of another nonlinearity, which stems from the nonlinear kinematic conditions determined by the contact geometry. The equations define the wheel and rail profiles and were used simultaneously with the dynamic system to determine the points of contact between the wheelsets and the rails as long as they touch each other. When a normal force at a contact point becomes negative, the constraint equations are substituted by dynamical equations for the motion of the wheelset under the action of gravity and inertial forces on that wheel until contact happens again. The running behaviour of the railway vehicle which is S-train in Copenhagen was described by considering vertical and lateral dynamics and the longitudinal component of wheel rolling velocity was assumed to be constant.

The rolling, pitching and yaw motions were taken into account by Eva [4] for the railway vehicle with one bogie thus realized with 5 DoF. Newton's method was used to setup the motion equations of railway vehicle and these equations were derived by projecting forces and rotations on to the X, Y and Z axes in inertial coordinate system using appropriate transformations. All suspension elements of the mathematical model of the S-train were assumed to be homogeneous and linear. A track dynamic interaction model comprising of one truck was analysed by Cai and Raymond [5]. The wheel axle model consisting of two unsprung masses, side frame mass with pitch moment of inertia and primary suspension elements. The rail surface was modelled to be discrete support elastic beams system describing the rails and 40-sleepers length. The model investigated the dynamic response of the system subjected to different wheel and rail defects. It was found that the wheel and rail impact behaviour depends highly on the train speed.

Half model of a bogie was developed by Nielsen & Igeland [6] for studying the vertical vibrations. It was assumed that the loading from the full bogie is symmetrically distributed on the two rails. The model consists of 6 DoF including the two wheel rail contact points. Each un-sprung mass represents half a wheelset and parts of a traction motor. A lumped mass of the car body was considered and the inertia of this sprung mass above the secondary suspension is neglected. A complete model of the wagon was represented by Zhai & Sun [7] with two bogie multi-body system. The track was built as an infinite Euler beam on a discrete–continuous elastic support comprising of three slabs of rail, sleeper and ballast. The importance of dynamic effect of the wheel axle through the rail and the bogie was analysed in this study. A dynamic train-track interaction model was developed by Sun & Dhanasekar [8] to investigate the vertical interaction track and wagon. The Wagon with four wheel axle and two bogies was modelled as a 10 DoF subsystem, the track was modelled as a four-slab subsystem and the two subsystems were coupled together through the non-linear Hertz contact theory. The car body and bogies were allowed vertical displacement and in-plane rotation (bounce and pitch motions respectively) while the wheelsets were allowed vertical displacement (bounce motion) only, thus representing the wagon as a 10 DoF model.

Multi body dynamics method was used by Andersson & Abrahamsson [9], which permits for modelling structures in which suspension elements, i.e. springs and dampers allow large relative displacements and rotations between components experience their own small elastic deformations. Use of this method illustrated the concept of flexible multi body dynamics and the wheel-rail contact forces. A multi-dimensional model with flexible wheel axles and a rigid bogie frame was formulated. The vehicle motion was controlled by the wheel-rail contact without imposing any other constraints. The wheel axle was modelled according to elastic beam concept while the wheels were considered rigid. Zhai et al [10] formulated a three-dimensional (3D) vehicle track coupled dynamic multi-body system model with 35 DoF. Two parallel continuous beams sustained by a discrete elastic foundation of three slabs with sleepers and ballast were used to formulate the conventional ballasted track. Two parallel continuous beams supported by multiple elastic rectangular plates on a viscoelastic foundation were used to model the non-ballasted slab track. The vehicle and track subsystems were coupled through a wheel-track spatial coupling model whereas DoF in vertical, lateral and torsional directions was assigned to the rail vehicle model. Coupled vertical-lateral mathematical model of an ICF GS coach used by Indian Railways with 37 DoF has been formulated using Lagrangian dynamics [11-12]. Car body and bogie frames are assigned with lateral, vertical, roll, pitch and yaw DoF. Bolsters are assigned lateral, vertical, roll DoF and wheelsets are assigned lateral, vertical, roll and yaw DoF. Multi body dynamics modeller DADS (Dynamic Analysis and Design Software) was used to build the automatic guided transition (AGT) vehicle with single axle bogie [13]. A 15 DoF model was simulated to study the lateral motion parameters of the AGT.

