



# Investigation for Failure Response of Suspension Spring of Railway Vehicle: A Categorical Literature Review

M. A. Kumbhalkar · D. V. Bhope · P. P. Chaoji ·  
A. V. Vanalkar

Submitted: 10 January 2020 / in revised form: 8 July 2020  
© ASM International 2020

**Abstract** Helical spring is used as primary suspension to absorb shock and vibration in rail vehicle system which calls for investigation under failure response because of different loading conditions. This paper is based on the categorical literature review on case study of failure response of suspension spring of railroad vehicle. Here, the investigation of a multibody framework approach is introduced that can be utilized to create complex model of railroad vehicle suspension system. The literature presented encounters results in various domains of analysis including static and dynamic analytical analysis, experimental investigation, dynamic model and finite element analysis for its failure study and examination. It has been observed that the stress may initiate at the inside diameter of spring due to curvature effect during manufacturing occurs residual stress. Also, it induces due to lateral and longitudinal load due to curving and tracking of the rail vehicle system.

**Keywords** Railway vehicle · Finite element analysis · Vibration · Helical spring · Rail track

## Introduction

Railway vehicles are among the most broadly utilized techniques for shipping travelers and products [1]. Indian railway is widely spread across country hauling passengers and goods for the very large distances and running for 3–4 days continuously. The rail road vehicle is one of the most complex dynamic systems. An assembly of dynamics model of railway vehicle is carried out from wheelsets, car bodies and intermediate structures which are flexible, and which are connected by segments, for example, springs and dampers [2]. An Indian railway vehicle is shown in Fig. 1.

Suspensions are the significant machine component of railway vehicle which retain the stock and vibration during tracking, curving and furthermore secure the axle motion. The helical compression sort of spring is utilized to permit axial deformation and furthermore give some horizontal twisting at ebb and flow. A cargo rail vehicle has the regular failure of primary suspension with real accentuation on the failure of composite spring of middle axle of the two casings. A suspension spring is normally viewed as static if an adjustment in deflection or load happens just a couple of times, for example, under 10,000 cycles during the normal life of the spring. A static spring may remain loaded for very long periods of time. The shear or fatigue failure of suspension spring may be caused due to several reasons of rail vehicle movements in dynamic way.

Literature review carried out in the area of analysis on suspension spring of rail road vehicle in context to the present work is presented in classified manner (Fig. 2). The objective of this review is to exhibit and summarize the

---

M. A. Kumbhalkar (✉)  
Department of Mechanical Engineering, JSPM Narhe Technical  
Campus, Pune, Maharashtra, India  
e-mail: manoj.kumbhalkar@rediffmail.com

D. V. Bhope  
Department of Mechanical Engineering, Rajiv Gandhi College  
of Engineering, Research and Technology, Chandrapur,  
Maharashtra, India  
e-mail: dvbhope@rediffmail.com

P. P. Chaoji  
Electric Locomotive Workshop, Bhusawal, Maharashtra, India  
e-mail: ppchaoji@rediffmail.com

A. V. Vanalkar  
Department of Mechanical Engineering, KDK College of  
Engineering, Nagpur, Maharashtra, India



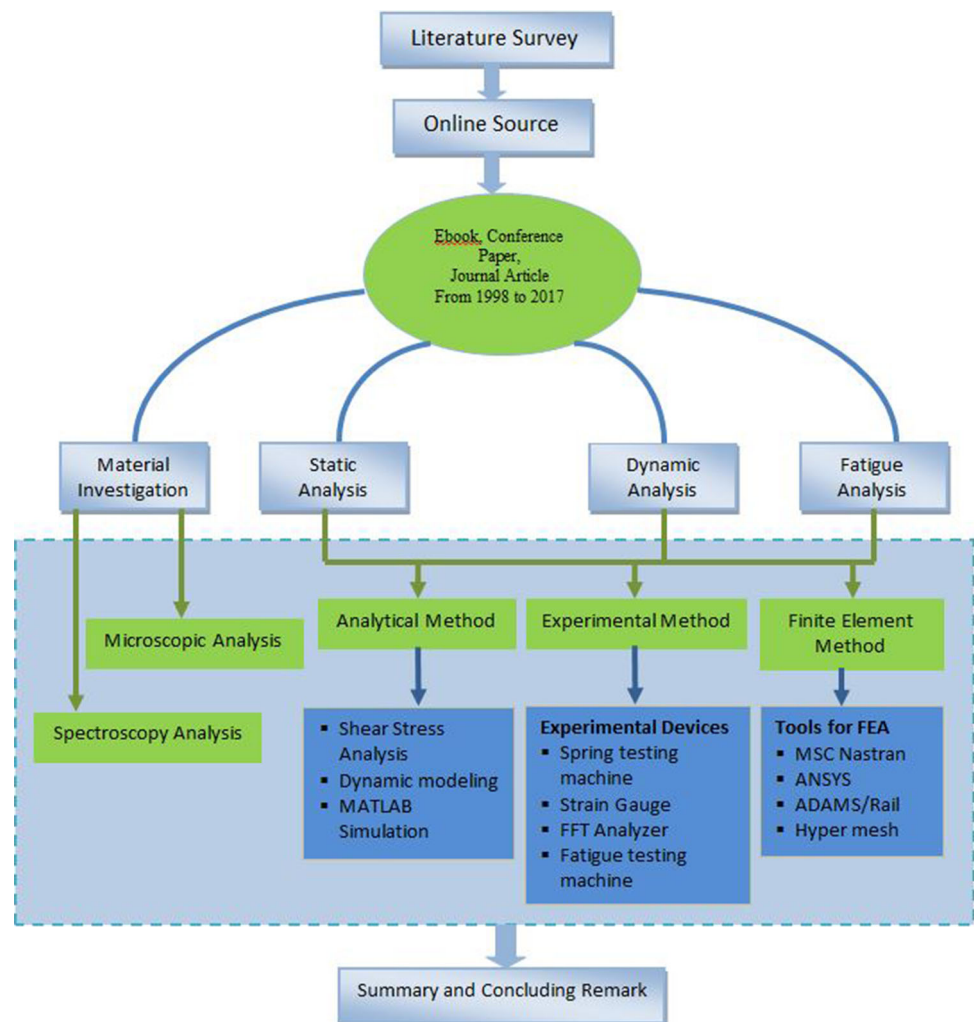
**Fig. 1** Railroad vehicle (Courtesy: Indian Railway)

important aspects for failure of suspension spring of rail road vehicle in a categorized manner as static analysis, dynamic analysis and fatigue analysis which is further categorized as analytical, experimental and finite element analysis. The time frame for this literature review is 1998 to till date, and only one paper of 1990 is taken for reference.

### Static Stress Analysis of Suspension Spring

Research work in the area of static stress analysis of suspension spring, using analytical, experimental and finite element method is presented as follows.

**Fig. 2** Methodology for literature review



Static Stress Analysis of Suspension Spring Using Analytical Method

A new method of calculation is explained for change of axial twisting angle of compressed helical spring's end coils in the case of rotary-free supports, and the equation is derived for deflection of spring which is experimentally verified. This method is easy to apply and gives results much closer to experiment as compared to presently used method [4]. The process of design optimization and its techniques with optimization packages are presented to optimize mechanical and structural elements. The design variables such as mean diameter, wire diameter and number of turns are optimized for design problem of a helical compression spring. Design imperatives incorporated buckling, surging, critical stresses and side requirements too. The optimum solutions are given which are based on the minimal mass design and later combined both of the minimal mass and maximum safety in a linear composite function. The results of optimization techniques are reported using analytical design process and using computer packages CONMIN, MSC/NASTRAN and GENESIS [5]. Prawoto et al. [6] talked about a few contextual investigations of failures of suspension spring. For the assurance of integrity of coil spring, failure analysis of failed springs is important for short-term and long-term modifications in design for car manufacturers. The author discussed the coil spring failures as a result of crack initiation and shear stress formation, unrefined material deformations and manufacturing defects. The shear stress distribution on circular cross section of helical spring is shown in Fig. 3.

