Numerical analysis of long-haul structure laying on nonlinear foundation subjected to moving load

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Abstract. The article deals with a long structure laying on nonlinear foundation subjected to moving load. Such problems often arise due to design of an upper-track structure in railroad engineering, specifically due to design of floating slab track structures in tunnels. The design procedure aims at calculating static and dynamic parameters of a floating slab track structure, that consist of reinforced concrete track slab and a number of nonlinear-elastic elastomeric pads, that supports the track slab. In order to get detailed analysis of the floating slab track structure, the analysis is performed using FE-model in MSC Patran/Nastran software package. FE-model includes rails, railway fastenings, track slab, elastomeric pads and supports. The results of the static analysis are the deflections of the upper-track structure and stress-strain state of the floating slab. The results of the dynamic analysis include transfer-function of the floating slab and evaluation of insertion loss under excitation frequencies of moving trains over different speed.

1. Introduction

The dynamic interaction between the train and the upper-track structure produces vibration that spreads through the ground to the buildings adjacent to railway or underground railway lines [1, 2] and disturb the inhabitants [3, 4] or even damage the load-bearing structures [5, 6]. Floating slab track (FST) is a popular approach used to reduce vibration transmitted from the railway line into the surrounding soil and thence into nearby buildings. Figure 1 shows the typical arrangement of an underground railway line using FST.

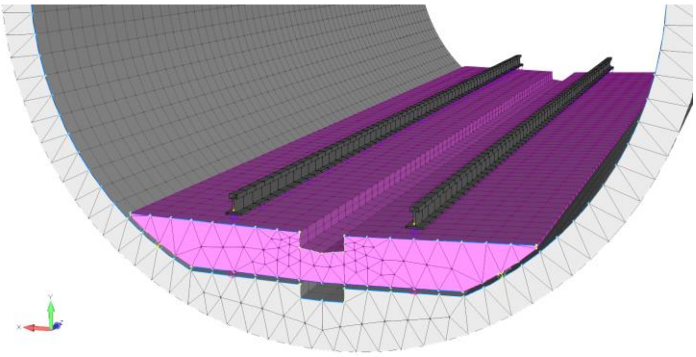

Figure 1. Finite element model of a FST in tunnel.

The rails are fixed directly to a massive reinforced concrete slab by means of elastic railway fastenings, which provide protection to the concrete as well as some reduction in noise produced [7]. The slab is mounted on resilient elements (rubber or elastomeric bearings or even steel springs – according to SP 23-105-2004 [8]) to isolate the track from the tunnel invert or the ballast bed.

There are many types of floating slabs built recently and thoroughly described in [8]. FST systems in Moscow underground are used since 1977 [9], where a massive slab is supported by rubber bearings or by steel springs (“Mejdunarodnaja” metro station).

The wheel-to-rail interaction provides vibration due to out of balance forces and disturbances from the driving system, the frequency of wheels passing over a rail support point end, impact forces on rail joints and unevenness of the rail profile [10 – 12]. The major portion of the vibration energy is known to be concentrated at low frequencies from 15 to 200 Hz [10]. Using elastic railway pads can have some benefit on high-frequency noise, can provide good protection against impact forces and smooth the rail deflections, but no adequate isolation can be obtained at low frequencies. The main function of a FST is to provide low frequency vibration isolation system with its fundamental system frequency between 7 and 17 Hz depending on required efficiency. According to the well-known equation for SDOF system fundamental frequency, the mass of a floating slab should be as great as possible (from 4 up to 12 t/m), the stiffness of the supports designed according to the required vibration isolation efficiency. However, the effectiveness of vibration attenuation of early-built floating slabs does not compare well with the design values, obtained from single-degree-of-freedom (SDOF) model, typically used in design of these tracks. The research reported in this paper uses models of infinite length to investigate the performance of FST and FE models to thoroughly investigate its stress-strain state.

