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NUMERICAL INVESTIGATION ON TRAIN-INDUCED ENVIRONMENTAL VIBRATION IN FLOATING LADDER TRACKS

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A floating ladder track is established in the present paper as a next-generation non-ballasted track system. The three-dimensional model consists of a track (mass-spring-damping system) and the underlying soil. Rectangular pulse loading with an amplitude of 60 kN is considered as the wheel loading system. A time domain coupled finite element with a semi-infinite absorbing boundary condition is employed using FEM software. Due to axial symmetry of the model instead of the track axle, only half of the model is simulated. It is observed that the performance of the floating ladder track is better in mitigating measured vibration than that of the traditional ballasted track. Numerical results of the floating ladder track reveal that the increase of damping and stiffness yields more vibration responses, which is a straight nonlinear relationship. Although increasing density of the protective layer decreases vibrations on the ground, it has no effect on structural components of the track except for the protective layer. Furthermore, this kind of track is more effective at a closer distance to the source of vibrations.

Keywords: track dynamics, floating ladder track, traditional ballast track, train induced vibration

1. Introduction

Railway induced vibrations are ones among the most important concerns of railway systems. Waves generated by the dynamic interaction between the train and the track (Zakeri *et al.*, 2016b; Solonenko *et al.*, 2017) propagate from surrounding soils to adjacent buildings, resulting in structural vibrations. Although there are several methods to mitigate train-induced vibrations (Esmaeili *et al.*, 2014; Zakeri *et al.*, 2016a; Mosayebi *et al.*, 2017), in order to reduce vibration effects to an acceptable level, a floating slab track can be used in railway systems. A review of the available literature illustrates that there are several numerical, analytical and experimental studies on the dynamic behavior of floating ladder tracks.

Cui and Chew (2000) developed a receptance method to investigate the behavior of a floating slab track system with both stationary and moving harmonic loads. Later on, in 2004, Okuda conducted a research on a floating ladder track under impulsive load due to the wheel flat. The effectiveness of the floating slab system has been assessed in several investigations. Auersch (2012) employed a dynamic model to assess the effectiveness of the floating slab track system in vibration reduction. Hussein and Hunt (2006) developed floating slab tracks on rigid foundations using the Euler-Bernoulli beam to evaluate some vibrational concepts of such a system. Later, they developed a new approach, the so called pipe-in-pipe, to simulate floating slab tracks with discontinuous slabs in underground railway tunnels (Hussein and Hunt, 2009). The Euler-Bernoulli beam was used in another study to investigate the response of the system due to a steadily moving load. The fourth-order Runge-Kutta method was deployed by Kuo to study the behavior of a floating slab track (Kuo *et al.*, 2008). An analytical dynamic model was employed to assess vibration characteristics and effectiveness of the floating slab system. Furthermore, the effects of bending resonances of the floating slab system were evaluated in the literature. For this aim, a comparison was made between the performance of several vibration isolation systems including medium and short length floating slabs and floating ladders (Hui and Ng, 2009). The evaluation of the vibration isolation performance of continuous and discontinuous floating slab tracks was presented by Gupta and Degrande (2010). Vibration of a discrete and continuous system under constant moving loads was studied by Kumaniecka and Prącik (2015). Moreover, the effect of load velocity and load frequency was assessed through analytical solutions by Mohammadzadeh and Mehrali (2017). The aforementioned works were based on analytical models for prediction of railway induced vibrations in floating ladder tracks.

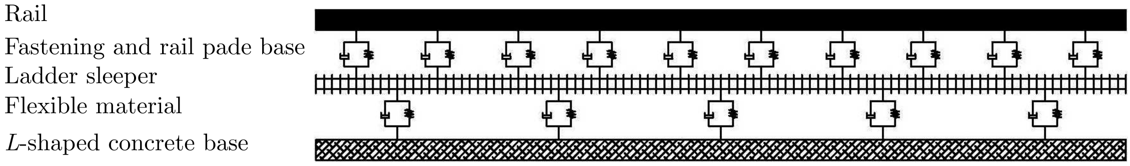
In addition, there are few researches which evaluated the performance of the floating ladder track experimentally. A field test was carried out by Xia *et al.* (2010) to compare the response of the floating ladder track and the common slab track in a bridge. They demonstrated that vibration decreased significantly in the ladder track system. Most recently, several in situ experiments (Ma *et al.*, 2017) have been performed to assess the performance of the floating ladder track.