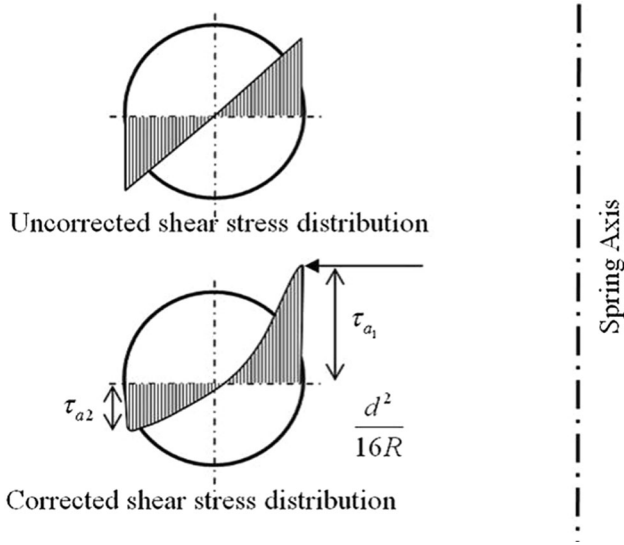


Fig. 3 Uncorrected and corrected shear stress distribution on circular cross section of helical spring [6]

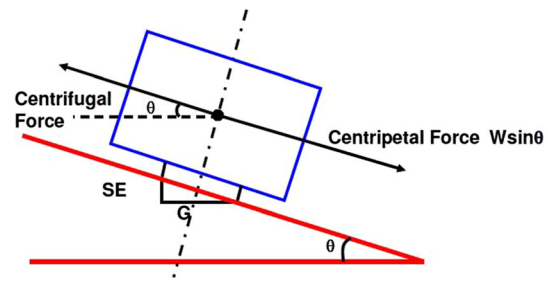


Fig. 4 Forces on rail vehicle during movement on curve [7]

The nature of forces experienced by vehicle is different on curved track as compared to straight track. To design and maintain Indian rail curves, the forces acting and their effect on track and vehicle are required to be studied first. It is seen that the maintenance exertion on curves is about 25% extra when contrasted with straight track because of the transaction of the forces. Therefore, vehicle speed and its movement on curves shown in Fig. 4 are very important as it wear out the track due to high forces and hence require maintenance. So it is very important for engineers to manage rail curves and design the rail vehicle suspension with better understanding to reduce maintenance of rail vehicle and track [7]. Various relations for shear stresses in helical spring are derived for calculating the stress correction factor. The various values of shear stresses are obtained by using shear stress factors like Wahl's factor and Bergstrasser's factor. Therefore, an analysis of helical spring is carried out for various stress correction factors and for increase in pitch angle and justified with the assumptions introduced in each relation [8]. The important parameters are provided which affect tracking and curving ability, i.e., conicity of wheel rail and angle of attack of wheelset which get affected by radius of curve, design of vehicle suspension, frictional characteristics at the rail-wheel contact, wear of rail and different components of vehicle along with several other parameters [9]:

$$\frac{GV^2}{gR} = C_a + C_d \tag{Eq 1}$$

$$\text{Speed of rail vehicle on curve, } V = \sqrt{\frac{g}{G}} \sqrt{(C_a + C_d)R} \tag{Eq 2}$$

where  $g = 9.81 \text{ m/s}^2$  is the acceleration due to gravity,  $G = 1750 \text{ mm}$  is the rail track gauge,  $C_a$  is the cant provided in track,  $C_d$  is the cant deficiency in mm for the vehicle traveling on curve,  $R$  is radius of curvature in mm, and  $V$  is the velocity of rail vehicle on curved track in m/s.

Two mathematical models are proposed for analysis of spring having the wire made of strands. The error in precise and approximate mathematical model have been

determined by increasing screw pitch and diameter ratio which is relatively smaller for strands with the same number of coils. The outcomes acquired are satisfactory by approximate mathematical model just when the proportion of screw pitch to diameter of wire ( $S/d$ ) is two times bigger than number of strand. In comparative and analytical investigations, it was resolved that for strands with a similar number of wires, the relative mistakes between two models are smaller for large ratio of  $S/d$  [10]. The braking performance which depends on total weight carried by passenger or freight vehicle is discussed. The genuine braking execution of a rail vehicle is not the same as the ostensible one because of number of causes. There are various parameters which affect the braking performance and actual deceleration of rail vehicle. The adhesion coefficient between is one of the parameter wheels and rails. A probabilistic examination of train deceleration is depicted, beginning from probability distributions of parameters influencing the braking separation to assess security margins in order to guarantee an emergency braking performance or deceleration [3].

#### Static Stress Analysis of Suspension Spring using Experimental Method

The premature failure of spring is examined due to material defects. Preliminary visual examination for its failure due to shear or fatigue along with detailed scanning using electron microscope is carried out for the damaged surface and fracture surface of the failed spring. Also they have determined the chemical composition and macrostructure investigations along with hardness measurements to understand reason for the premature failure. According to the examination, the inappropriate heat treatment procedure of the spring material is in charge of failure of spring [11]. The characteristics of a coil spring using experimental methods are investigated to verify as per its standard material properties, i.e., spring constant, yield strength and tensile strength. A simple compression testing has been carried out on UTM machine, and deflections are determined. This experimentation is performed for tensile testing to affirm the consistence of SUP12 spring toward JIS 4108 [12].

The connection for change of axial twisting angle of helical compression spring's end coils on account of turning-free supports is created. The derived analytical relation has been verified experimentally on a spring for car suspension system and also for its deflection on spring testing machine. It is accounted for that the test results are having great concurrence with analytical findings [4]. Microscopic experimental analysis for material defects in automotive suspension spring is carried out. In raw material, it is observed that there is small inclusion present at

the surface. It is reported that this surface imperfection might have occurred as small hardening cracks due to poor shot peening condition [6]. The use of strain gage as a sensor is explained to find change in strains on mechanical component to particular area. A strain gage is attached at the internal diameter of helical compression spring for determination of its shear strain as shown in Fig. 5 and hence the stress under applied load. The experimentation is carried out to confirm the effectiveness of sensors [13].