2. Analytical model

The analytical model for the FST can be considered as a double Euler-Bernoulli beam resting on Winkler foundation, depicted in Figure 2. Consider that the train speed is much smaller than the wave speed of vibrations transmitted down the rail and slab. Using this assumption, the Euler-Bernoulli formulation for the beams was chosen instead of the Timoshenko one [13]. Both the rail and a slab are modelled as an individual beam, whether the railway pads and the elastic bearing are modelled as a point springs with equivalent dynamic stiffness. The influence of the wheel axle moving at a speed v is modelled as a point force F(t) excited at a law that accounts for rail irregularities.

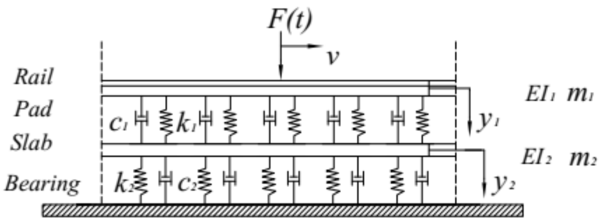

Figure 2. Design scheme for the floating slab track.

The equation for rail and track slab oscillation is as follows:

$$\begin{aligned} &EI_1\frac{\partial^4 y_1}{\partial x^4}+m_1\frac{\partial^2 y_1}{\partial x^2}+k_1\left(y_1-y_2\right)+c_1\left(\frac{\partial y_1}{\partial t}-\frac{\partial y_2}{\partial t}\right)=F\left(x,t\right) \\ &EI_2\frac{\partial^4 y_2}{\partial x^4}+m_2\frac{\partial^2 y_2}{\partial x^2}+k_2 y_2-k_1\left(y_1-y_2\right)+c_2\frac{\partial y_2}{\partial t}-c_1\left(\frac{\partial y_1}{\partial t}-\frac{\partial y_2}{\partial t}\right)=0 \end{aligned}, \quad (1)$$

where EI_1, EI_2 are bending stiffness of rail and slab; m_1, m_2 is the weight of rail and slab; k_1, k_2 are stiffness of railway pads and elastomeric pads; c_1, c_2 are damping in railway pads and elastomeric pads; $F\left(x,t\right)=e^{i\omega t}\delta\left(x-vt\right)$ is train excitation.

3. Numerical model

In order to get a deeper insight into the FST behaviour, the FE model was created in MSC Patran/Nastran commercial software package, depicted in Figure 1. The model consists of the rails, simulated using 1-D beam elements, intermediate railway fastenings, simulated using spring elements, reinforced concrete slab, simulated using 2-D plate or 3-D solid elements and resilient elements simulated using nonlinear grounded spring elements.

3.1. Resilient elements

The dynamic behaviour of the FST system is dominated by the dynamic properties of the resilient elements used to support the track slab. Metal steel springs have a linear dependence between the load and deflection in a wide frequency range of external excitation, which doesn't depend on the load level. However, due to high investment costs of such bearings and maintenance problems due to fatigue and corrosion, rubberlike elastomeric materials are widely used.

It is known [14], that the most important parameter which describes the quality of a resilient element, made of natural or artificial rubber, is the ratio between its static k_{stat} and dynamic k_{dyn} stiffness. The ratio of k_{dyn}:k_{stat} for rubber materials lies between 1,50 – 2,50, whether PUR-bearings (like Sylomer or Sylodyn made by "Getzner") make it possible to limit the increase of stiffness due to dynamic loading by a factor of 1,30 [14, 15].

Proper representation of resilient elements viscoelastic properties taking into account its frequency, load dependency, should provide an accurate and reliable design model. There exist different methods to simulate elastomeric material behaviour. First one is to apply complicated material models like Yeoh [16] or Mooney-Rivlin [17]. The second one is to use equivalent elastic or viscous properties of such materials and include them into simplified, e.g. one-dimensional Kelvin-Voight models [18]. Although those approaches sometimes provide reliable results, they are not as robust and need a lot of additional experimental data to fit the model.

