Int. J. Advanced Design and Manufacturing Technology, 2023, Vol. 16, No. 3, pp. 19-29

DOI: 10.30486/admt.2023.1973746.1392 ISSN: 2252-0406 https://admt.isfahan.iau.ir

Comparison of Vibration Amplitude in Isfahan Subway Due to Track Structure- An Experimental Study

Sajjad Sattari
Department of Mechanical Engineering,
Najafabad Branch, Islamic Azad University, Najafabad, Iran
E-mail: sajjad.sattari@gmail.com

Mohammad Saadat*, Sayed Hasan Mirtalaie, Mehdi Salehi, Ali Soleimani
Department of Mechanical Engineering,
Najafabad Branch, Islamic Azad University, Najafabad, Iran
E-mail: saadat@pmc.iaun.ac.ir, mirtalaie@pmc.iaun.ac.ir,
mehdi.salehi@pmc.iaun.ac.ir, soleimani@pmc.iaun.ac.ir
*Corresponding author

Received: 27 November 2022, Revised: 24 January 2023, Accepted: 21 February 2023

Abstract: Increasing the stability of structures and reducing the maintenance cost of slab track superstructures compared to ballasted tracks are among the reasons for the tendency to use this category of superstructures in the railway industry. Vibration reduction methods can be divided into three categories, source, propagation path, and receiver. In general, the slab track structures in Iran are divided into three categories: direct fixation track (DFT), floating slab track (FST), and high resilient fastener (HRF). Although railway tracks are a safe, economical and fast transportation system and can lead to the strengthening of the tourism industry, in the long term, vibrations can damage many historical structures in the city of Isfahan. FST and HRF systems are used in the structure of Isfahan subway track. In this paper, the accelerations (longitudinal, lateral, and vertical) of the Isfahan subway vehicle were measured in 30 stations (15 go stations and 15 return stations). The results showed that the HRF system compared to the FST has a significant effect in reducing the range of vibrations and ultimately the safety of the train and the ride comfort. For example, in the area between Si-O-Se-Pol and Imam Hossein Square, due to the track structure type (HRF), the maximum acceleration and RMS acceleration are in the range of 1.5 and 0.3 m/s^2, respectively, while in other stations these values were extracted up to 4 and 0.7 m/s^2, respectively.

Keywords: Fastening Systems, Floating Slab Track, Isfahan Subway, Vibrations

Biographical notes: Sajjad Sattari is PhD candidate of Mechanical Engineering at Islamic Azad University of Najafabad (IAUN), Iran. His current research focuses on railway engineering and solid mechanics. He received his MSc in Mechanical Engineering from IAUN in 2016. **Mohammad Saadat** received his PhD in Mechanical Engineering from IUT in 2016. **Sayed Hasan Mirtalaie** received his PhD in Mechanical Engineering from UK in 2017. **Mehdi Salehi** received his PhD in Mechanical Engineering from IUT in 2011. **Ali Soleimani** is Assistant Professor of Mechanical Engineering at IAUN. He received his PhD in Mechanical Engineering from TMU in 2016, Iran.

