Dynamic Analysis of Ballastless Rail Superstructure on a Track Switch

V A Smirnov¹,²
¹Leading research scientist, Laboratory #34, Research Institute of Building Physics (NIISF RAANS), 21 Lokomotivnij proezd, 127238 Moscow, Russian Federation
²Associated professor, Structural and Theoretical Mechanics Department, MGSU, 26 Yaroslavskoe sh., 129337 Moscow, Russian Federation

E-mail: belohvost@list.ru

Abstract. Proposed article presents design procedure and dynamic analysis of a ballastless rail superstructure used to decrease the vibration from the moving trains in underground tunnels located adjacent to residential and commercial buildings. The rail superstructure features a floating slab consisting of a reinforced concrete (RC) slab with direct fixation of railway fastenings and elastomeric bearings, that transfer the loads from the floating slab to the tunnel casing. A track switch is mounted on a FST. The aim of the design procedure is to select required static and dynamic properties of elastomeric bearings made of cellular polyurethane as well as the amount of reinforcement taking into account deteriorating properties of both materials. FE-model created in MSC Patran/Nastran software package is used to get an insight on stress-strain state of this floating slab track structure. Proposed FE-model consists of switch track with direct fixation railway fastenings, RC track slab, elastomeric supports. Static analysis is performed to get the upper-track structure elements’ deflections as well as stress-strain state of RC slab under moving trains. Dynamic interaction of the ballastless rail superstructure is investigated using derived from FE-analysis transfer-function between the superstructure and tunnel invert. Vibration isolation efficiency under excitation frequencies of moving trains over different speed is obtained from the transfer function.

1. Introduction
Vibration from underground railway lines is produced at dynamic interaction couple between the moving train and the upper-track structure. It further spreads through the ground directly to the dwellings adjacent to those underground railway lines, especially shallow ones or those laying in rocks [1, 2]. Vibration transferred to the building and reradiated structure-borne noise disturb inhabitants inside residential or commercial premises [3, 4]. Excessive vibration levels can even damage the load-bearing structures or building’s coating [5, 6].
Floating slab track (FST) is a widely-accepted approach used to reduce vibration transmitted from the underground railway line into the surrounding soil and thence into nearby buildings [7]. It has high economical potential due to the fact that this type of structure decreases the vibration at the source. Figure 1 shows the Finite Element (FE) model of an underground railway line using FST in a circular tunnel used in Moscow Underground. It has direct rail fixation to the reinforced concrete slab track by means of elastic railway fastenings DFF, which provide both protection to the concrete slab as well as some reduction in noise produced [7, 8].

FST is located in a ramp chamber where a track switch is mounted on it. The track switches and turnouts are known to be the sources of additional vibration impact. As investigations [9] shows, vibration impact form turnout is normally 2 times higher than that of a straight line situation. Figure 2 depicts typical switches & crossings (S&Cs, turnouts) arrangement that contains a switch panel and a crossing panel that are connected by a closure panel [9, 10]. Due to higher complexity in S&Cs structure, dynamic interaction between vehicle and track is more complex in S&Cs than on tangent or curved tracks. For example, wheel–rail impact loads with large magnitudes and significant contributions from high-frequency vehicle–track interaction are generated when the nominal wheel–rail contact conditions are disturbed at various locations in the S&C, such as at wheel transfer from wing rail to crossing nose [9] (facing direction). Field measurements shows, that impact loads created by S&C and turnouts produce significant amount of disturbing or dangerous ground vibration and noise.

One of the most important sources for ground vibration are the switch panel and the crossing panel as there is a change in a rail cross-section, track curvature, and due to high impact loads they accumulate track irregularities and track stiffness variations [11].
There is great amount of investigations performed connected with wheel transition through the S&Cs that produces vibration turnout-amplifications, see e.g. [12] and partially [13]. There is a distinction between a wheel transition over a frog with a fixed frog or a flexible frog, that is discussed in [12] and in [14].

Additional dynamic loading on a turnout occurs at track geometrical irregularities are [9]: 1) sudden change in track vertical or lateral alignment, implying changes in contact point location and number; 2) track stiffness variation due to rail cross section variation and stiffness variation coming from different sleeper settlement (due to their different size across the turnout), ballast stiffness and railpad stiffness. In contrast in straight lines, the predominant excitation is mostly wheel and rail unevenness, which also occurs at the turnout.