A review of the literature reveals that there are limited numerical investigations regarding the effectiveness of the floating ladder track. Lombaert *et al.* (2006) used a three-dimensional (3D) numerical model to evaluate railway induced vibrations. Li and Wu (2008) developed several track models to determine the vibration isolation performance of the floating slab track. An innovative idea of using recycled rubber is available in the literature dealing with the behavior of the floating slab track (Jin *et al.*, 2017). The behavior of the floating slab track was optimized using the numerical optimization method, called the multipoint approximation method, and also using a genetic algorithm-based approach (Yan *et al.*, 2014). The dynamic behavior of these types of tracks was also discovered in previous studies (Jee *et al.*, 2018; Wei *et al.*, 2018).

As indicated above, most of the studies carried out on the dynamic behavior of the floating ladder track are based on analytical methods and no numerical investigations were performed on the effect of the floating ladder track on track components, which is fully addressed in this paper. Furthermore, there is a dearth of study on the finite element model of train track interactions. Therefore, a finite element model has to be presented to investigate train track interactions as well as the behavior of the structure. Moreover, most of the previous parametric studies investigated mitigation of vibration for a constant and specific harmonic load frequency, and only a few examined train-induced vibrations, which also considered a static load system. In the present study, the model is under an impact and moving load of the train at a speed of 180 km/h, and the load history is defined for nodes 0.1 m apart. On the other hand, it is necessary to investigate random behavior of slab tracks using numerical methods, due to random behavior of the subgrade and loading system of the wagon. In fact, in this method, the random behavior of the slab track can be evaluated using a closed form solution.

2. Development of a three-dimensional (3D) model for ladder and ballasted tracks

In this study, a 3D model of the railroad track has been developed using the ABAQUS software. The proposed model in this study is based on data given by Zoccali *et al.* (2015), which is also calibrated based on previous researches. In the current study, the induced vibrations are recorded on the ground surface and structural components of the track by applying appropriate dynamic boundary conditions and loading systems. The model is investigated using implicit dynamic analysis, which is categorically stable. Each component is tied to the underneath component, e.g. rails and springs are moving as a uniform structure. Since the ladder track consists of two concrete sleepers, these sleepers are connected by transverse steel pipe connectors at an interval of 2.5 m, which are made of a thick-walled pipe and prevent horizontal displacements. Furthermore, resilient and cushioning materials are applied to prevent longitudinal and transverse movement. A two-dimensional view of the floating ladder track is outlined in Fig. 1. As presented, the rail is laid on the ladder sleepers which are considered to be a uniform distributed mass and the fasteners which are considered to be discrete distributed massless springs with 0.625 meter spacing. Both the rail and ladder sleepers are modeled by solid elements. A resilient material is considered between the ladder sleepers and the concrete base, which is discretely distributed on each 1.25 m. More details of the model are addressed in the reference (Zoccali *et al.*, 2015; Ebrahimi, 2017).



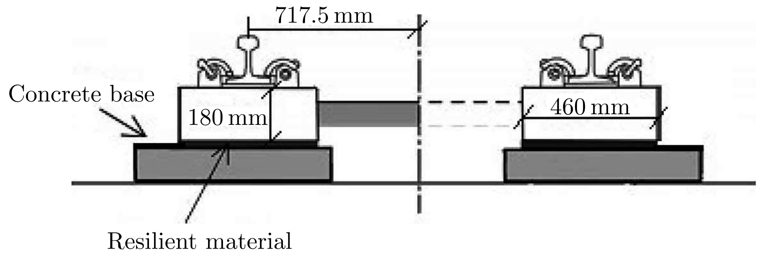


Fig. 1. The selected floating ladder track for analysis with geometrical dimensions

The developed model is a section of a high-speed track with the dimension of 50, 40 and 30 m in length Z, width X and height Y, respectively. As shown in Fig. 2, the proposed model is symmetric with respect to the plane perpendicular to the railway track axis (Z axis). For the sake of simplicity, the rail section is assumed to be I shape and uniform. Rectangular rail pads are tied to the rails and the floating ladder. The floating ladder is connected to the rectangular concrete base by a spring. In this study, the soil is considered as homogeneous, elastic and isotropic. In order to model a half-space system in a finite-element software, viscous boundary conditions are applied to the model. For this aim, semi-infinite elements with absorbing boundary conditions are considered for surrounding soil boundaries except for the symmetric plane where any movement is restricted along the x-direction. The boundary conditions are applied by using vertical and shear dampers. All components of the model are meshed by 8-node hexahedral elements. Rail elements are modeled with 3D wire elements with length of 10 m. The ladder sleeper is modeled by 3D solid elements. Lengths of these elements are not constant due to non-uniform partition. Soil elements are made by 3D solid elements as well. The elements dimensions in x, y and z-direction are determined as follows.