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1 INTRODUCTION

In classic tracks, two subsystems can be specified in the track: superstructure and substructure. Track superstructure is very important due to its direct connection with the train wheel. The components of the superstructure should be designed in such a way that each component, while bearing the applied loads, adjusts them to the tolerance of the underlying layer and finally transfers them to the subgrade. In general, and structurally, the types of superstructures in railway tracks can be classified into two general groups: ballasted and slab tracks. Depending on the conditions of the track and technical and economic studies, both types of these tracks can be used. According to the type of design and the conditions of its execution, the slab track consists of components including rails, fastening systems, sleeper, concrete slab, resilient layer, concrete base, and subgrade. Some of the above components, such as sleeper, resilient layer, and concrete base, can be removed from the system according to the design conditions and the location of the slab track. In cases where there is a need to reduce the vibrations transmitted around the track, the use of resilient layer under the concrete slab is one of the solutions to reduce the vibrations. Also, in places such as bridges, where implementation of the slab base superstructure has high rigidity, the concrete base is removed from the slab superstructure. In general, slab track superstructure systems in which concrete plays the main structural role are divided into two main parts (a) system with discrete supports and (b) system with continuous supports. This type of slab track superstructure classification is related to the way the rail is connected to its underlying assembly. Among the advantages and disadvantages of slab tracks, the following can be mentioned. Advantages: - lower height of the structure and in some cases less track weight, - longer durability of structure track geometry, - reduction of maintenance operations, - suitable damping of vibrations, - suitable electrical insulation, - reducing the wear of the rail head and its uniformity along the track, - less stress on the rail due to the better geometry of the track, and disadvantages: - low flexibility to implement future reforms, - the need for more investment except for tunnels, bridges, and the like. The increase in population, traffic, and the lack of suitable parking spaces in big cities have made the use of underground trains even more necessary. The vibrations caused by the passing of the trains in the distance between the stations can cause vibration and noise, and subsequently disrupt the lives of the people in the area of the subway passage. In addition, the resulting vibrations may cause damage to buildings and sensitive equipment. Based on this, in the design of new urban train tracks, the evaluation of the vibrations caused by the movement of trains on passengers, surrounding buildings and their residents is one of the main parameters. The main sources of vibration and noise are trains and rails. In fact, the movement of the train along the rail and the mutual effects that occur between the wheels, rail, and rail structure cause vibration. Stationary and moving trains both produce vibration. Stationary trains, depending on their weight, produce a force that is released from the wheel and/or rail and is transmitted to the ground by the rail, sleeper, etc., which can be defined as a static load. When the train moves, the force resulting from the static load moves along the rail with the train. This load will change depending on the differences in the different parts of the train and rail systems, such as the irregularity of the rail and wheel surface and the characteristics of the supporting structures under the rail. There are many parameters that affect the level and characteristics of vibrations caused by subway movement. The parameters and characteristics of the train (train weight, characteristics of primary and secondary suspension systems, train speed, etc.), track (type of materials, fastening systems, etc.) and driving style are among these factors [1-5].

Blanco-Lorenzo et al. [6] compared the dynamic responses of railway tracks in four track conditions with Simpack software: the traditional ballasted track, and three types of slab tracks: the RHEDA 2000 track, the STEDEF track, and a floating slab track. Zhao et al. [7] investigated the effect of elastic rubber mats on vibrations and noise in China's high-speed railway tracks. Some researchers like Kumar et al. [8] and Graa et al. [9] used the RMS acceleration to evaluate the vibrations and ride comfort of the passengers. Sadeghi et al. [10] investigated the effect of fastening system properties on wheel-rail dynamic forces. Sadeghi et al. [11] proposed a model for predicting ride comfort. They used Isfahan and Tehran metro tracks to compare and confirm the model. The connection of the rail to the sleeper in railway tracks is provided by means of so-called fastening systems. The most important role and task of the fastening system is to keep the rail fixed on the sleepers and prevent its longitudinal, transverse, and rotational movement. In addition, this system must meet other structural and operational expectations, some of which include: - absorption of forces from the rail and safe transfer to the sleeper, - reducing the intensity of vibrations caused by the passage of the train, - having the ability to not conductivity of electricity, - having the strength and proper resistance against phenomena such as mechanical wear, creep, chemical corrosion, etc. Although today there is a great diversity in the structure and components of fastening systems, they can be classified from two perspectives (ballasted and slab tracks): (i) the way of establishing the connection (direct and indirect) and (ii) the degree of rigidity (rigid and elastic). Basically, elastic fastening systems can be used for speeds higher than 80 km/h and high-speed tracks. Among the big manufacturers of fastening systems, Vossloh of Germany, Pandrol of England and Nabla of France can be mentioned. Fastening system, as components which main task is to create a safe connection between rails and sleepers in the tracks, should be able to provide sufficient structural resistance against the effects caused by the repeated loads of the rolling stock. In other words, the main issue is that the behavior of the fastening system remains in the elastic and linear range. On the other hand, it is important to limit displacements and vertical strains created in the fastening system. The next thing is that these components have the ability to properly hold the rail against rolling. The control of design criteria in all types of fastening systems depends on performing analytical calculations [1-5].

Studies related to the track structure types and the ride comfort of passengers in Isfahan Metro are limited and can be referred to [4], [11-14]. In similar papers, for example, in references [4], [12-14] the comparison of Iran railway track structures and the difference in track stiffness have been mentioned, or in reference [11] only the ride comfort in two Metro stations of Isfahan and Tehran has been compared. In this paper, the vibration amplitude analysis of the Isfahan subway track was performed by measuring the acceleration in three directions. For this purpose, by moving the train in 30 different stations (15 go stations and 15 return stations), the acceleration was taken and then the effect of the difference in the track structure on the number of vibrations was investigated.