Wheel–Track model with a wheel flat of a wheel axle was developed to study the parameters influencing dynamic interaction [14]. The Wheel–Track model was examined in the vertical plane incorporating linear, nonlinear, elastic and damping elements which are discrete. Popp et al [15] formulated a rail vehicle model considering the car body and two bogies, where each bogie consists of a bogie frame, bolster and two wheel sets. Bolsters were attached to car body through pivot and are assigned yaw DoF only. All other bodies were assigned all 6 DoF and linear suspension was considered, only yaw damping of centre pivot attaching bolsters and the car body observed non-linear behaviour. To account for the wheelsets flexibility the vehicle is modelled as an elastic multi-body system (EMBS). A 17 DoF mathematical model of an EMU Indian Railway Coach was developed by Hemantha Kumar et al [16] to carry out lateral dynamic response analyses. Linear governing equations of motion of the coach model were solved assuming that the train is travelling along straight track. Mathematical model of the full coach of EMU/T moving on Indian suburban track formulated using rigid body concept [17].

2.2. FE modelling of railway coach & bogie

The recent practice in advanced vehicle analysis is to develop FE models, which resemble the real systems compared to conventional rigid body models. With the development of computer aided design and analysis tools in combination of FE methods and analysis most vehicles including the railway coach have been modelled using CAD software. To simulate the static and dynamic behaviour of the railway coach FE analysis based software has been used widely by researchers across the globe. Stribersky et al [18] have employed modular design concept to model and assemble the components of a metro train which are stored as sub structures of the vehicle component database. Virtual vehicle concept has been successfully used to simulate the vehicle dynamic behaviour using ABAQUS and Simpack FEM. Various levels of vehicle analysis in Simpack have been explained, where in first stage vehicle model is represented and in second stage vehicle substructure systems such as bogie, bolster and side frames are represented, in third stage individual elements of the substructure like the wheel axle and also force elements spring and damper are represented, fourth stage contains the standard input data (SID) file in the form of tables which integrates the data obtained from FE analysis and fifth stage consists of postprocessor data like frequency response spectra.

Analysis of EMBS model of a railway vehicle concludes that motions due to the deformation are imposed on the motions of the un-deformed body, known as rigid body motions. Consideration of the deformed motions is analysed through modal synthesis. Modes of the modal synthesis were determined with the use of a model for the structural dynamics identical to FE model [15]. Modal functions for the wheel axles are extracted by FE method. This model benefited from the symmetric properties of the structure, i.e. symmetry about the middle plane and rotational symmetry. Popp et al [19] have formulated the rail wheel rolling contact with a FE model. Coupling between wheel axle and the truck frame was represented by linear functions of constant coefficients. Eigen values and eigenvectors of the free wheel axle were computed using FEM analysis of the wheelset and used as modal functions. Since no point of the wheel axle is fixed continuously, no geometrical constraint is imposed to the wheelset, so the Eigen functions of the free wheel axle were utilised. Due to the correspondence of the middle plane, one half model of wheel axle was acceptable to in the analysis. Rigid bodies were used to build the brake discs with wheel axle bearing models. Wheel axle was modelled as a Rayleigh beam in a 1D continuum, with the properties of a bar and torsional rod. Longitudinal and torsional deformations were characterized with linear shape functions; whereas bending was characterized by cubic shape functions. The wheel was described as with a disc and Kirchhoff plate characteristics in a 2D continuum. In circumferential direction, trigonometric functions were used which have edge due to the whirling association of the wheel axle. Linear and cubic shape functions were used to signify the disc and the plate respectively, in radial direction.