The approach used in this paper was to test the materials used for resilient elements and use that experimental curve as a stiffness parameter for nonlinear spring element in the floating slab FE-model.

Dynamic material tests were performed according to GOST ISO 10846-2 on a test rig, with a MTS hydraulic actuator, capable of providing 250 kN of axial force at a frequency up to 100 Hz. Test set-up is plotted in Figure 3 (a).

(a) (b)

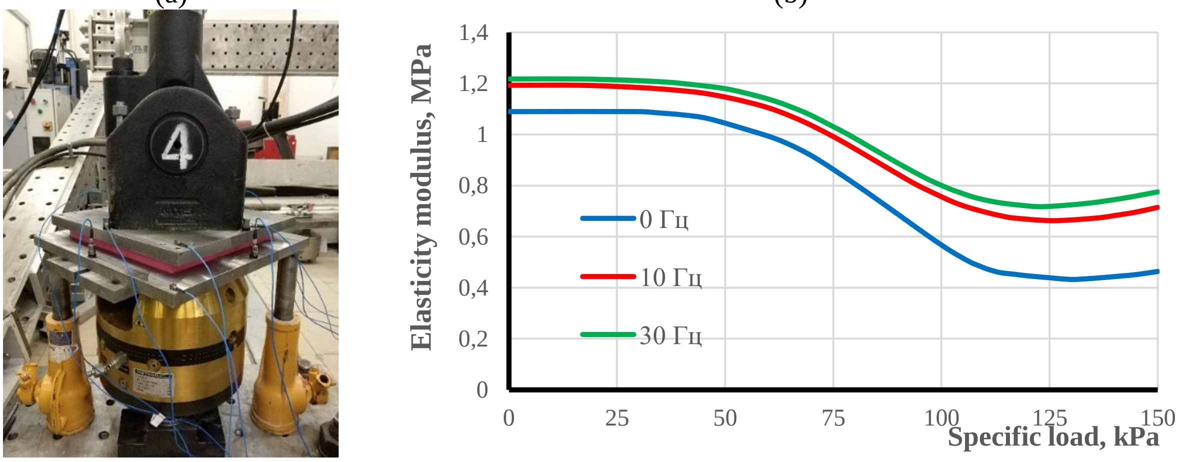

Figure 3. Test arrangement to get material data (a). Results (b).

The tests provide us with an elasticity modulus values at 0 (static), 10 and 30 Hz, shown in Figure 3 (b). The resilient element static and dynamic stiffness was further obtained from the test data and used in FE-model.

3.2. Railway fastenings

The rail fastenings must permanently hold down the rail firmly, ensuring at the same time resilience of the track in the upward direction, and good lateral stability. The elastic downward pressure is essential for the smooth control of the rail's upward movement and high creep resistance. In an elastic rail fastening the screws are tightened so that an initial tension is developed via the elastic clip or the spring washers. this initial tension maintains the influence of the force on the fastening, even if the spring is pressed in farther due to the wheel load. The result is a fastening which is permanently effective under the influence of different forces. The force takes a pulsating course fluctuating around the value of the initial tension. The holding down force significantly influences the creep resistance between rail and sleeper. Therefore, it is of particular importance to guarantee a minimum holding down force by choosing an appropriate rail fastening.

Rail fastening test setup is shown in Figure 4 (a). According to the European CEN standard [19], to obtain the quasi-static elasticity, rail fastening specimens should be loaded to a maximum vertical force of 80±1kN at a loading speed of 50±5kN/min. The Mullins effect of the rubber material must be excluded by repeating the loading–unloading cycle for five times and then recording the test data starting with the sixth cycle [20]. Vertical stiffness is defined by the secant slope, also referred to as the secant stiffness, i.e. the slope of the loading interval [5 kN, 80 kN] versus the corresponding displacement.