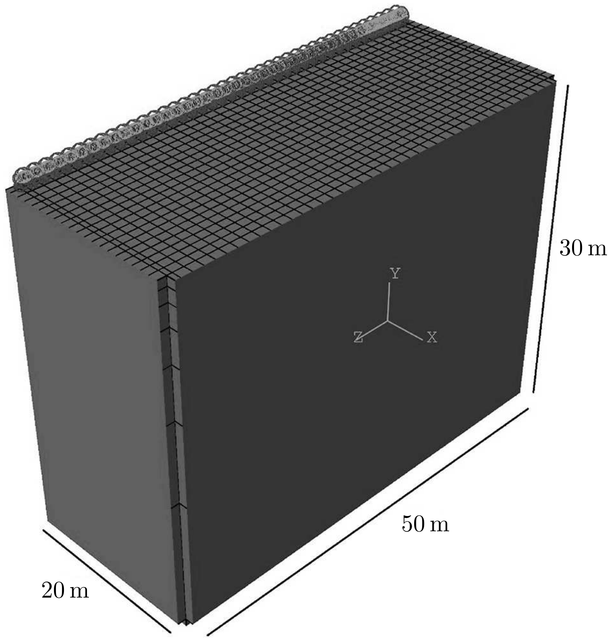


Fig. 2. The 3D model of the selected track with real dimensions and the FEM generated mesh

In the y-direction, it has been decreased downward. On the ground surface, because it is significant, a smaller mesh is applied. In the x-direction, the element size is calculated based on the wavelength

$$L_e = \frac{\lambda_w}{n} \tag{2.1}$$

where λ_w represents the wavelength and n represents the time step which generally is in a range of 10 to 15. In the z-direction, it is considered to be 1.25 m. The rail pads are modeled by 3D solid elements and an area of $25 \times 25\,\mathrm{cm}^2$ and thickness of 2 cm. The spring stiffness is considered to be $2.5 \cdot 10^7$ N/m. Also, the dashpots coefficient is 10000.

3. Validation of the model

The performance is validated from a comparison of the current model with the results reported by Zoccali *et al.* (2015). The geometric and mechanical characteristics of the ballasted track are presented in Table 1. For the evaluation and validation of the obtained results, the model is compared to the reference model. According to Fig. 3b, eight points (a-h) are considered in the middle of the model, on the surface of the ground, in a direction perpendicular to the railway track axis and 1 m apart. The distance between the points and edges of the finite element model is 25 m. The locations of the points are presented in Fig. 3a.

The peak particle velocity generated by the passing of trains is investigated for the points considered on the ground surface and in three directions; in the direction perpendicular to the ground surface (Y), in the direction of wave propagation (X) and in the direction perpendicular to propagation of waves (Z). As can be observed in Fig. 3b, the results are consistent with the results of the reference model and show a highly good agreement with them.

Table 1. Geometric and mechanical properties of the track (Zoccali *et al.*, 2015)

Layer	Density [kg/m^3]	Elasticity modulus [Pa]	Poisson ratio	Thickness [m]
Rail	7850	2.07e11	0.28	–
Rail pad	–	2.49e8	0.25	0.01
Concrete sleepers	2400	3e10	0.2	0.2
Ballast	1250	1.3e8	0.3	0.35
Sub-ballast	2200	6e9	0.4	0.12
Protective layer	2000	1.6e8	0.45	0.3
Soil	2000	6e7	0.3	30

