Floating slab track efficiency tests in Moscow underground

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Abstract. The article deals with field tests of a floating slab track (FST) – a railway track structure used in Moscow underground. The upper track structure to be tested was erected in 1977 and consists of a concrete track slab with embedded wooden sleepers, rails R50 with "metro" fastenings and a series of rubber isolators, that support the concrete slab and transfer all the loads down to the tunnel casing. The aim of the test is to get substantial experimental data and understand its static and dynamic behaviour in order to use in further development and verification of FST’s design models. During the test under moving trains different load parameters are acquired: dynamic vertical and horizontal forces, rail & slab deflection and acceleration at different points on the slab and tunnel casing. On the basis of this multifactorial survey, verification data is acquired and weak points of the FST are investigated.

1. Introduction
Underground railway lines are commonly preferred way of mass public transport in crowded urban areas due to its great carrying capacity. However, the noise and vibration caused by underground lines might be disturbing or even hazardous when the building locates closer 40 m to the tunnel. The vibrations originated at the wheel-to-rail interface are transmitted through the ground to the nearest buildings. Ground-borne vibration can excite structural components such as walls and ceilings at frequencies in the hearing range and cause so-called structure-borne noise usually in the range of 16–250 Hz [1]. Excessive vibration levels can be controlled usually by changing the track support system. In subways, the level of ground-borne vibration can be reduced by using floating slabs, resilient fasteners and ballast mats [2].

Floating slab track (FST) is a railway track superstructure used to reduce dynamic forces occurring at wheel-to-rail interface. FST is a popular approach [3] used to reduce vibration transmitted from the railway line into the surrounding soil and thence into nearby buildings [4]. It has high economical potential due to the fact that this type of track superstructure reduces vibration at the source.

FST consists of rails, railway fastenings, track slab and resilient mounting. The rails are fixed to a concrete slab track using direct fastening. The slab track itself is supported on a resilient mounting, thus isolating the track from the tunnel invert. Recent studies [5] show that the effectiveness of the vibration attenuation does not compare well with the simple single degree of freedom (SDOF) models typically used in the analysis of these tracks.

Although extensive research has been made to investigate FST’s static and dynamic behavior [3,4,6–10], there are an order less researches made on field tests, moreover of those FST’s that were in operation for more than a decade. Saurenman and Phillips [11] tested the rubber floating-slab track used on the current San Francisco Bay Area Rapid Transit (BART) system. Hwang et al. [12]
performed the laboratory mock-up test to understand the dynamical behaviors of the rubber floating-slab track more accurately. A three-bay track system prototype supported on resilient slabs has been tested experimentally in [13]. A numerical model of the prototype has also been developed, which showed satisfactory agreement with the test track system. In [14], the noise and vibration acceleration measurements were taken before and after the FST system installment in order to evaluate the effectiveness of the isolation work. The collected acceleration data were analyzed and the resulting vibration velocity levels were compared. However, measurements were performed on the ground surface, none of the static or dynamic properties of the FST itself were acquainted. Montella in [15] deals with an innovative floating-slab track system obtained by introducing elastic elements made of recycled rubber. This research applies numerical analysis, validated by an exhaustive experimental campaign in an attempt to understand the static and dynamic behavior of the railway track studied in different configurations. Nevertheless, the experimental data was obtained on a laboratory test mockup.

According to the performed survey, the lack of FST in-situ (“inside tunnel”) measurements under moving trains is evident. That’s why the purpose of this study is to perform field measurements of a FST used in Moscow underground for 43 years and gather useful data – both deflections, rail stresses and acceleration in order to upgrade current design models and get an insight in static and dynamic behavior of FST.

2. Test track characteristics
Field measurements were performed on Moscow underground line, where 140 m long FST section was erected in 1977. Taking into account average traffic density of 40 mln gross tons per year, till 2019, when the test was performed, total passed tonnage reaches 1,64 billion gross tons without any failure of the FST. The cross-section of this FST is presented in Fig. 1.

![FST cross-section](image)

**Figure. 1.** FST cross-section

The rails are fastened directly to the concrete slab through cased wooden sleepers. The track plate consists of a prefabricated fixed reinforced concrete formwork 3.3m width and 3.0m long, into which a rail and sleeper grid is installed, reinforced with steel mesh and longitudinal reinforcement and poured with concrete. Track slab is supported on resilient elements, made of NO-68 rubber bricks with a thickness of 70 mm. Slab stability in horizontal and longitudinal direction is achieved by special V-shaped resilient restraints with 30mm rubber blocks, that support the track slab on either sides. Transfer zones between FST and standard track superstructure are constructed 12.5 m long by reducing the thickness of rubber resilient elements. The stiffness of rubber resilient elements was selected to achieve 4 mm of vertical deflection under train loading which was supposed to be enough to get reasonable vibration reduction in 16, 31.5 and 63 Hz octave band frequencies.