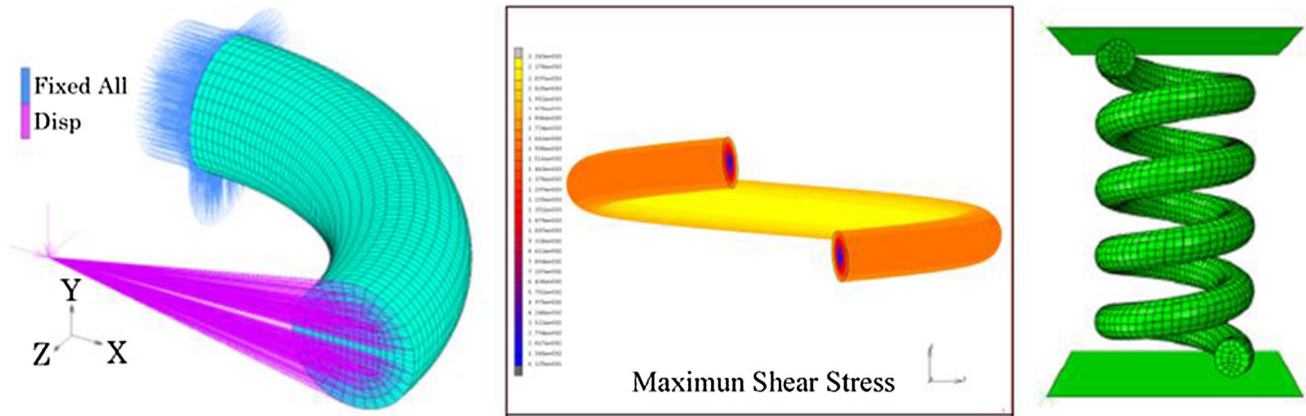
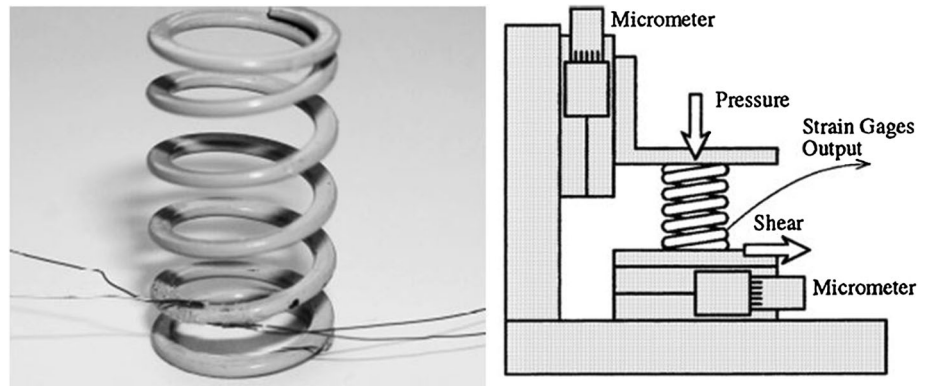
#### Static Stress Analysis of Suspension Spring using Finite Element Method

A typical failure analysis of automotive suspension in light of stress distributions around typical failure location by FE analysis of coil spring model with and without defect is presented. The spring sub-model is also developed to achieve further accuracy in the results. The stress concentration is observed to be more at area of failure and particularly at the crack location [6]. Ruzicka and Doubrava [14] and Watanabe et al. [8] dealt with the problem of helical spring by a simplified equation using various shear stress factors. A diagram of the maximum shear stress and maximum principal stress that contemplates the initial pitch angle is prepared to utilize the design of experiments and FE analysis. FE analysis represents one-fourth circular beam model, and one turn coil of helical spring is shown in Fig. 6 to determine maximum shear stress and maximum principal stress and its comparison with analytical values obtained by different stress correction factors like Wahl's and Bergstrasser's factor.

Finite element analysis for helical spring is used to validate its experimental results for strength. The required stiffness of spring is resolved utilizing HYPERWORKS software according to explicit client necessity, for example displacement at full rebound, curb length and full bump [12]. The pseudoelastic response of shape-memory alloy (SMA) helical springs under axial force utilizing finite element analysis is examined. In the numerical examinations, the three-dimensional constitutive conditions are executed in a finite element method, and utilizing solid elements, the loading–unloading of a SMA helical spring is reproduced and is shown in Fig. 6. Scientific and numerical results are compared. The course of action subject to the SMA curved bar torsion gives an exact stress examination in the cross section of the helical SMA spring despite the global load–deflection response [15]. The effect of a uniform loading for steel helical spring related to light vehicle suspension system is furthermore examined.

Finite element analysis is completed for three diverse composite helical springs E-glass/epoxy, carbon/epoxy and kevlar/epoxy, and it is seen that the spring optimization for change of spring material causes considerable reduction of

**Fig. 5** Helical spring with strain gage foil and its experimentation on spring testing machine [13]



**Fig. 6** FE analysis of one-fourth, one turn coil and helical spring using FEA package [8] [14] [15]

spring weight and maximum stress [16]. A problem of helical compression spring is solved by finite element method for nonlinear governing equation. The wave propagations in axially affected helical springs are portrayed by numerical technique. A Galerkin approach of the finite element method is applied to compute the results which evolved axial and rotational strains and velocities in different sections of spring. This analysis indicated that the amplitudes of axial and rotational waves depend on the excitation, geometrical and mechanical characteristics of the spring [17]. Finite element method is used for dynamic analysis of the cylindrical isotropic helical spring using hybrid-mixed formulation to calculate rigidity. The mass matrices are formed using lumped mass approach. The dynamic equations are solved to determine natural frequencies of spring [18].

### Dynamic Analysis of Suspension Spring

Literature cited in the area of dynamic analysis of suspension spring, using analytical, experimental and finite element method is presented as follows.

### Dynamic Analysis of Rail Vehicle using Analytical Method

Dynamic analysis of rail vehicles is explained which experiences large lateral displacement occurring due to track curves and imperfections bringing about enormous suspension deflection and car body displacement with respect to the track. The author additionally examines an impact of crosswind on a rail vehicle arranging a curve by multibody simulation model exposed to unsteady aerodynamic loads [19]. A suspension arrangement of rail vehicle has the likelihood to diminish guiding force magnitude in small-radius curves by methods for dynamic components and wheel rail connection on curves effects wear of wheel and rail. The guiding force depicts the lateral force communication between the rail vehicle and the track. Therefore, it is required to reduce quasi-static guiding forces for rail vehicle passing through curves by means of system of active yaw dampers. Computer simulations analyze the influence of force produced by the active yaw dampers, the coefficient of friction in wheel/rail contact and the curve radius [20]. The dynamic condition of rail-road vehicle is identified by determining critical speed,

which is very important because railroad vehicles can experience severe lateral and yaw oscillations at that speed. The lateral stability of rail vehicle is researched by generally utilized techniques to decide the critical speed of railroad vehicles, for example linear theory [21]. Dynamic behavior of helical spring is dissected to help overwhelming loads. A physical examination of the effect of axial load on the propagation of an elastic waves in helical shafts is proposed subject to the equation of motion of loaded helical Timoshenko beam. The dimensionless conditions are made for beams of circular cross-area, and parametric investigation is led on four parameters, helix angle, helix index, Poisson coefficient and axial strain. The parametric examination reveals that the impact of loading is evaluated in high-, medium- and low-frequency ranges, and the impacts of stress and geometry deformation are non-negligible on elastic wave propagation [22].

Yildirim [23] developed the free vibration states of cylindrical isotropic helical springs loaded axially which is comprehended numerically subject to the transfer matrix method to perform buckling analysis in a dynamic manner. The axial and shear deformation impacts with the rotatory inertia effects are viewed as dependent on the first-order shear deformation theory. For the investigation of the vertical tip deflection of helical springs with large pitch angles, author obtained the closed-form equation dependent on Castigliano's first theorem that is utilized to think about the full effect of resulting stresses, for example axial and shearing forces, bending and torsional moments on tip deflection. A decent understanding is seen with related benchmark studies. The legitimacy scope of alternative theories is gotten to by examination of the area of the dispersion curves. This work additionally contains a thorough asymptotic investigation of the precise dispersion equation with two small parameters being utilized. It takes into account the distinguishing proof of noteworthy systems of linear wave motion in a helical spring. In every one of these systems, straightforward condition for wavenumbers is acquired by the dominant balance technique and their legitimacy reaches are checked against direct numerical arrangement. Mode shapes related to each wavenumber are likewise displayed [24].

The dynamic reaction of railroad vehicle is determined by analytical equations of two-degree-of-freedom system to random excitations created by vertical track inconsistencies. The dynamic response of body bogie suspension stroke and body acceleration estimated by the analytical equation is found to be acceptable [25]. A mathematical model for the dynamics of railroad vehicle system to derive governing equation of motion using Newton's law for linear and nonlinear phenomenon is developed. This nonlinear mathematical model is used to assess the contact forces of the wheel rail. For lateral vibration, the degrees of

freedom represent lateral and yaw movements of wheelsets along with lateral, yaw and roll movements of the bogie [26]. Nishimura et al. [27] addressed the possibility of dynamic stabilization and the chance of derailment involving serious movements of the vehicle's body, wheel lifts and derailling behavior. The dynamics motions of vehicles result in dynamic forces between vehicle body and bogie shown in Fig. 7 which emphasizes the developed new vehicle dynamics simulation with an exceptional modeling. A simulation is used, and the numerical outcomes are evaluated to evaluate the safety of cars on excited paths with sinusoidal displacements.