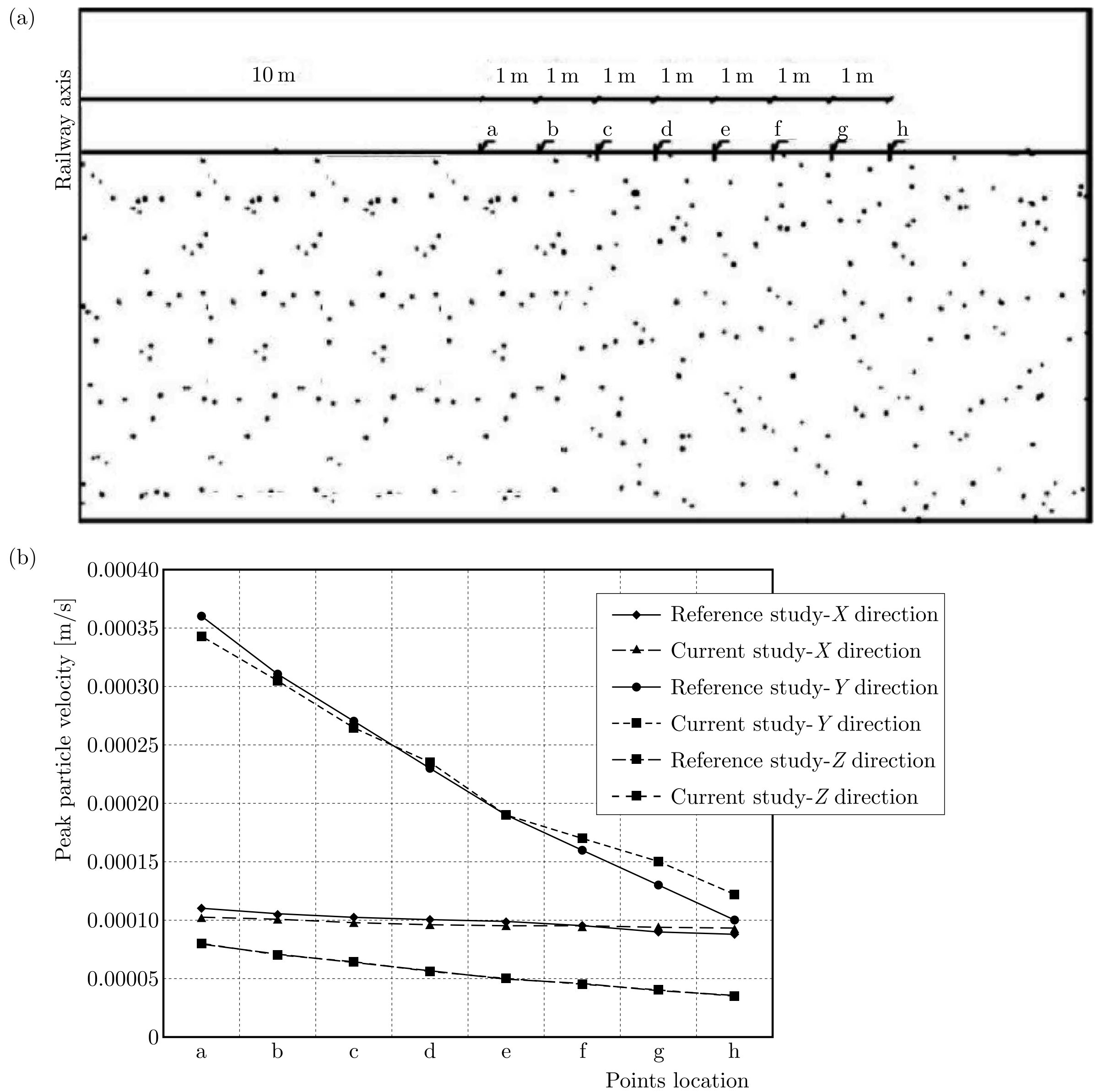


Fig. 3. (a) Locations of the points in the model; (b) the maximum vibration velocity (at the case study points) of the soil particle on the ground surface in the three directions X and Y, Z

4. Comparison of responses obtained from several types of railway tracks

A comparison is made between the ballasted track, the floating ballasted track and the floating ladder track to evaluate the maximum acceleration generated due to the passing of high-speed trains. The properties of materials used in all three types of tracks are assumed to be the same. The mechanical properties of the damper and pipes are given in Table 2. Moreover, the length of floating slabs is considered to be 6.25 m.

Table 2. Mechanical and dynamic characteristics of dampers and pipes

Material	Moment of inertia [m^4]	Elasticity modulus [Pa]	Poisson ratio	Stiffness [N/m]	Damping [Ns/m]
Damper	–	–	–	25E+6	1E+4
Pipes	6.32E-6	4E+10	0.17	–	–

As specified, the floating ladder track induces the lowest value of maximum acceleration in a 1 to 3 m distance from the track axis. However, the performance of all three types is the same in far distances from the track axis. The following trend can be observed in intervals of 3 m and more. All the graphs are presented at the maximum distances of 4 m from the track axis. Moreover, it can be noted that the performance of the floating ballasted traditional track is more effective than that of the traditional ballasted track.

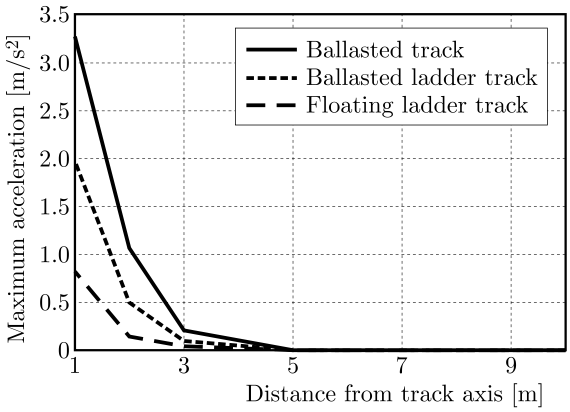


Fig. 4. Comparison of the maximum acceleration obtained in different track types versus distances from the track axis

5. Investigation of the effect of dynamic behavior of the floating ladder track

The dynamic behavior of the floating track is studied on both the ground surface and the track components. As shown in Table 3, several variables are taken into account as the inputs. The effects of the stiffness K and damping ratio of the damper C, train speed V, and train load F along with the effect of density of the lean concrete ρ are evaluated on the soil and track components, separately. For this aim, several types of models are developed to examine the variation of different parameters. According to Table 3, 20 unique models are established to be compared with the reference model. In this table, FLS represents the reference floating ladder sleeper.