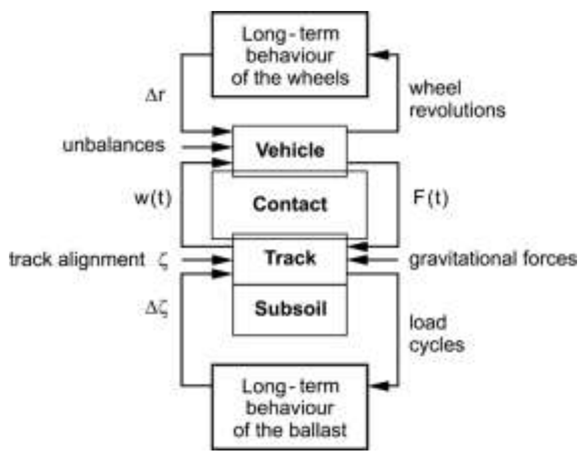

Fig.1: Structure of Wheel-Rail system [19]

Deshpande et al [20] built a multi body parametric model of a LHB coach analysed using ADAMS and the proportions of wheel-rail contact patch were calculated.

Different mathematical models were formulated to determine sliding speeds and interface temperature increase of the wheels while in motion. FE model was developed in Hypermesh software for computation of temperature field in the wheel. The temperature effects on resulting phase transformation of the wheel material were helpful in estimating the extent of damage. The extracted results show that the wheels with disc brakes are more likely to slide due to large braking force. It was also found that high temperature generated at the rail-wheel contact region while sliding, spalls the wheel. Cera et al [21] used commercial FE package ANSYS to develop numerical model of a railway bogie frame as per European standards and critical fatigue analysis of various welded joints of the bogie frame were carried out. External forces generated from sources such as double sprung masses comprise of payload, track inputs, lateral accelerations during curve negotiation and longitudinal accelerations during traction and braking were used in life calculation of bogie frame. FE models of bogie frame joints were discretized using solid or brick elements and also shell elements [21]. Nominal stress, hotspot stress and effective Notch stress methods were used in ANSYS to determine the fatigue strength of the bogie frame joints. Simulated results of fatigue life of welded joint are compared with that of theoretical calculations based EN13749 standards.

The limitations of 1D and 2D FE crash simulation models of Korean high speed train (KHST) were presented and the advantages of 3D crash simulation model of the KHST using FE model and MBS were discussed [22]. Predictions of gross motion of the wheel axles and derailments occurring in various crash scenarios were studied. Frontal crash modelling was emphasized due to the problems entailed by rigid body. FE modelling using ANSYS12.1 has been used to perform rail vehicle static stress and vibration analysis. Stress plots and mode shapes have been obtained for an Indian railway RCF bogie [23]. Rail dynamics have also been analysed using the FEM using FORTRAN program [14]. The irregularities of the rail and the wheel of the wheelset have been accounted through the contact between the rail and the wheel. The dynamic analysis of railway wheel with the wheel flat running at speed 60 kmph was simulated [21]. FEA has been widely used to carry out vehicle static and dynamic analysis by researchers [23-26]. CAD tools have been used to model railway bogie and perform dynamic analysis using FEA. The dynamic natural modes obtained have also been matched with the harmonic peaks of the railway bogie subjected sinusoidal excitation [27].

Nackenhorst et al [28-29] and Damme et al [30] have developed an algorithm based on FEM which facilitates engineers in treating both the wheel-rail contact issue and nonlinearity in materials with single simulation tool. The developed conceptual approach and numerical realization was limited to elastic material in the initial level. One discretisation for each load case is applicable in the case of static conditions or dynamic applications without large rigid body motions. Applying this formulation to rolling contact is very complex. A nonmaterial discretisation using the Arbitrary Lagrangian-Eulerian (ALE) method was proposed by Nackenhorst [28-30] as an alternative method for the numerical simulation of problems with time dependent boundary conditions. This method breaks down the total deformation of the wheel into two parts. The first is a rigid body motion similar to Eulerian approach since the material was moving through the descritized area as in computational fluid dynamics. The second part is a superimposed motion of the endpoint of the position vector into its last position which is the deformation of a material body using the Lagrangian approach.