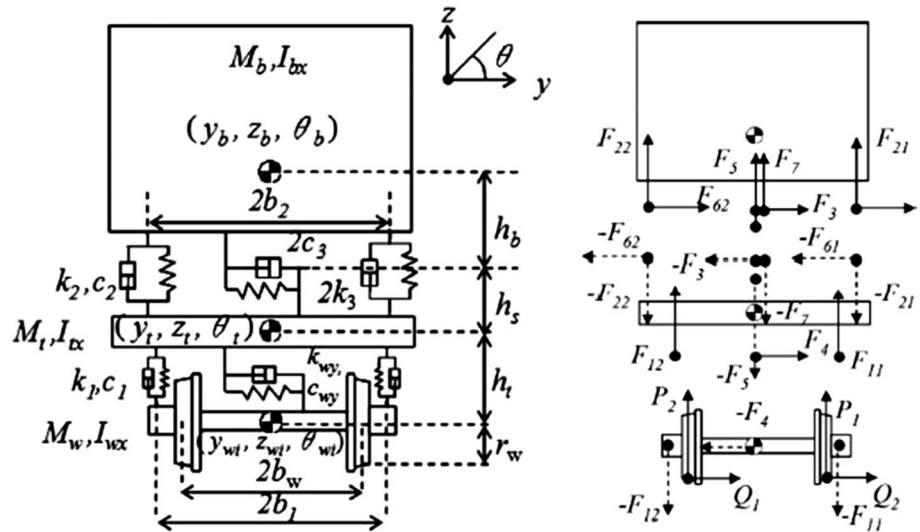
The ride quality related to safety is required to be evaluated for dynamic performance of a railroad vehicle and is deciphered as the capacity of the railroad vehicle suspension to keep up the movement inside the scope of human solace [28]. The responses of the railway vehicle and track segments as far as contact forces and displacements are displayed by considering a five-DOF lumped parameter quarter vehicle model to be upheld on two-dimensional track frameworks involving three layers. The vehicle body is connected with wheel by primary and secondary suspension and damper elements. This study illustrates that wheel flat has enormous influence on all the components of vehicle and track system. It affects not only contact forces but also the displacements responses which are represented by the magnitudes of forces transmitted which increases considerably under a flat-induced excitation and may cause rapid fatigue of the vehicle components and track [29]. The imperfection of the wheel and rail is also liable for the dynamic reaction of the concrete track sleeper owing to the interaction of the wheel track. A rail track is a flexible structure which allows vertical oscillation and causes excitation to the rail vehicle. The dynamic interaction analysis of vehicle and track is required to determine the time response of the wheel load reaction transmitted to the base of track which can be expressed as follows where  $W_L(t)$  and  $W_R(t)$  are the reactions at the left and right rail, respectively [30].

$$\begin{aligned}
 W_L(t) = & m_w \ddot{z}_{w1} + 2C_p \dot{z}_{w1} - 2C_p \dot{z}_{b1} + 2C_p l_b \dot{\theta}_{b1} + 2k_p z_{w1} \\
 & - 2k_p z_{b1} + 2k_p l_b \theta_{b1} + 2k_w z_{w1} - J_{wx} \ddot{\phi}_{w1} \\
 & + 2C_p l_g \ddot{\phi}_{w1} l_p + 2C_p l_b \dot{\phi}_{b1} l_p - 2k_w \phi_{w1} l_g^2 \\
 & + 2k_p l_g \phi_{w1} l_p + 2k_p l_b \phi_{b1} l_p
 \end{aligned}
 \tag{Eq 3}$$

$$\begin{aligned}
 W_R(t) = & m_w \ddot{z}_{w1} + 2C_p \dot{z}_{w1} - 2C_p \dot{z}_{b1} + 2C_p l_b \dot{\theta}_{b1} + 2k_p z_{w1} \\
 & - 2k_p z_{b1} + 2k_p l_b \theta_{b1} + 2k_w z_{w1} + J_{wx} \ddot{\phi}_{w1} \\
 & - 2C_p l_g \ddot{\phi}_{w1} l_p - 2C_p l_b \dot{\phi}_{b1} l_p + 2k_w \phi_{w1} l_g^2 \\
 & - 2k_p l_g \phi_{w1} l_p - 2k_p l_b \phi_{b1} l_p
 \end{aligned}
 \tag{Eq 4}$$

Approximate analytical solutions for semi-active on-off

**Fig. 7** Half car rail vehicle dynamic model and force acting on the model [27]



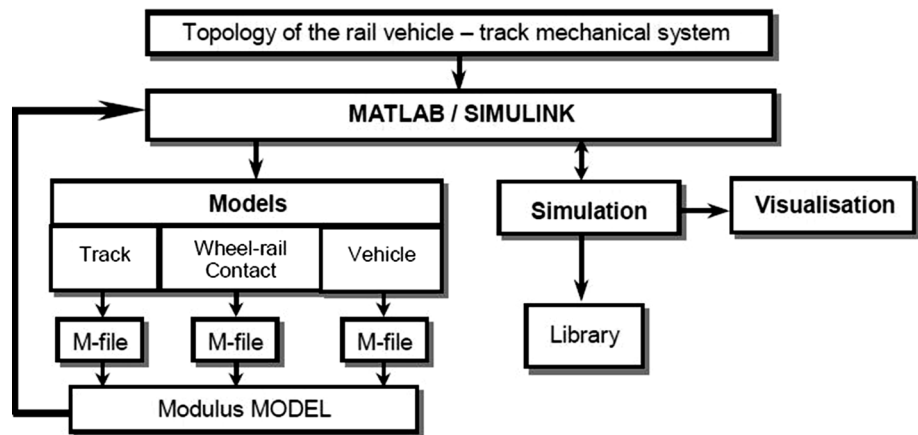
DVAs, named as velocity–velocity and velocity–displacement-based ground-hook control and displacement–velocity and displacement–displacement-based ground-hook control by the averaging technique, are introduced. The parameters including the stiffness and damping ratio of the subsystem are streamlined to get amplitude–frequency equations from approximate analytical solutions. Additionally, the irregular excitation for primary systems, including single-degree-of-freedom framework, the ideally detached DVA framework, and four semi-active on–off DVA frameworks are exhibited [31]. The numerical simulations for vibration behavior of railroad vehicle dependent on a linear model with 17 degree of freedom having impact of lateral and longitudinal suspension damping are developed. The frequency response using equations of motion developed for vehicle car body and wheelset in lateral, roll and yaw is obtained in a harmonic and also in a random behavior. It is concluded that the car body center is dominated by the resonances of the lateral displacement and the roll coupled movement [32, 33].

Based on different types of irregularities which may present on track, Kumar and Rastogi [34] considered a bump type of irregularities to evaluate acceleration frequency response for vertical dynamic behavior of rail vehicle and to determine Sperling ride comfort index. The mathematical model for vertical and rotational displacement for car body, bogie and wheel to study the time response of displacement, velocity and acceleration of car body and to determine track load due to wheel rail interaction is presented [35]. A linear oscillatory model of transport is dissected with three-degree-of-freedom damped system with excitation by the power spectral density (PSD) of the harshness of asphalt-concrete pavement in great condition. The investigation is led through a

simulation, in frequency domain, utilizing dynamics equations. A program made in the product MATLAB is utilized to dissect the transfer functions, spectral density and RMS of oscillatory parameters. The consequences of the examination demonstrate that the parameters which guaranteed good oscillatory solace of the driver are clashing with the parameters which guaranteed the best stability of the bus and the comparing wheel travel [36]. The stability of rail vehicle model is analyzed by defining different combinations of wheelset suspension parameters. It is significantly affected by the coupler torsional stiffness which is dominated by the relative spin that would become unstable even at a lower speed. It is also seen that the torsional damping shows more influence when torsional stiffness is small. Due to variation in conicity of wheelset, the excitation frequency is twice of natural frequency of the dominant mode for reduction in critical speed which depends on the value of coupler stiffness [37–40].