Table 3. Characteristics of the models for evaluation of the floating ladder track

Model	Stiffness of damper K [MN/m]	Damping ratio of damper C [MN/m]	Train speed V [km/h]	Axial load F [kN]	Density of lean concrete ρ [kg/m^3]
FLS	25	10	180	120	1500
FLS-K 0.5	12.5	10	180	120	1500
FLS-K 0.75	18.75	10	180	120	1500
FLS-K 1.25	31.25	10	180	120	1500
FLS-K 1.6	40	10	180	120	1500
FLS-K 2	50	10	180	120	1500
FLS-C 0.5	25	5	180	120	1500
FLS-C 0.75	25	7.5	180	120	1500
FLS-C 1.25	25	12.5	180	120	1500
FLS-C 1.6	25	16	180	120	1500
FLS-C 2	25	20	180	120	1500
FLS-V 120	25	10	120	120	1500
FLS-V 150	25	10	150	120	1500
FLS-V 240	25	10	240	120	1500
FLS-V 280	25	10	280	120	1500
FLS-V 320	25	10	320	120	1500
FLS-F 120	25	10	180	240	1500
FLS-F 30	25	10	180	60	1500
FLS-ρ 2000	25	10	180	120	2000
FLS-ρ 3000	25	10	180	120	3000

5.1. Study on the dynamic behavior of the track components

5.1.1. The effect of damper stiffness

As expected, with increasing stiffness, the induced vibrations increase. That is, since the stiffness of the damper increases, as a result, more forces are absorbed by the damper, and thes forces are transferred to the underneath soil and, consequently, more vibrations are received by the soil. Considering that the damping ratio is assumed to be approximately 5%, different trends are observed in the results. It appears that at distances far from the track axis, the maximum value of acceleration is more logical.

5.1.2. The effect of damping ratio of the damper

The maximum acceleration indicator represents a consistent increase in vibrations with the increasing damping level of the damper. It is necessary to note that the percentage of reduction or increase in vibrations due to the influence of increasing or decreasing the number of dampers or any other factor, is not measurable, and only the decreasing or increasing trend of vibrations due to the variation of the parameters can be determined.

5.1.3. The effect of train speed

Given a significant change in the maximum acceleration at the speed of 150 km/h, it can be realized that at this speed the phenomenon of resonance occurs, which causes a considerable change at the distance of 1 m to 2 m from the track axis. In this range, attenuation by about 87% of the maximum acceleration is observed. This value is reduced to approximately 50% at other

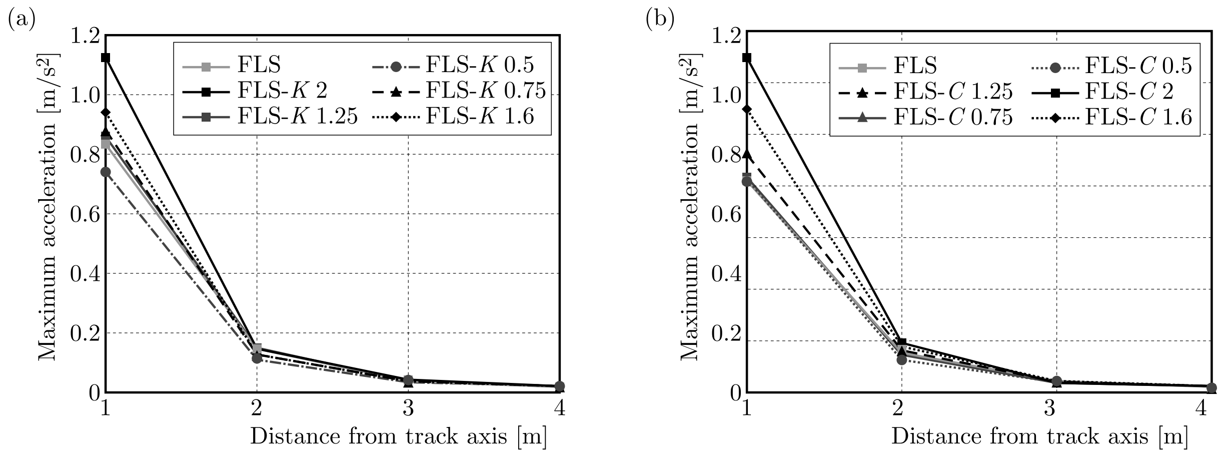


Fig. 5. Comparison of the maximum acceleration due to variation of damper stiffness (a) and damping ratio of the damper (b) versus different distances from the track axis