2 VIBRATION REDUCTION METHODS AND FASTENING SYSTEMS

The methods of controlling and reducing vibrations in railways can be divided into two general categories, active and passive. The active method is related to the use of methods applied to the rail vehicle itself. For example, the methods that make changes in the train suspension system led to the reduction of the forces applied to the rails and other parts of the superstructure. This method is more effective for reducing the vibrations transmitted to the wagon and passengers. Passive methods are also divided into three categories, source, propagation path, and receiver. Generally, the source method is preferable due to being less costly and more practical. In the following, several methods of reducing vibrations will be briefly explained.

(1) Floating slab tracks: floating slab track systems are designed based on the principles of vibration isolation of mass-spring systems, and therefore they are also referred to as mass-spring systems [3]. This method is generally divided into three general modes: (i) full surface support, (ii) linear support, and (iii) point like support [3], [6].

(2) Subgrade treatment: improving the quality of subgrade treatment can be done by cement and lime or by pilling the subgrade [3].

(3) Pilling building to bedrock: this method is generally useful for newly constructed buildings near railway tracks [3].

(4) Rail straightness: in this method, the vibration reduction will be about 2 to 10 dB for rails with normal wear, and 10 to 20 dB for rails with severe irregularities and steps [15].

(5) Pipe supported track: this method can be effective in reducing ground vibrations in a wide range of frequencies [3].

(6) Wave impedance barrier (WIB): the results of some studies show that this method can reduce ground vibrations [16-17].

(7) The use of trenches and barriers: the depth and width of the trench is effective on reducing vibrations [18-20].

(8) Using the railpad: this method will increase the track elasticity. The use of these elements will cause the uniform distribution of the load from the train between the superstructure elements and thus lead to an increase in the lifespan of the superstructure [21].

(9) Pad under the baseplate: with this method, the forces and vibrations entering the lower parts are reduced. With this method, it will create a suitable level of elasticity for the track [3], [21].

(10) Using elastic fastening: fastening systems are used to connect the rail to the sleeper and prevent lateral movement and twisting of the rail. Fastening systems are divided into two categories, direct and indirect, depending on the type of connection [22].

(11) Use of spring separators: this method can be used to reduce vibrations in the low frequency range where vibrations can be felt in that range [3].

(12) Rubber plates under the sleeper: improving the quality of the track, the possibility of increasing the axial load, the ability to reduce the ballasted depth, etc. are among the advantages of this method [23-24].

(13) Embedded rail system: a part of the rail is placed inside the elastic elements, and this reduces vibrations and noise [3].

Fastening system is one of the important components of slab track superstructure. The task of this system is to establish a safe and reliable connection between the rail and the slab track in order to transfer longitudinal, lateral, and vertical forces from the rail to the underlying assembly. According to the type and components of the slab track superstructure, the connection of rail to sleeper and/or rail to concrete slab is done through the fastening system. The fastening system consists of various components such as springs, screws, washers, pads, baseplate, and various types of this system have been used so far. According to the type of fastening system, its components can be less and/or more. In general, two types of rigid and elastic systems have been used in different superstructures. Only conventional elastic fastening systems are used in superstructure of slab tracks. Elastic and super-elastic systems are two general categories of fastening systems in slab tracks. Since the subway tracks may pass under and/or next to a sensitive structure, it is necessary to control the amount of vibration to the adjacent structures. From this point of view, the use of super-elastic systems to reduce vibrations has good luck. Each of these fastening systems has its own merits and limitations and should be used according to the conditions. Usually, the choice of the type of fastening system is done by taking into account the necessary technical specifications, the geometrical conditions of the track, the climatic conditions of the region and the economic justification. Technical and economic views are effective in the final selection of a suitable fastening system. First, technical considerations should be taken into account in the design and the design should be done based on the operating conditions and the region. Then, from an economic point of view, the price, installation and maintenance cost and useful life should be evaluated [7], [10-14], [25-30].

3 FIELD STUDY

The tests were carried out on the Isfahan subway track, the second largest subway network in Iran and one of the historical cities with a large number of historical structures that have been registered by UNESCO. Isfahan subway goes through Charbagh Avenue in the central part of the city in which there are several nationally and internationally registered historical monuments including Si-o-Se-Pol, Madreseh-Charbagh, and SarDar-E-KHeymeghah which have 8 m, 26 m, and 15 m away from the subway centerline, respectively ("Fig. 1") [14].