FEM analysis of bogie frame was carried out under different loads such as vertical and transverse loads, bogie frame self-weight, torque arm reaction loads with spring, shell, rigid and gap elements using IDEAS software by Sam Paul et al [31]. Three different FE models of EMU/T coach travelling on Indian suburban track formulated with improved levels of refinement [17]. Mass and inertia of the superstructure were lumped on the under frame centre of gravity in the simplest FE model of the EMU/T coach. The next level of the EMU coach FE model was built by cumulating the superstructure framework on top of the previous simplest model, ignoring the sheet metal framework. Superstructure framework and sheet metal panels comprise of the last and most detailed FE model of EMU coach. In the FE model, the track was modelled as an Euler Bernoulli beam resting on Winkler's foundation with vertical translation and rotation about lateral axis being present which was termed as beam on elastic foundations (BEF). For vertical dynamic model primary and secondary suspensions were modelled as springs with vertical DoF, whereas for the coupled vertical-lateral model springs were assumed of having both vertical and lateral DoF. 3D beam elements with 6 DoF were used to model wheel axle, bogie frame and under frame with sole bar, cross bearer and superstructure framework. Triangular plate elements were used to represent all sheet metal panels.

FE idealization and simulation of Indian railway vehicle was carried out using Hypermesh and ANSYS to perform in terms modal, harmonic and transient response vehicle dynamic analysis [32]. Bogie frame, side panels, upper roof and chassis of car body were taken into account in the FE modelling of railway coach, whereas remaining components' masses were lumped at appropriate nodes of the FE model. 3D beam elements were used to model body pillar, longitudinal stiffeners, light rail and waist rail assuming 6 DoF at each node. Shell element were used to build the bogie frame, side panels, upper roof and chassis of car body assigning 6 DoF at each node. Combination elements were used to model the primary suspension and secondary suspension assigning 6 DoF.

2.3. Railway coach modelling using alternate methods

Other methodologies like Boundary Element Method (BEM) and Bond graph were also employed in parallel for railway coach modelling and simulation. Similar to FE based software where the CAD model of the railway coach is translated into packages like ANSYS, NASTRAN to carry out various analyses, CAD models of the railway coach are also imported into multi body dynamic software such as ADAMS and ABAQUS to carry out dynamic analyses using rigid body concepts. However, using multi body dynamic packages has many limitations to the solution in terms of DoF. One of the most complex problems in wheel–rail contact mechanics is the estimation of stress and strain status of the wheel-rail under rolling contact boundary conditions. In general, the BEM based on Kalker's theory [33] was utilised for this purpose. Difficulties arise when material nonlinearities have to be considered in place of purely elastic material or real wheel and rail cross-sections instead of elastic half spaces. 3D rigid body ML95 trailer vehicle was modelled accounting 11 rigid bodies for dynamic analysis using DAP-3D multi-body program [34]. The results obtained were compared with the commercial program ADA MS/Rail (MDI, 1995, 1999) for the same conditions. ADAMS/Rail considers the multi-body approach to construct the ML95 vehicle model but is different in suspension modelling. In ADAMS/Rail air spring models are available, whereas spring and damper elements were employed in DAP-3D to represent the suspension.

The mathematical analysis of vertical dynamic behaviour of a conventional rail vehicle also carried out by modelling through bond graph technique [35]. The developed model comprises 17 DoF accounting wheel set, bogie frame and car body. Ride comfort is determined through Sperling ride index which is a standard considered by Indian railways. Ride index is calculated via filtered RMS accelerations. The bond graph technique for modelling and its simulation of rail vehicle is performed using SYMBOLS SHAKTI software in capsulated form. Numerical simulation of a typical North American freight locomotive was carried out using ADAMS/RAIL and ADAMS/VIEW as a part of the study of failure of primary suspension spring travelling at hunting speed of 132 kmph [36].