speeds in the same range. By comparing the rest of the speeds, it can be found that in floating ladder tracks, shifting in velocity, except at the distance of 1 m to 2 m from the track axis, does not have much effect on vibrations, and even is less effective than the vibration induced by traditional ballasted tracks.

5.1.4. The effect of axial load

As shown in Fig. 6b, due to a change in the wheel load, vibrations on the soil surface are considerably reduced. The major reduction is observed at the distance of 1 m to 2 m from the track axis, where up to 82% of the maximum acceleration decreases. Moreover, 78% and 80% of attenuation is achieved for the axial loads of 60 kN and 30 kN, respectively. Moreover, by increasing the distance from the track axis, the effect of axial load on the vibrations remains insignificant. Obviously, the axial load is not an effective factor on both near and far field vibrations.

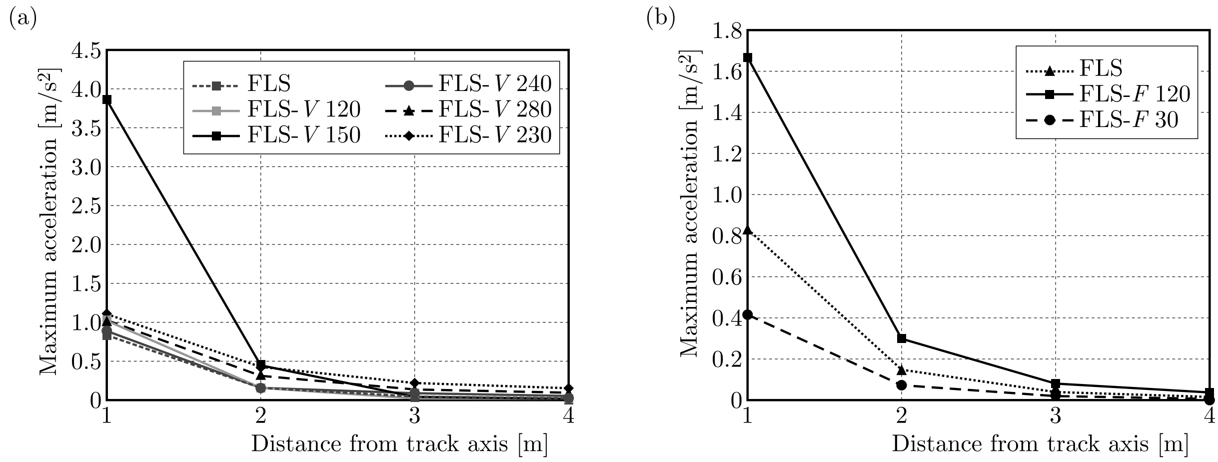


Fig. 6. Comparison of the maximum acceleration due to different train speeds (a) and axial load (b) versus different distances from the track axis

5.1.5. The effect of density of the protective layer (the lean concrete)

As designated, at the distance of 1 m to 2 m from the track axis, with the increasing density of the protective layer (the lean concrete), the vibrations on the soil surface are reduced. However, the declivity of all three diagrams is approximately equal, where the maximum acceleration decreases by about 83%. This value decreases to 73% at the distance of 2 m to 3 m, which is still considerable. As a result, it can be concluded that density of the lean concrete cannot be considered as an effective parameter.

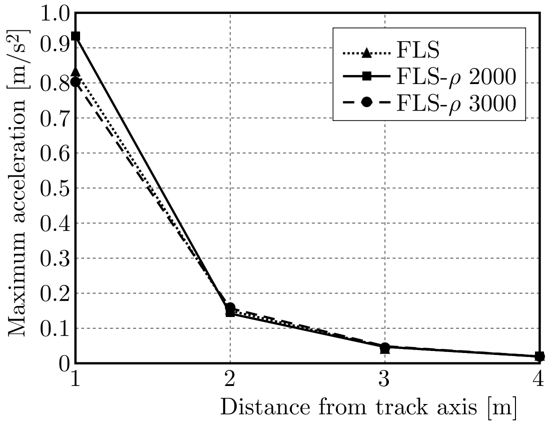


Fig. 7. Comparison of the maximum acceleration obtained for different density of the lean concrete versus distances from the track axis

5.2. Study on the dynamic behavior of the track components

To investigate the effect of vibration on the track components, it should be evaluated whether the measurements need to be made in the middle of the track, which is the gap between the blocks 4 and 5, or in the middle of a single block. In this paper, since the transmitted vibrations on the soil are measured in the middle of the track, and the aim is simply to increase or decrease vibration by the effect of increasing or decreasing the values of the variables, the measurements for the track components are also performed in the middle of the track.