As Euler beam is supported by springs and dashpots, the vertical dynamic direct of the vehicle track coupled plan is intended for the vehicle body, bogies and rail can explore the impact of flexibility of the vehicle on basic unique reaction. The equation of motion for substructure and vehicle-rail coupled structure is developed by linear Hertzian theory. The wheel–rail contact force and deflection of rail at contact point are predicted by rail vehicle model [49, 61]. The algorithm for simulation of rail vehicle system using MATLAB Simulink package is shown in Fig. 8. Telli and Kopmaz [41] contemplated the movement of a mass grounded by means of linear and nonlinear springs in series which prompts a lot of differential algebraic equations (DAE). Notwithstanding, presenting a reasonable variable that speaks to the diversion of nonlinear spring, a nonlinear ordinary differential equation (ODE) is acquired. The arrangement of DAE in new factors is illuminated

**Fig. 8** Algorithm for simulation of rail vehicle system using MATLAB Simulink package [61]



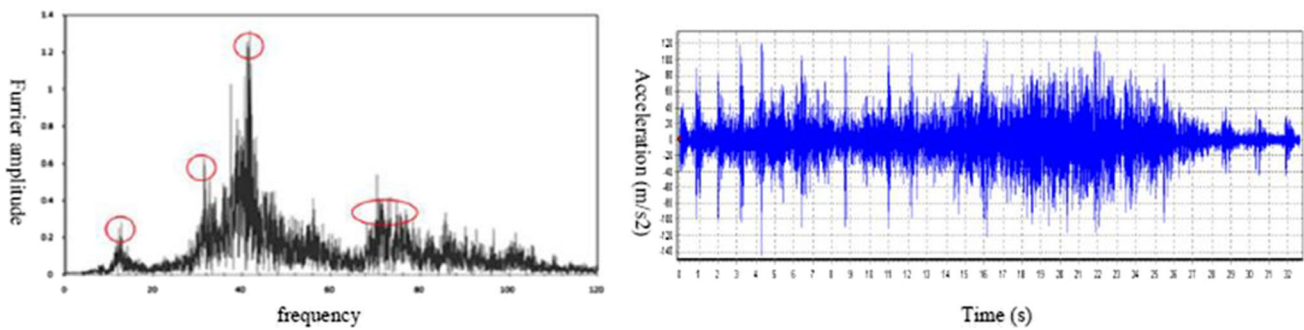
**Fig. 9** Recording of vibration of rail vehicle suspension at a speed of 60 km/h [43]

utilizing ode15s that is a worked in ODE solver in MATLAB. For the subsequent strategy, analytical arrangements are gotten by strategies for the Lindstedt and the harmonic balance systems and it is seen that numerical and analytical solutions found for both methods are in very good agreement.

#### Vibration Response of Rail Road Vehicle using Experimental Method

The oscillatory behavior of a spring-mass system is studied by considering influence of varying spring diameter on elastic constant, damping factor, angular frequency, and the dynamics of the oscillations under simple harmonic motion of spring-mass system. The frequency of oscillation of spring-mass system is found out by attaching a spring at one end, and a load is attached on other end and is freely suspended vertically. The force sensor is used to measure attached load or change in load. An interface is used to transfer signal of oscillation to the computer considering the influence of the damping on the oscillations [42].

Through testing, the dynamic conduct of wheel and rail is assessed. An accelerometer is used to record vibration response of rail vehicle over uneven track during running condition by mounting it at axle box, bogie frame and car body as illustrated in Fig. 9. All right field information is filtered using a MATLAB code, and a sample of time- and frequency-domain filtered outcomes measured on train wheelsets between stations is shown in Fig. 10. The rail irregularities are investigated by comparing measured track forces before and after rail grinding and to find its excitation frequency. Dynamic performance of train suspension systems has been investigated by evaluating natural frequency of primary and secondary suspensions as well as their ability to lessen dynamic forces. The natural frequency of primary suspension system can be gotten by looking at axle and bogie frame acceleration in frequency domain [43]. Nonlinearities of spring and damper are considered while getting ready quarter vehicle model. A FFT analyzer is utilized to acquire acceleration response of sprung mass quarter vehicle model because of street profile. Because of street profile, the deterministic driving



**Fig. 10** Acceleration measured on the wheelset in frequency and time domain [43]

forces are given by harmonic shaker which gives information motion to shock absorber. The sprung mass acceleration response gotten by FFT analyzer for quarter vehicle model is contrasted, and the outcomes are acquired by linear and nonlinear MATLAB Simulink models [44].

Experimental and analytical evaluation of Sperling's ride index and ride comfort analysis of railroad vehicle using finite element model is shown. Track power spectral densities with frequency response are used as system inputs, and random vibration theory is used for assessment. To obtain the dynamic response under normal operating conditions, spectrum results are also acquired at different parts on the coach and bogie of an electrical multiple unit trailer running on a broad gauge track [28]. The numerical model for induced vibration with primary and secondary suspension system of rail vehicle and railway track with rail-pads, sleepers, ballast and background is presented. Railway track is discrete as a finite Timoshenko beam component with 4 degrees of freedom for each node and rotation insignificant axial deformation. The numerical results obtained for mathematical model of train-induced vibration using MATLAB are compared with experimental results taken with the help of series of accelerometers [45].

Track irregularity data are registered by different sensors required for data mining and random track irregularity modeling to show the relationship between the procedure of high-speed trains and the track geometry [46]. Railway vehicle vibrations in vertical direction are constrained by the utilization of customary PID and parameters which are versatile to PID controllers. A parameters adaptive PID controller is designed to control vertical rail vehicle vibration to improve the passenger comfort. Sinusoidal vertical rail misalignment and rail irregularities are measured using fast Fourier transform technique for active vibration control applied to secondary suspension. The outcomes are resolved in time and frequency domain and streamlined by methods for genetic algorithm tool compartment of MATLAB [47]. The vehicle model of Honda Accord car for vehicle suspension is designed to determine

heave and pitch frequencies over a range of road wavelengths to evaluate rigidity and damping parameters for a given road and comfort criterion. An experimental data are acquired with the help of accelerometer and engine rpm recorder equipped on a car, and it is compared with simulation results which are in close agreement [48].

#### Dynamic Analysis using Finite Element Method

An intelligent rail road hybrid vehicle, in particular on its functional aspects and its mechanical behavior, is discussed. The dynamics of the vehicle is modeled and analyzed in the software simulation package ADAMS. A hybrid freight rail road vehicle of 40 tonnes is modeled with 4 axle and generic air suspension spring and analyzed for various speeds of 5–20 m/s for its lateral displacement, roll angle of car body and axle steering angle [49]. The dynamic behavior of a new double deck passenger vehicle designed by China to meet the demands of high-speed railway passenger transportation is presented. A full vehicle model including all nonlinear factors is built in the mechanical software ADAMS/Rail. The results of simulation in the form of lateral and vertical acceleration and ride index are compared with the measured data of field test and simulation results using random equivalent linearization method in frequency domain, to verify the model and determine the track irregularity level. The track irregularity has important effect on the car body acceleration and ride comfort for both straight and curve track case. The effect of suspension positions on dynamic behavior can be studied using this model, to decrease roll motion of the car body and also to improve lateral ride comfort of low floor of the car body [50].