2.4. Railway coach modelling & simulation in international context

Sebesan & Zakaria [37] studied static behaviour of the railway bogie frame used on LDE 060-DA locomotives; simulated using two FE based software packages Solid works and ANSYS. Loads are considered to be vertical and the deformations of the bogie frame are elastic and the obtained stresses are within elastic limit. Critical speed was calculated for the numerical model of a Pendolino train in ADAMS/Rail using FE analysis [38]. The Eigen frequency modes were extracted and also transient dynamic analysis was performed for the FE model in ADAMS/Rail module. Researchers performed analysis of motor bearing failure in the BB series EMU (Electrical Multiple Unit) vehicle of the Far East Asia (Taiwan) Railways [39]. A 23 DoF track-transmission model was modelled to incorporate linearity and nonlinearity together in the system. The influence of the irregularities from periodic track unevenness called as rail corrugation, track misalignment also termed as dipped rail joint and motor torque ripple harmonics on drive line dynamic performance was completely studied. Parametric optimization was carried out and it was found that at 40 Hz the unsprung mass was bouncing on the track 'spring'. This vibration mode was observed to be predominantly influenced by track elements and the vehicle's primary vertical suspension. Primary vertical damping and end-stiffness has significant influence on the drive line dynamic characteristics. It was determined that the optimum primary vertical damping as 20-30 kNs/m and the end-stiffness 15-25 MN/m per wheelset.

2.5. Railway coach modelling & simulation in Indian context

Typical railway BOXN wagon was modelled as an assembly of rigid bodies with two stage suspensions. A virtual spring which is Hertzian spring was introduced at the rail-wheel contact and is under consideration only when a compressive force exists at the contact [40]. The nature of the Hertzian spring is nonlinear; however, it was proved by Lu and Gill [39] in the past that for the working range of rail-wheel interaction, the Hertzian spring was considered as linear, i.e. the spring force is directly proportional to the relative displacement between wheel and rail. It was concluded that random unevenness is not the sole reason of high contact force (CF) for the speed range 36 kmph to 216 kmph. For a track with high stiffness, CF increases with speed particularly due to presence of dip, whereas softer track is less sensitive to such unevenness. Tracks with surface irregularities are result of bad maintenance practices and such tracks also get affected severely by the dynamic effects of rail-wheel interaction.

Natural frequencies of the EMU railway coach modelled as a 17 DoF model were determined [16]. Dynamic response of the coach in frequency domain with power spectral densities of track gauge as well as alignment irregularities as input was determined. An EMU/T coach moving on suburban Indian broad gauge track was modelled by Gangadharan et al [17]. The model includes a car body, two bogie frames and four wheelsets. The vehicle has two tier suspension bogies. FE modelling and the rigid body modelling were the two approaches used for modelling the track vehicle system. Mathematical modelling of the full coach was carried out using rigid body concept [17]. FE models of railway coach were developed by several researchers [17, 27 and 36] to perform dynamic analyses in terms of harmonic response and random response with PSD inputs.

3. Dynamic Behaviour of Railway Coach

3.1. Modal analysis of railway coach

The first step in identifying the dynamic behaviour of any moving vehicle is to determine its natural frequencies. Free vibration analysis of the developed mathematical or numerical vehicle model is generally carried out to find its dynamic modes in longitudinal, lateral and vertical directions. The frequency response of the railway vehicle [15] simulated with FE shows distinct peaks in the frequency range of around 100-200 Hz for symmetric vertical excitation and around 130-220 Hz for anti-symmetric lateral excitation. These peaks appear due to wheelset elasticity, they are not attained using MBS considering different rigid bodies. The comparatively high number of necessary modes results from the coupling between the wheelsets and the bogie frame. The higher angular speed of the wheelsets tends to a split off the resonance peaks generated due to the bending modes that is crucial for gyroscopic effects.