5.2.1. The rail

As illustrated in Table 4, in order to investigate the dynamic behavior of the rail, the maximum value of acceleration is obtained at a fixed point in the center of the rail, and the results are compared to those of the reference model. The values of the acceleration are only significantly changed in one of the models. This value changes because of the influence of train speed, which is a typical factor in generating vibrations in railway systems. Moreover, as discussed earlier, a resonant phenomenon occurs due to the passing of trains with different speeds.

5.2.2. The ladder sleeper

In order to evaluate the dynamic behavior of the ladder sleeper, a fixed point is considered on the sleeper, which corresponds to the points measured on the rails and the ground. Several models are presented in Table 4. A comparison is made between the proposed and reference model. The effect of changing the damping ratio and stiffness of the damper as well as the protective layer density on the ladder sleeper similar to the rail is not considerable. It only changes due to variation in characteristics of trains, such as wheel load and speed and, as expected, there is an ascending linear relationship between the axial load and generated vibrations.

Table 4. Comparison of the obtained results with those of the reference model

Model	Max acceleration with respect to reference model [%]		
	Rail	Ladder sleeper	Protective layer
FLS	0	0	0
FLS-K 0.5	0	1.4	−4.2
FLS-K 0.75	0	0.8	−2.4
FLS-K 1.25	0	−0.9	3.3
FLS-K 1.6	0	−2	8
FLS-K 2	0	−3.1	13.8
FLS-C 0.5	0	−0.4	−40.9
FLS-C 0.75	0	−0.3	−20
FLS-C 1.25	0	0.3	19.2
FLS-C 1.6	0	0.6	45
FLS-C 2	0	1	72.9
FLS-V 120	−33.1	−40.6	−24.2
FLS-V 150	80.1	47.4	35.7
FLS-V 240	−60.7	−34.9	−7.5
FLS-V 280	−52.1	−53.9	−43.6
FLS-V 320	−41	−53.7	−7.8
FLS-F 120	100	100	100
FLS-F 30	−50	−50	−50
FLS-ρ 52000	0	0	121.4
FLS-ρ 53000	0	0	−25.4

5.2.3. The protective layer

The same pattern, as discussed previously, is used for comparison of the proposed models. As shown in Table 4, by increasing the stiffness and damping ratio of the dampers, vibrations induced by the passing of trains are increased while there is an inverse relationship between density of the protective layer and vibrations; that is, the vibrations raise with the increasing density. Consequently, it can be concluded that the performance of the protective layer due to variation of the train speed or axial load is the same as that of the ground, as discussed earlier in details.

With the objective of comparing variations for various parameters, the results obtained for a specific indicator are plotted, and then by comparing the fitting trend line slopes, one can assess the variables. With respect to Fig. 8, at far distances, the effect of stiffness and damping ratio of the damper as well as the effect of density of the protective layer decrease, which has already been explained. In addition, by comparing the presented diagrams at a distance of 1 m from the track axis, the slope of the trend line for stiffness, damping ratio and protective layer density graphs is 0.073, 0.1137 and 0.078, respectively. That is, to optimize the results in the same conditions, the damping ratio of the damper is the first choice to change the results. Given that this is a numerical analysis, a more detailed analysis should be carried out from the operational or economic point of view. There is a straight linear relationship between the effect of train speed and axial load with induced vibrations. As the speed of the train increases, vibration increases as well, unless at a frequency equal to the natural frequency of the structure, which causes the resonant phenomenon. In general, it is important to note that at the same speed, the floating ladder track is more efficient than traditional tracks in terms of the ride quality index.