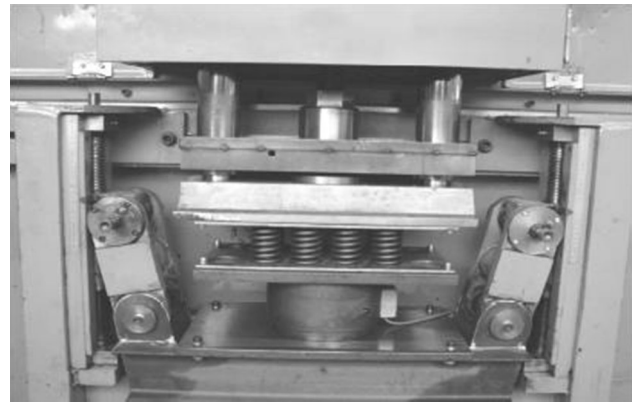
Finite element analysis involves the dynamic analysis of rigid body model which are closer to real systems. Gangadharan et al. [28] presented an FE analysis of rail carried out by considering it as beam on elastic foundations with vertical translation and rotation about lateral axis. The primary and secondary suspensions are displayed as

springs with vertical degrees of freedom if there ought to emerge an event of the vertical model and as springs with vertical and lateral DOF by virtue of the merged vertical and lateral model. The connection examination is completed among vehicle and track for dynamic excitation in the time domain utilizing MSC/NASTRAN. Finite element model of sleeper is utilized for dynamic investigation for its isolation to discover load time narratives. The dynamic practices of railroad vehicle and track have been assessed for different excitation frequencies under various vehicle–track parametric conditions [30]. A finite element method is disclosed to explore train wrecking brought about by harm to suspension frameworks. Nonlinear moving wheel elements, spring-damper elements, and a lumped mass scheme are developed to simulate a moving train with damaged suspension systems to examine the behavior between the train derailment coefficient and the damage ratio of the suspension. Damage of primary or secondary suspension system affects derailment coefficient has little influence by train speed because it is not located at the wheel or rail and can cause cyclic contact problems [51].

### Fatigue Analysis of Suspension Spring

The literature is cited in the area of fatigue analysis of helical compression spring using analytical, experimental and finite element method. The interaction or point contact and tangential creep force between wheel and rail is responsible for the formation of rolling contact fatigue in rails. The analysis has been confined to investigations of the quasi-static behavior of vehicles in curves with the assumption of no geometric imperfection in rail but actually the dynamic response of vehicles also has a significant influence on the rolling contact fatigue behavior [52]. The application of various failure criteria to find fatigue behaviors of mechanical component for its cyclic loading is discussed. The consequences of fatigue tests on an assortment of helical springs with various mean stresses are assessed up to  $10^7$  cycles utilizing Goodman criteria to explore the fatigue properties of helical springs for five diverse wire diameters [53, 60]. The vibration fatigue which is firmly identified with structural dynamics is contemplated which is one of the key pieces of mechanical structure, and for the most part considered in the frequency domain with vibratory loads.

For time-domain estimation, the frequency area can in like manner exhibit by fatigue life estimation, ideal as especially when considered. Fatigue life estimation in the frequency domain can in this way demonstrate beneficial as for time-domain estimation, particularly when thinking about the significant performance gains it offers, regarding numerical computations. Vibration fatigue life is estimated

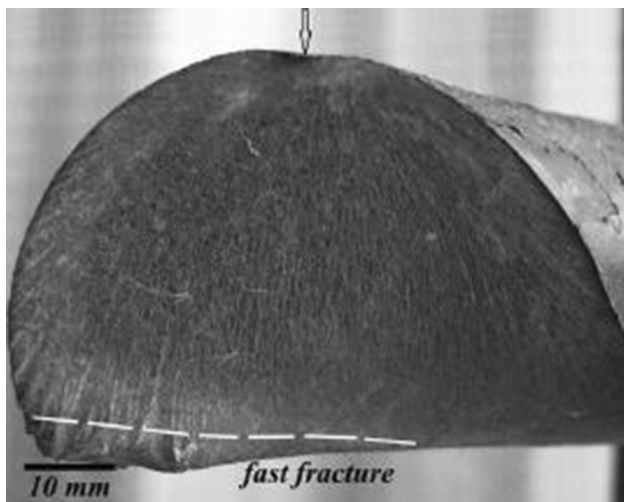


**Fig. 11** Fatigue analysis of helical compression spring using fatigue testing machine [53]

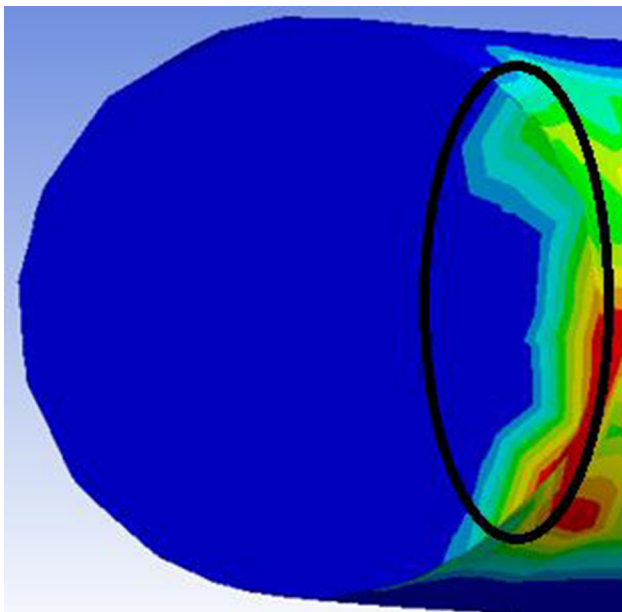
from frequency response which is based on vibration of mechanical system and numerically simulated signals. This examination centers on a correlation of various frequency-domain techniques as for genuine tests [54]. A connection between vertical vibration and fatigue life of spring is read for various street excitations. The fatigue life of coil spring is described by the vertical acceleration are measured by strain signals for various road conditions. The acceleration sign are then utilized as contribution to multibody suspension model for force time history which is utilized for coil spring fatigue life forecast [59].

The use of special purpose fatigue testing machine as shown in Fig. 11 to check fatigue properties of helical compression spring is reported. The results of fatigue tests for variety of helical springs with different mean stresses are obtained on fatigue testing machine and compared with statistically evaluated results [53]. An experimental investigation on a car suspension framework is examined and considered the test signal excitation of various frequencies from 1 Hz to 10 Hz. To quantify the fatigue sign and vibration reaction, the strain gauge and an accelerometer is mounted on the inward surfaces of the coil spring. The strain sign is seen to be straight and comparatively recognized with the responses to the vibration [55].

An analysis of wheel rail rolling contact fatigue using Vampire, ADAMS/Rail and NUCARS to do recreations for a scope of vehicles running on new and worn wheels has been clarified. A rail vehicle model is prepared in ADAMS with the primary suspension having four coil springs on each axle with two vertical dampers and with the secondary suspension having four coil springs, two vertical dampers, two lateral dampers and two yaw dampers. The simulation results reveal that the wheel is oscillating from left to right on the rail, and afterward arrives at a steady position in the bend [52]. The failure of exhaust valve spring of I.C.



**Fig. 12** Fatigue fracture surface of helical spring [60]



**Fig. 13** Fatigue zone of helical spring using FEA

engine for reliability is discussed. An oscillatory displacement occurred during start/stop time of IC engine which is responsible for its fatigue failure. A fatigue analysis of modeled spring is carried out under cyclic loading using simulation tool MSC NASTRAN. An expected life of spring is estimated for the predetermined loads during its operation [56]. The fatigue fracture surface of helical compression spring is shown in Fig. 12. ANSYS is used for fatigue analysis of spring suspension system for cyclic loading to determine its fatigue life. A finite element model for helical compression springs as shown in Fig. 13

subjected to cyclic loads (compression) is developed for fatigue stress analysis. The results are determined for fatigue life of suspension spring and compared with the experimental observations [57, 58].