SBB performed a number of field vibration measurements [15 – 17] to gather turnout-amplification values. Figure 3 [9] depicts frequency dependent amplification values on several switches which shows predominant amplification levels in frequency range 12 – 40 Hz. The numbers after “EW” in Figure 3 indicate curve radii of the switch in deflection (e.g. EW 300 = radius 300 m). These frequencies fall inside the resonant frequency range of typical reinforced concrete floors, so that the buildings adjacent to the turnout are subjected to a substantial vibration level increase as well as structure-borne noise. Figure 3 shows that the vibration isolation solutions for turnout should be effective for frequencies lower than 40 Hz.

Figure 3. Amplified vibration of turnouts compared to track at grade in about 8 m distance to the open line near the unmoving frog.

The principal aim 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. Taking into account the design 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), and the elastomeric supports’ stiffness designed according to the required vibration isolation efficiency, which according to Figure 3 should be less than 12 – 16 Hz.

The research reported in this paper uses FE model of a FST under a rail switch in order to thoroughly investigate its stress-strain state under dynamic conditions and design efficient solution that can decrease the vibration from the rail track on the adjacent buildings. The utilization of a FE software was substantiated by FST’s complex geometry and sophisticated layout of the elastic bearings.
2. Numerical model
The FE model of a rail switch on the FST was created using Femap commercial software package, depicted in Figure 4. The model consists of the track switch with fixed frog, simulated using 1-D beam elements, intermediate elastic railway fastenings DFF, simulated using linear spring elements, reinforced concrete track slab, simulated using 3-D solid elements and resilient elements simulated using nonlinear grounded spring elements. Discussion about numerical model element’s properties was early provided in article [7].

![Figure 4. Finite element model of a FST in a ramp chamber.](image)

The FST’s slab was loaded with a system of point forces simulating the car’s wheelset. The value for each of the vertical and horizontal axle loads were acquired from the field tests performed on the same type of cars that will be running on this switch. In order to model the train passage over the whole slab, the system of point forces was applied to the rail step-by-step. Symmetry conditions were applied at

Static analysis was performed to get the stress-strain state of the FST at different train locations and select static stiffness of the elastomeric bearings. Dynamic analysis was performed in order to calculate the insertion loss of the FST.

3. Analysis results
The contour plot of the normal stresses in the deformed slab when a train drives to the slab, drives through the frog and goes off the slab is shown in Figure 5a – 5c, respectively.
Figure 5 shows that the maximum compression stresses in a slab under the boogie reach -3.27 MPa, whether maxim tension stresses +3.12 MPa. Averaged normal stresses versus slab length are plotted in Figure 6 for three positions of the train on the slab.

Rail deflection and slab deflection under the rail are depicted in Figure 7 together with the slab’s deflection for different positions of the train. It can be shown, that the peak values of the rail deflection are averaged by the slab flexibility and stiffness. Whether maximum combined deflection of the rail and the slab varies from 4.5 to 5.4 mm, the slab’s deflection stays 0.3 – 0.5 mm lower. The added rail deflection compared to the slab’s one is due to the stiffness of the railpads. Considerable deflections at the ends of the FST mostly results from the symmetry conditions and the varying slab’s width, which is narrow (3.2 m) at the start and quite wide (7.2 m) at the end. Iterative static analysis was performed in order to limit the variance between the rail deflection down to 5±1 mm in order to get required vibration isolation efficiency.

Figure 6. Averaged normal stresses in FST’s slab.

Figure 7. Slab and rail deflection of a FST.
During each iteration both elastomeric bearing properties were adjusted as well as their location underneath the slab. As a result, the first eigenfrequency of the FST according to modal analysis is 12.7 Hz.

4. Conclusion
The FST is the most effective track vibration isolation solution, provides high maintenance indicators (geometry constancy of the track gauge, minimization of operating costs) and a long service life. It’s the only solution that provides high rail deflection required for the vibration isolation with high stiffness and positioning quality of the track upper structure.

Design procedure applied for the FST in a ramp chamber shows great potential for decreasing vibration impacts from the rail switches, which are known to be one of the major sources of additional vibration impact. Using proposed results of the static analysis, the reinforcement for the slab was calculated as well as concrete admixtures were selected to withstand high tension and compression stresses in a slab under a moving train.

Proposed design methodology and full-scale measurements, enforced with experience in laboratory testing of vibration damping materials, allows to guarantee effective work of FST with a track switch in a wide range of loads from moving trains and reduce vibration and structure-borne noise in the premises of residential and public buildings located near the underground railway lines.

5. References
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