(a) (b)

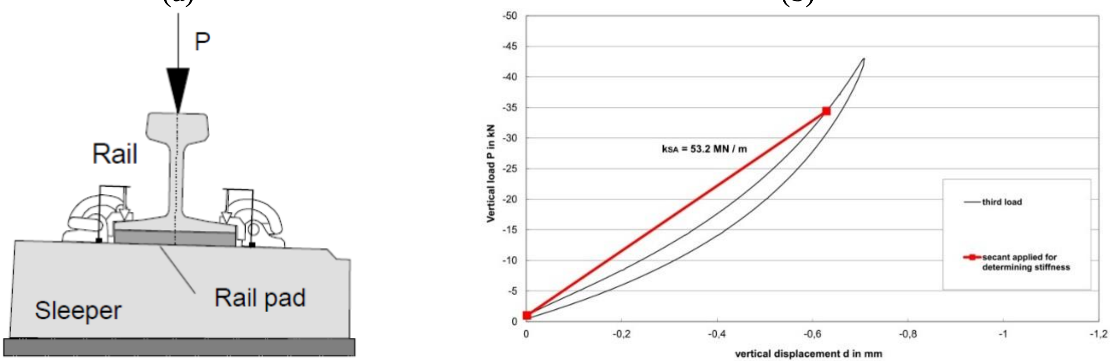

Figure 4. Rail fastening.

Vertical and lateral stiffness for the rail fastening was obtained as in [21]. Different vertical and lateral stiffness, obtained from experimental data, was used in a spring-damper element for the simulation of the railway fastening.

3.3. Track slab

The amount of attenuation, the FST provides, rely on different parameters, but the slab mass is one of the most important. Taking into account, the SDOF analogy, to increase the attenuation far from the mass-spring system resonance, we have to reduce the resilient element stiffness or to increase the slab mass. In practice the engineers are limited to the tunnels cross-section confined with the safety margins according to GOST 23961-80.

Concrete track slab shows non-linear behaviour, depending on the live load intensity, stiffness of the resilient elements and bending stiffness of the track slab under permanent loads. Simulation of non-linear behaviour of the track slab relies on the requirements of national standard SP 63.13330.2011 and SP 35.13330.2011. Usually, the track slab is designed to withstand live loads without cracking, therefore the linear track slab behaviour can be assumed. But, from the experience [14], for a correct prediction of the systems' dynamic characteristics, all the load history as well as other long-time effects should be taken into consideration.

For the simulation of the track slab in the FE-model, 3-D solid hexagonal elements CHEXA are used. In order to account for high-frequency bending modes, at least 3 elements between the rail fastenings are used in longitudinal direction of the slab.

4. Analysis results

For the design of FST different types of analysis should be performed: static, modal, transient dynamic, fatigue, etc. due to different combination of vertical and horizontal forces, occurring from train to rail interaction in straights and curves. This leads to parameter studies with different boundary conditions and material properties.

One of the main analyses is the modal one, which gives a brief and fast (when large FE models with hundreds thousands DOF's are used) estimation of the system's stiffness parameters and insertion loss. First four eigenfrequencies of a FST's draft design for a 6-m diameter tunnel are shown in Figure 5. The first mode, the rigid body one, (figure 5 (a)) lies in range of 12 – 16 Hz depending on the type of resilient elements used. The insertion loss of the system in analytical model is calculated using this first rigid body frequency.