### Summary and Conclusion

This paper is categorized in three sections, analytical, experimental and finite element method revealing static and dynamic consideration for analysis of helical suspension spring system. A helical compression spring commonly used to absorb shock and vibration causes shear stress in the inside diameter due to twisting by axially applied load. The different stress factors like Wahl's, Bergester's can be used to find shear stresses in the spring. The experimental investigation for shear stress in spring emphasizes use of strain gages in static condition or stiffness of spring can be confined for its static deflection for varying loading condition. Railroad vehicle with primary and secondary suspension system experiences a large deformation in vertical and lateral direction in dynamic condition. The vibration is reduced by primary suspension, and to stabilize, a vehicle secondary suspension is used. The primary suspension causes very high fluctuation due to wheel flatness, track imperfection or irregularities in track by several ways. Hence the natural frequency of rail vehicle predicted in many studies by considering 10–17 degree of freedom for vertical, lateral and rotation motion of rail vehicle system. But for the simplicity to find harmonic response of rail vehicle model 2–4 degree of freedom damped vibration system is also considered. The frequency response of railroad vehicle system computed by software package MATLAB program and Simulink model represents maximum amplitude of displacement, acceleration and power spectrum density. Also mathematical models are also presented to find excitation frequency of railway track by considering infinite beam using Timoshenko beam theory or Euler–Bernoulli beam theory.

The dynamic response wheel rail interaction for rail irregularities is also presented by acquiring an experimental result of track using accelerometer or FFT analyzer for its frequency response. An experimental dynamic response is also presented experimentally for rail vehicle and compared with excitation frequency of railway track. Mainly, it is observed that the excitation frequency is twice of natural frequency of rail vehicle but sometimes it matches with natural frequency and causes a resonance and responsible for failure of rail components. Standard finite elements tools are used for static and dynamic analysis of mechanical components. A structural analysis of helical compression spring to present stress concentration on inside diameter is presented for fixed and rotary surface at

bottom and top of spring, respectively. A static analysis is also presented for one-fourth and one turn coil of spring. Modal and harmonic analysis represents dynamic analysis in FEA tool. The frequency response of dynamic railroad vehicle and railway track is also analyzed in FEA tool like MSC NASTRAN or ANSYS.

The dynamic response of rail vehicle may be responsible for fluctuation of suspension system which causes cyclic response to reduce its fatigue life. Literature presented experimental fatigue analysis of helical spring using fatigue testing machine, but many found its fatigue life using finite element method for the ratio of minimum and maximum force acting on spring. The suspension spring of rail road vehicle is not responsible for large deformation while moving over straight track but responsible while moving over curved track in vertical as well as in lateral direction. The wheel rail interaction also causes wear of wheel and railway track on curvature. Hence, the suspension system is the important part of rail vehicle which gives ride comfort, reduces vibration of bogie and also stabilize a rail body. Hence, the literature discusses a railway vehicle may also derail due to damage to the suspension system.

## References

1. A.A. Shabana, K.E. Zaazaa, H. Sugiyama, *Railroad Vehicle Dynamics: A Computational Approach* (Taylor & Francis Group, CRC Press, New York, 2008)
2. A.H. Wickens, *Fundamentals of Rail Vehicle Dynamics: Guidance And Stability* (Swets and Zeitlinger Publishers, Netherland, 2005)
3. M. Malvezzi, A. Bonnet, C. Cork, R. Karbstein, and P. Presciani, A Numerical Model for the Probabilistic Analysis of Braking Performance in Railways (2006)
4. K. Michalczyk, Analysis of Helical compression spring support influence on its deformation. *Arch. Mech. Eng.* **LVI**(4), 349–362 (2009)
5. K.Y. Maalawi, M.A. Badr, Design optimization of mechanical elements and structures: a review with application. *J. Appl. Sci. Res.* **5**(2), 221–231 (2009)
6. Y. Prawoto, M. Ikeda, S.K. Manville, A. Nishikawa, *Failure Analysis of Automotive Suspension Coil Spring* (ASM International, Yokohama, 2008)
7. V.B. Sood, *Curves For Railways* (Indian Railway Institute of Civil Engineering, Pune, 2009)
8. K. Watanabe, H. Yamamoto, Y. Ito, H. Isobe, and H. Isobe, Simplified Stress Calculation Method for Helical Spring, Tokyo, Japan (2013)
9. Nilmani, Tracking and Curving by Railway Vehicle: Issues in Heavy Haul, Pune, India, IRICEN (2010)
10. S. Wang, S. Lei, J. Zhou, H. Xiao, Mathematical Model for Determination of Strand Twist Angle and Diameter in Stranded-Wire Helical Springs. *J. Mech. Sci. Technol.* **24**(6), 1203–1210 (2010)
11. H. Roy, D. Ghosh, T. Sahoo, A. Shukla, Failure analysis of spring for fuel pump bracket assembly. *Indian J. Eng. and Mater. Sci.* **16**, 33–36 (2009)
12. M.I.Z. Abidin, J. Mahmud, M.J.A. Latif, A. Jumahat, Experimental and numerical investigation of SUP12 steel coil spring. *Proc. Eng.* **68**, 251–257 (2013)
13. N. Takesue, A. Sano, H. Mochiyama, R. Kikuuwe, T. Ishiguro, H. Fujimoto, Analysis and experiment of helical spring-type pressure and shear sensor. *J. Syst. Des. Dyn.* **1**(3), 629–637 (2007)
14. M. Ruzicka, K. Doubrava, Loading regimes and designing helical coiled springs for safe fatigue life. *Res. Agric. Eng.* **51**(2), 50–55 (2005)
15. R. Mirzaeifar, R. DesRoches, A. Yavari, A combined analytical, numerical, and experimental study of shape-memory-alloy helical springs. *Int. J. Solids Struct.* **48**, 611–624 (2011)
16. M. Bakhshesh, M. Bakhshesh, Optimization of steel helical spring by composite spring. *Int. J. Multidiscip. Sci. Eng.* **3**(6), 47–51 (2012)
17. S. Ayadi, E. Hadj-Taieb, Finite element solution of dynamic response of helical spring. *Int. J. Simul. Model* **7**(1), 17–28 (2008)
18. M. Taktak, F. Dammak, S. Abid, M. Haddar, A finite element for dynamic analysis of a cylindrical isotropic helical spring. *J. Mech. Mater. Struct.* **3**(4), 641–658 (2008)
19. D. Thomas, B. Diedrichs, M. Berg, S. Stichel, Dynamics of a high-speed rail vehicle negotiating curves at unsteady crosswind. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **224**, 567–579 (2010)
20. T. Michaleka, J. Zelenkaa, Reduction of lateral forces between the railway vehicle and the track in small-radius curves by means of active elements. *Appl. Comput. Mech.* **5**, 187–196 (2011)
21. K.E. Zaazaa, A.A. Shabana, Study of the lateral stability of railroad vehicle system using the elastic contact approach. *Arab. J. Sci. Eng.* **29**(1C), 3–12 (2004)
22. A. Frikhaa, F. Treysede, P. Cartraud, Effect of axial load on the propagation of elastic waves in helical beams. *Wave Motion* **48**, 83–92 (2011)
23. V. Yildirim, Numerical buckling analysis of cylindrical helical coil spring in a dynamic manner. *Int. J. Eng. Appl. Sci.* **1**(1), 20–32 (2009)
24. S.V. Sorokin, Linear dynamics of elastic helical springs: asymptotic analysis of wave propagation. *Proc. R. Soc.* **465**, 1513–1537 (2009)
25. G.R.M. Mastinu, M. Gobbi, and G.D. Pace, Analytical formulae for the design of a railway vehicle suspension system, in *Proceeding of Institution Mechanical Engineers*, pp. 683–697 (2001)
26. P.M. Jawahar, K.N. Gupta, E. Raghuram, Mathematical modeling for lateral dynamic simulation of a railway vehicle with conventional and unvonventions wheelset. *Math. Comput. Model.* **14**, 989–994 (1990)
27. K. Nishimura, Y. Terumichi, T. Morimura, K. Sogabe, Development of vehicle dynamics simulation for safety analyses of rail vehicles on excited tracks. *J. Comput. Nonlinear Dyn.* **4**, 011001-1–011001-9 (2009)
28. K.V. Gangadharan, C. Sujatha, and V. Ramamurti, Experimental and analytical ride comfort evaluation of a railway coach, in *IMAC-XXII: Conference and Exposition on Structural Dynamics*, India, pp. 1–15 (2004)
29. R.U.A. Uzzal, W. Ahmed, S. Rakheja, Dynamic analysis of railway vehicle-track interactions due to wheel flat with a pitch-plane vehicle model. *J. Mech. Eng.* **39**(2), 86–94 (2008)
30. G. Kumaran, D. Menon, K.K. Nair, Dynamic studies of rail track sleepers in a track structure system. *J. Sound Vib.* **268**, 485–501 (2003)
31. Y.-J. Shen, L. Wang, S.-P. Yang, G.-S. Gao, Nonlinear dynamical analysis and parameters optimization of four semi-active on-off dynamic vibration absorbers. *J. Vib. Control* **19**(1), 143–160 (2012)