3. Sensors set-up
Field tests of track dynamics require the measurements of wheel–rail dynamic forces, track, and substructure displacements and track structure vibrations [16]. The measurement of dynamic effects of
vehicles on the track must be conducted onsite, and assessed by processing the measurements taken when the vehicles are passing the instrumented track section.

Wheel–rail force is the most important indicator for evaluating vehicle–track interaction [17]. Low-frequency vertical and lateral wheel–rail forces were measured using strain gauges. To measure vertical wheel–rail force, FLA-5-11 foil strain gauges were placed on both sides of the rail web in the midpoint between two sleepers, along the neutral axis according to GOST R 55050. To measure lateral wheel–rail force, two types strain gauge arrangement were used: strain gauges were placed on the top surface of the rail foot, 20 mm away from its outer edge in the midpoint between two sleepers and on both sides of the rail web. The mounting position is depicted in Fig. 2.

![Figure 2. Mounting positions of strain gauges on the rail web](image)

Track structural deflection is also a key indicator for assessing vehicle–track interaction, which includes rail vertical and lateral displacements and slab vertical and lateral displacements. Leaf spring displacement sensor was used to measure the dynamic displacements of rails and track slab. Displacement sensor consists of a uniform cross-section cantilever made of spring steel and a foil strain gauge with standard resistance of 120 Ω mounted at the middle of it which forms a quarter-bridge as shown in Fig. 3. Displacement sensors were calibrated using a servo-hydraulic actuator in laboratory environment.

Track structural vibration which result from vehicle–track interaction, were measured using piezoelectric accelerometers PCB 352C04. They were placed both on the track slab (in the middle line of it and on both sides to measure its rocking modes) and on the tunnel invert. Sensors arrangement on the instrumented track section is depicted in Fig. 4.

All of the sensors were connected to multichannel acquisition hardware with discretization frequency of 2 kHz for all the channels and 24-bit data resolution.
4. **Measurement results**

Measurements were performed during one-day form 5 a.m. till 23 p.m. At least 450 train passes through instrumented track section were recorded. Each train consists of eight series 81-714/717 carriages. Train occupancy differs in time from empty to fully occupied (each car capacity varies from 308 to 330 persons).

All the time data was divided into groups for each of the train pass and then analyzed. Displacement data as well as strain data for all train passes was subjected to statistical analysis in order to get minimum, mean and maximum value as well as 95%, 99% and 99.99% percentile [18,19]. Rail and track slab deflections data is depicted in Fig. 5.

Overall vibration levels in dB for the track slab (its centerline and edge) as well as tunnel invert (tunnel casing and duct) are depicted in Fig. 6 for each train pass.

**Figure. 3.** Deflection sensors on the rail and track slab

**Figure. 4.** Schematic location of accelerometers on the track slab and tunnel invert
5. Results and discussion

According to Fig. 5, the vertical rail deflections vary greatly between sleepers. Maximum mean rail deflection is 4.5 mm, near the slab joint, when the minimum mean is 1.5 mm. This spread of values is due to weak bond between the wooden sleeper and the track slab. Due to concrete shrinkage and wood drying, a clearance occurs between the sleeper and the concrete of the track slab. Moreover, not all of
the railway fastening are fastened enough, so the rail feels loose under train loading. Near another slab joint, in the middle of the test section, the deflection of both rails is the lowest – at R5 & L5 – 1.7 mm and 1.2 mm. This variation between rail deflections at both slab joints can be related to the slab rotation due to uneven support stiffness, which can result from debris (or concrete leakage from the formwork) under the track slab, uneven spacing between the resilient mounts or their ageing. The last factor was thoroughly investigated in [20].

Mean vertical track slab deflection varies from 0.8 to 1.7 mm. Maximum mean slab deflection occurs at slab joint where the rail deflection is minimal. Horizontal slab deflection shows up to 0.4 mm.

Track slab vibration is governed by the train loading [21] which differs with car weight (due to variation in occupancy, car type), train speed, wheel roughness, etc. The overall analysis of measured acceleration shows (Fig. 6) that vibration level variation lies in ±13 dB corridor for the track slab and ±10 dB corridor for tunnel invert. The shape of acceleration data for tunnel invert reduplicates the one for track slab which proves linear (or close-to-linear) relation between the input (track slab vibration) and output (tunnel invert vibration).

6. Conclusion
Although, according to original design, the vertical slab deflection should be not less than 4 mm, the test track data shows double reduction which was caused by wrong rubber stiffness calculation, which shows frequency-dependent stress stiffening.

The weakest point of the FST consisting of discontinuous slabs are their joints, that should be made stiffer or the railway fastenings should be better coupled to the track slab in order to redistribute train load for both slabs.

Linear relation between the vibration levels at the input and the output allows for transfer function analysis. Decrease in corridor width for tunnel invert shows some damping related both with friction and hysteretic damping of rubber resilient elements.

On the basis of this multifactorial test, verification data is acquired for further FST design which is partly implemented in National Standard “Protection of buildings against underground train vibration”.

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