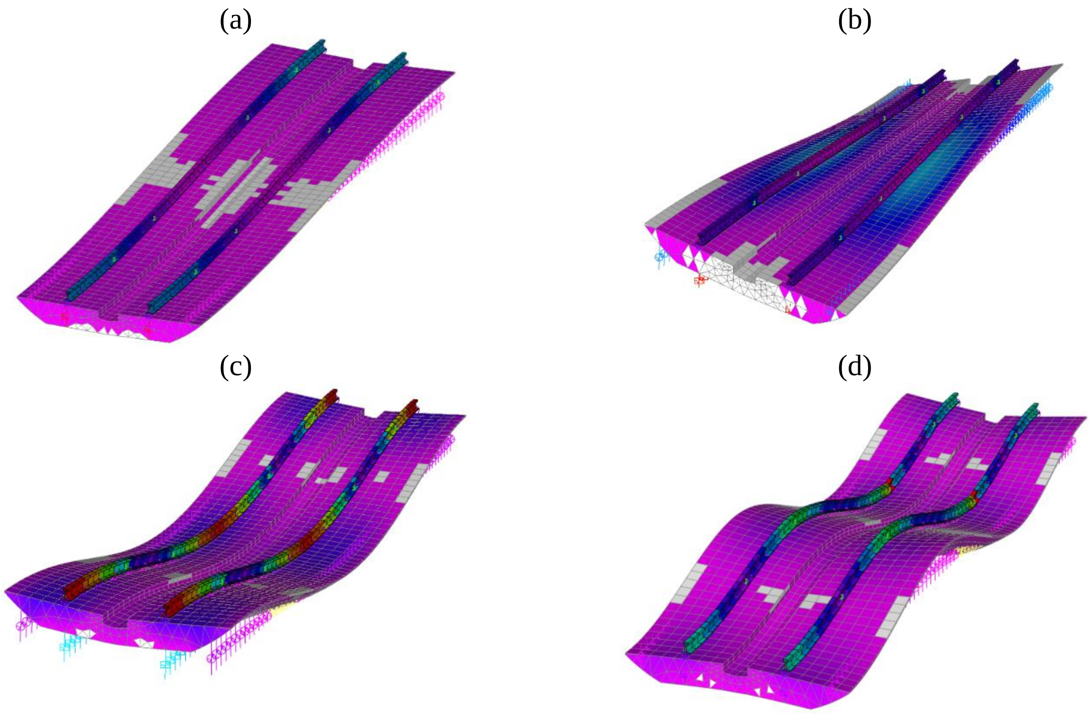

Figure 5. Eigenfrequencies of the FST for a 6-m diameter tunnel.

For the system, depicted in Figures 1, 5 transfer function is plotted in figure 6, which shows that the maximum transmissibility (or the negative vibration isolation efficiency) occurs at the system resonance.

For long slabs torsional modes like depicted in Figure 5 (b) should be accounted for in dynamic analysis, because thick slabs' rotational stiffness is considerably lower, than the bending one, which can be further increased by concrete pre-tensioning.

5. Conclusion

The FST is the most effective track vibration isolation solution, provides high maintenance indicators (constancy of the geometry of the track gauge, minimization of operating costs) and a long service life. Proposed design methodology and full-scale measurements, enforced with experience in laboratory testing of vibration damping materials, allows to guarantee effective work of FST in a wide range of loads from the rolling stock and reduce vibration in the premises of residential and public buildings located near the underground metro lines.

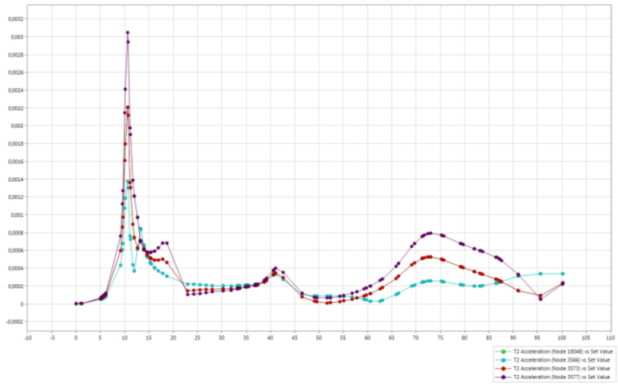

Figure 6. Transfer function for a FST.

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