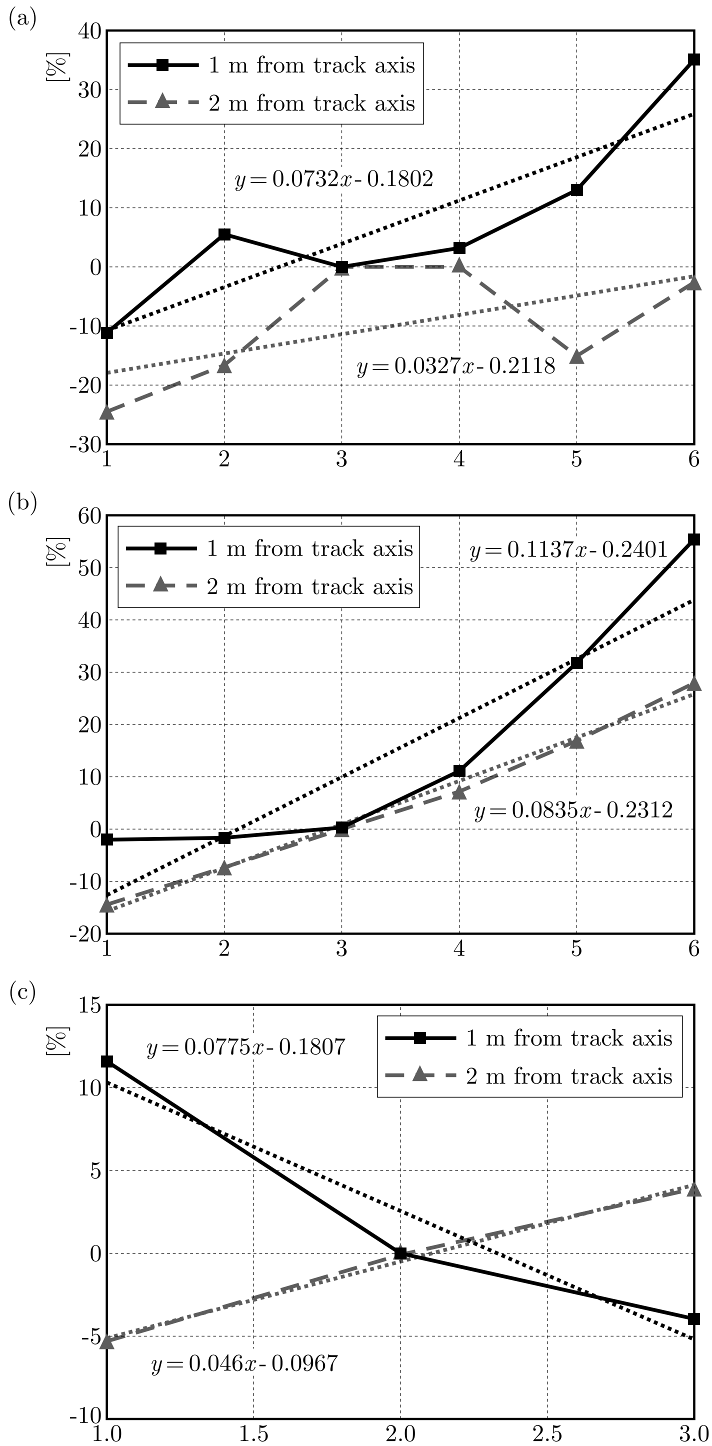


Fig. 8. The change trend of the vertical acceleration versus: (a) damper stiffness, (b) damping ratio of the damper, (c) protective layer density

6. Conclusion

In this study, the ballasted track model is simulated according to specifications and parameters provided by the previous researchers, and the accuracy of the model is evaluated according to the model developed by Zoccali *et al.* (2015). Comparison of the results indicates a good agreement with those of the reference model. Afterwards, a parametric study is conducted to evaluate the behavior of the floating ladder track. Then, the floating ladder track is simulated and, subsequently, the stiffness and damping ratio of the damper, density of the lean concrete, train speed and axial load are taken into account for analysis. The effects of these variables on the rail, sleeper, ground and protective layers are investigated. More generally, these basic findings are consistent with the research, showing that there is a straight nonlinear relationship between damper stiffness and induced vibrations on the ground. That is, with an increase in the damper stiffness, more vibrations propagate on the ground surface and the protective layer, and this value is reduced as damper stiffness decreases. However, the increase in vibrations on the ground is slightly higher due to the increase in damping ratio of the damper. Increasing the density of the protective layer reduces vibrations on the soil and has no effect on the structural components of the track. That is, with a decrease of density of the protective layer, growth in transmitted vibrations on this layer is observed. Accordingly, the train load is assumed as an impact load, and the amount of increase or decrease in the wheel load is entirely correlated with the increase or decrease of vibrations on the track. In addition, the current floating ladder track model at a speed of 150 m/h yields a resonance. At speeds above 200 km/h, as the train travels faster, vibrations on the ground and the components of the track structure increase.

Despite considerable research on the floating ladder track, more investigations can be carried out on the influence of fastening systems, optimization of the floating ladder track taking into the account various components simultaneously. Consideration of the resonant frequency range in different models will lead to a significant reduction of transmitted vibrations to adjacent structures.

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