32. S.-Y. Lee, Y.-C. Cheng, Nonlinear analysis on hunting stability for high-speed railway vehicle trucks on curved tracks. *J. Vib. Acoust.* **127**, 324–332 (2005)
33. M. Dumitriu, Influence of the longitudinal and lateral suspension damping on the vibration behaviour in the railway vehicles. *Arch. Mech. Eng.* **LXII**(1), 115–140 (2015)
34. V. Kumar, V. Rastogi, Investigation of vertical dynamic behaviour and modelling of a typical indian rail road vehicle through bond graph. *World J. Model. Simul.* **5**(2), 130–138 (2009)
35. T.S. Azoh, W. Nzie, B. Djeumako, B.S. Fotsing, Modeling of train track vibrations for maintenance perspectives: application. *Eur. Sci. J.* **10**(21), 260–275 (2014)
36. D. Sekulic, V. Dedovic, The effect of stiffness and damping of the suspension system elements on the optimization of the vibrational behavior of bus. *Int. J. Traffic Transp. Eng.* **1**(4), 231–244 (2011)
37. J. Lieh, J. Yin, Stability of a flexible wheelset for high speed rail vehicles with constant and varying parameters. *J. Vib. Acoust.* **120**, 997–1002 (1998)
38. D.B.I. Sebesan, Mathematical model for the study of the lateral oscillations of the railway vehicle. *U.P.B. Sci. Bull. Ser. D* **74**(2), 51–66 (2012)
39. K.H. Oostermeijer, A.W.M. Kok, Dynamic behaviour of railway superstructures. *HERON* **45**(1), 25–34 (2000)
40. Y. Chen, B. Zhang, N. Zhang, M. Zheng, A condensation method for the dynamic analysis of vertical vehicle–track interaction considering vehicle flexibility. *J. Vib. Acoust.* **137**, 041010-1–041010-8 (2015)
41. S. Telli, O. Kopmaz, Free vibrations of a mass grounded by linear and nonlinear springs in series. *J. Sound Vib.* **289**, 689–710 (2006)
42. C.A. Triana, F. Fajardo, Experimental study of simple harmonic motion of a spring-mass system as a function of spring diameter. *Revista Brasileira de Ensino de Fisica* **35**(4), 43051–43058 (2013)
43. J.A. Zakeri, M.H. Esmaeili, and M. Shadfar, Field Investigation on the Railway Train and Track Dynamic Interaction (A Case Study in Tehran Subway), in *15th International Conference on Railway Transportation*, Iran, pp. 1–9 (2013)
44. S.P. Chavan, S.H. Sawant, and J.A. Tamboli, Experimental verification of passive quarter car vehicle dynamic system subjected to harmonic road excitation with nonlinear parameters, *IOSR J. Mech. Civ. Eng.* 39–45 (2013)
45. R. Ferreraa, G. Leonardic, F. Jourdanb, Numerical modelling of train induced vibrations. *Proc. Soc. Behav. Sci.* **53**, 155–165 (2012)
46. M. Zhu, X. Cheng, L. Miao, X. Sun, Random field modeling of track irregularity of Beijing-Guangzhou high-speed railway with Karhunen-Loève expansion. *Int. J. Distrib. Sens. Netw.* **11**, 521437 (2015)
47. M. Metin and R. Guclu, Rail vehicle vibrations control using parameters adaptive PID controller, *Math. Probl. Eng.* 1–10 (2014)
48. S. Roy, Z. Liu, Road vehicle suspension and performance evaluation using a two dimensional vehicle model. *Int. J. Veh. Syst. Model. Test.* **3**(1–2), 68–93 (2008)
49. C.H. Verheul and J.J.M. Evers, A railroad hybrid vehicle: dynamic stability analysis, in *7th International Conference on Heavy Vehicle Weights and Dimensions*, Delft, pp. 489–504 (2002)
50. Z. Lu and M. Hecht, Dynamic analysis of new double deck passenger vehicle with Bogie PW200, in *4th ADAMS/rail users' conference*, Utrecht, pp. 1–9 (1999)
51. S.H. Ju, Study of train derailments caused by damage to suspension systems. *J. Comput. Nonlinear Dyn.* **11**, 031008-1–031008-8 (2016)
52. J. Evans and S. Iwnicki, Vehicle dynamics and the wheel/rail interface, Rail Technology Unit, Manchester Metropolitan University, Manchester, United Kingdom (2002)
53. B. Kaiser and C. Berger, Recent Findings to the Fatigue Properties of Helical Spring, Darmstadt, Germany (2010)
54. M. Mrsnik, J. Slavic, M. Boltezar, Frequency-domain methods for a vibration-fatigue-life estimation application to real data. *Int. J. Fatigue* **47**, 8–17 (2013)
55. S. Abdullah, N. Ismail, M.Z. Nuawi, M.Z. Nopiah, A. Ariffin, Study on correlation between strain and vibration signal using hybrid I-Kaz method. *Contin. Mech. Fluids Heat* **6**, 79–88 (2010)
56. S.R. Burgul, A.P. Kulkarni, Fatigue analysis for helical compression spring for determining design alternatives for enhanced life and performance. *Int. J. Technol. Res. Eng.* **2**(7), 1070–1078 (2015)
57. R. Puff, M.G.D. de Bortoli, and R. Bosco Jr, Fatigue analysis of helical suspension springs for reciprocating compressors, in *International Compressor Engineering Conference*, Purdue, pp. 1–8 (2010)
58. J.J. Pharne, R.G. Todkar, N.D. Sangle, Design, analysis and experimental validation for fatigue behavior of a helical compression spring used for a two wheeler horn. *IOSR J. Mech. Civ. Eng.* **11**(6), 5–11 (2014)
59. Y. Kong, D. Schramm, M. Omar, S.M. Haris, S. Abdullah, The significance to establish a durability model for an automotive ride,” *SAE Technical Paper 2017-01-0347* (2017). <https://doi.org/10.4271/2017-01-0347>
60. Y. Zhu, Y. Wang, Y. Huang, Failure analysis of a helical compression spring for a heavy vehicle's suspension system. *Case Stud. Eng. Fail. Anal.* **2**, 169–173 (2014)
61. A. Chudzikiewicz, MATLAB/simulink package as an environment for rail vehicle simulation study, in *International Design Conference—Design*, pp. 1041–1046 (2002)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.