Eigen value analysis of car-shell was carried out and seven modes have been obtained [18]. While Simpack uses a reduced FE method, Abaqus uses a full FE method with the help of a MBS algorithm to obtain 7 modes of the fully integrated metro train model. To import the elastic body properties into the multibody system the Guyan reduction method is used with FEM model of the car body without the elastic mounting. It was concluded that for the reduced FE model the calculate Eigen frequencies up to 20 Hz vary within 0.5% compared to the full FE model. For frequencies above 20 Hz higher variations than 0.5 % were accepted. For the 17 DoF lateral dynamic mathematical model of an EMU Indian Railway Coach developed by Hemantha Kumar et al [16]. The Eigen frequencies were obtained in the range varying from 0.82 Hz to 127.5Hz with nine clear distinct modes. Eigen frequency modal analysis was carried out for 37 DoF coupled dynamic model of an Indian railway general sleeper coach. Out of the 37 eigenvalues obtained, 15 modes are complex conjugate pairs [41]. Modal analysis of bogie frame individually and full railway coach was performed by Ramji et al [32] for the FE models developed. Predominant dynamic modes were observed including the bounce, pitch and roll modes which were in good correspondence with the frequency values of rigid body models. Eigen frequency analysis of an Indian railway ICF bogie was carried out under un-laden and laden conditions [27]. Roll, bounce and pitch natural frequencies and mode shapes were extracted for realistic FE model of the bogie.

3.2. Harmonic response analysis of railway coach

Equations of motion developed in formulating the bogie FE model by researchers [19] considers the force vector to consist of forces generated at wheel-rail contact patch, gravitation and non-linear yaw damping. Under vertical harmonic excitation, this motion equation was reduced to algebraic equations analytically so that the complex frequency response function for the vehicle was determined. The complex frequency response function of the vehicle was calculated with different numbers of modes to determine the convergence of the modal synthesis. The frequency limits for the bending modes correlate with the Eigen mode frequencies; angular speed of the wheelset corresponds to a travelling speed of 200 kmph. The convergence check shows that the behaviour <500 Hz can be sufficiently described using four bending modes, but deviations were observed on the curve for the wheelset 2 at 600 Hz. Since no geometrical constraint was applied to the wheelset, relatively more number of deviations results from the fact that the Eigen modes of the free wheelset were used. However, interfacing of the modes happens due to the coupling between wheelset and bogie frame. This study also predicts influence of the wheelset elasticity on its dynamic behaviour. In the frequency ranges of around 100-200 Hz, distinct peaks of the frequency response functions crop up which can never be determined by the assumption of rigid wheelset.

In the study of BB series bogies of EMU [39] of Far East Asia (Taiwan), a torsional vibration mode resonant peak at 168 Hz the linear frequency response was determined in pinion and armature out-of-phase. The natural frequency of the BB series motor is 120 Hz, which does not excite the torsional vibration mode. The computation of linear frequency response verifies a resonant peak in the 40 Hz region which matches with the bearing's natural frequency. Therefore it is strongly recommended that BB series motor bearing fails at the 40 Hz excitation frequency. Fast Fourier Transform (FFT) was applied to the time domain response to study the frequency contents of a ML 95 train [34]. The lateral and vertical accelerations spectra obtained experimentally and from simulation using DAP-3D are plotted against frequency. The experimental and simulated lateral PSD acceleration curve coincides perfectly where, resonant frequency of the experimental results is 0.9 Hz whereas for the numerical simulation results it is 1.1 Hz. For the vertical PSD accelerations, curves are in a reasonable agreement. Resonant frequencies for the experimental and numerical results were about 1.2 Hz and 1.7 Hz, respectively. It was observed that the resonant frequencies show higher values in the results obtained with DAP-3D. This indicates that the suspensions of the vehicle model formulated using DAP-3D were stiffer than the real suspensions.

From the comparative analysis of bogie and coach FE models it was noticed that the displacement response of the bogie is more than that of the coach at lower frequency [32]. It is due to the fact that the displacement response is declining with increasing mass. Harmonic response studies indicate that at bounce mode frequency 3Hz magnitude of displacement is higher for front portion of the car body compared to its middle & rear portions. Harmonic response peak frequencies were observed to be in good agreement with the natural frequencies of Indian railway bogie model [26-27].

3.3. Transient dynamic analysis of railway coach

Time domain solution techniques are applicable both in linear as well as nonlinear dynamic systems. Time domain models produce a sampled time history of each response variable like displacement or acceleration, however validation of the time domain models are difficult [42]. Hertz contact model was used to describe the wheel rail contact of rail vehicle of type ML 95 train and the variation of contact forces on two contact points with respect time was plotted [34].Vertical accelerations of the car body modelled using DAP-3D and also ADAMS/Rail was also plotted against time. The results of the plots were well matched, which presents similar medium values and variation ranges. The disagreements are the kinks in the results arising from the track abnormalities. It was noticed that, specifically for vertical accelerations determined experimentally, such discontinuities are much higher.

Results obtained through FE analysis indicated that as the vehicle moves over a semi-circular bump, the transient analysis can be well employed to investigate the Indian railway coach performance under most real time input excitations [32]. It was also determined that at vehicle speed of 80 kmph ellipsoidal bump the displacement response at coach rear portion was more than that of other portions. Transient dynamic response of a railway bogie was analysed at various salient points on the bogie frame [27]. It was considered that the vehicle run over a semi-circular bump in a period of 0.144 seconds with a speed of 100kmph. It was determined that bogie left and right corner locations in front and rear are more vulnerable.

3.4. Random response analysis of railway coach

Random track abnormalities presented in terms of track spectra are considered as system excitations by means of a time-frequency transformation technique. The author has also studied the coupled vertical-lateral dynamics of rail vehicle formulated by Lagrangian method assigning 37 DoF to different rigid bodies [11-12]. For a BB series EMU bogie, the wheelset accelerations measured on uneven track due to random unevenness were less than that are normally expected from a 1 mm sweep disturbance [36]. Random track profile in terms of track alignment and gauge as defined by Iyengar and Jaiswal [43] were fed as inputs to the Indian railway coach lateral dynamic model in terms of power spectral densities (PSD). The 17 DoF mathematical model of EMU railway coach was treated as lateral dynamic system with eight random disturbances [16]. Assuming that the vehicle is travelling at 30 kmph the lateral acceleration and displacement responses in terms of PSD have been obtained for the center of gravity of vehicle. The acceleration and displacement response in g2/Hz was plotted against frequency in Hz.

PSDs of the track were used as inputs to the vehicle model and the response was predicted using random vibration theory [17]. With an elaborate FE model of a suburban railroad vehicle, experimental and analytical assessment of Sperling ride index and ISO 2631 ride comfort was done. To study the dynamic response under normal operating conditions, simulation was performed at different locations of an electrical multiple unit trailer (AC/EMU/T) coach and bogie running on a broad gauge suburban track. Goel et al [44] have regarded track irregularities as auto spectral density and cross spectral density functions in terms of PSD values of five hundred twelve dataset points over a track length of 0.402 m applicable for Indian railway tracks. Vertical irregularities taken as a random function of time in the form of PSD were given as base excitation input at few identified wheel rail contact points of the FE model of Indian railway ICF bogie to carry out the response spectrum analysis [27].

4. Summary and Conclusions

Majority of the studies carried out by eminent researchers across the globe have used both mathematical modelling and FE methods to the core to define the dynamic vehicle model. Mathematical modelling concentrates on simplifying the governing equations of motion and extracts the dynamic response. FE analysis suitably assumes certain force elements like the suspension systems of the vehicle geometry as linear elastic and simplify the model to simulate the dynamic behaviour under different loading conditions. The use and advantage of computer based software packages have been highlighted by investigators making use of both the multibody dynamics and FE methods. However, FE based software packages seem to result in more accurate results due to their vicinity with the realistic geometry of railway vehicle. Also, the complexity in obtaining solutions is higher in multibody dynamics tools compared to that of FE based analysis tools.

The survey of various articles carried out indicate that the dynamic modes extracted for the railway vehicle in free vibration analysis form a basis in understanding the vehicle stability. Further harmonic and random response characteristics extracted by some investigators provide insights in improving the passenger ride comfort through ride index calculations and also the scope for better maintenance the railway track. Significant research has been carried out in the frequency domain in terms of harmonic input and PSD random input to the rail vehicle wheel, but limited studies were carried out by few researchers in the time domain probably due to its complexity. In Indian context, the dynamic response studies of typical Indian railway coach and bogie were carried out by renowned researchers majorly using mathematical modelling by means of rigid body concepts. Few studies were carried out using FE analysis but mostly assumed lumped mass at appropriate nodes.

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