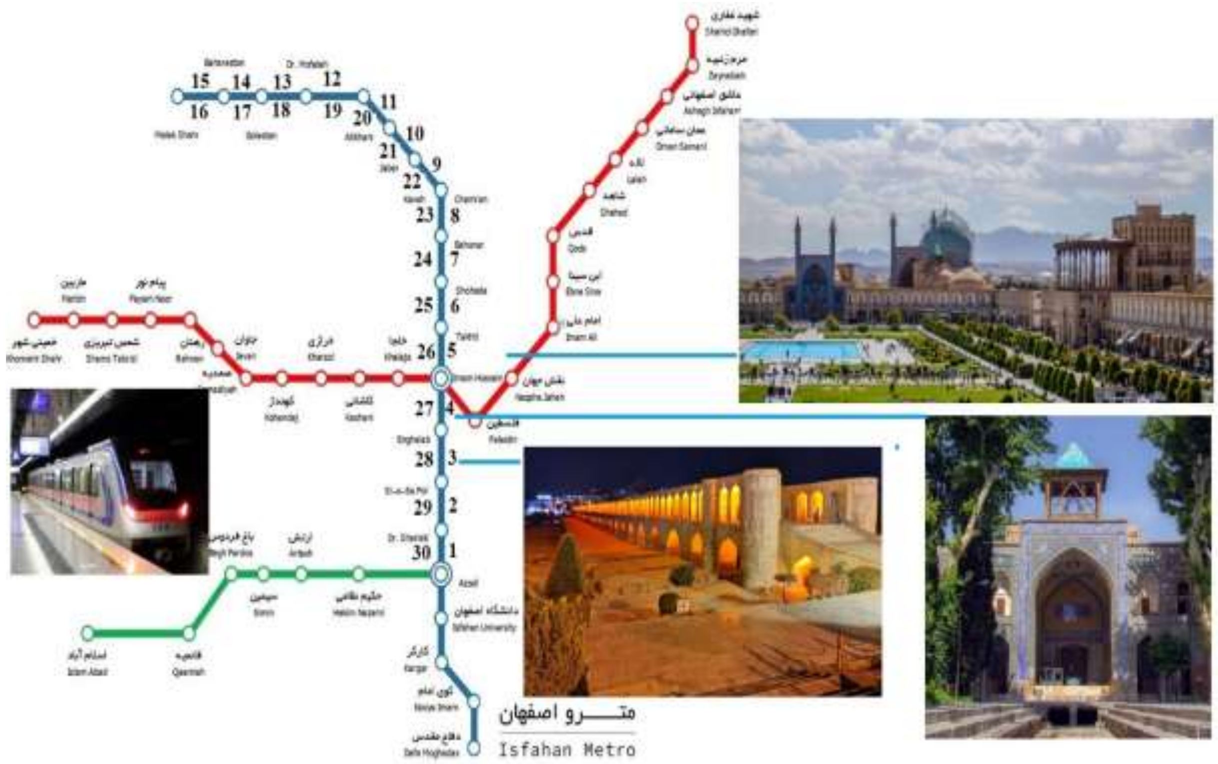

Fig. 1 Map of Isfahan subway.

The existing slab track superstructure in the field test site is a non-continuous slab track superstructure type. This superstructure is composed of a set of rails, fastening system, concrete slab, resilient layer, and concrete base; that this collection is placed on a consolidated soil subgrade. The fastening system in slab track superstructure consists of the W14 spiral spring assembly with the ZW700 pad of the very stiff type. Due to the numerous historical buildings in the area of Si-O-Se-Pol to Imam Hossein Square, including: Si-O-Se-Pol, Naqsh-e-Jahan Square, Ali-Qapu, Imam and Sheikh-Lotfollah Mosques, Chehel-Sotoun, etc., it is necessary that the amount of incoming vibration reach the minimum possible amount to the adjacent structures.

Because it should be noted that the vibrations of small amplitude with high number of cycles in the long term can reduce the strength of the structure. Therefore, in this area (station number 3 and 4) super-elastic fastening system has been used, which will be further explained. In this work, two 3-axis sensors of accelerometer and a gyroscope were installed on the floor of the train, and accelerations and frequencies were collected in all three directions, longitudinal, lateral, and vertical, and the results were compared. Subway tracks in Iran generally use three types of slab track systems, which are:

(i) direct fixation track (DFT)
(ii) floating slab track (FST)
(iii) high resilient fastener (HRF)

Tehran subway tracks are of DFT type with medium stiffness, Shiraz subway and Tabriz subway track are of FST type with low stiffness, and Isfahan subway track (current research) is of two types of FST with low stiffness and HRF mounted on FST [12].
Figure 2 shows a schematic of three types of track systems.

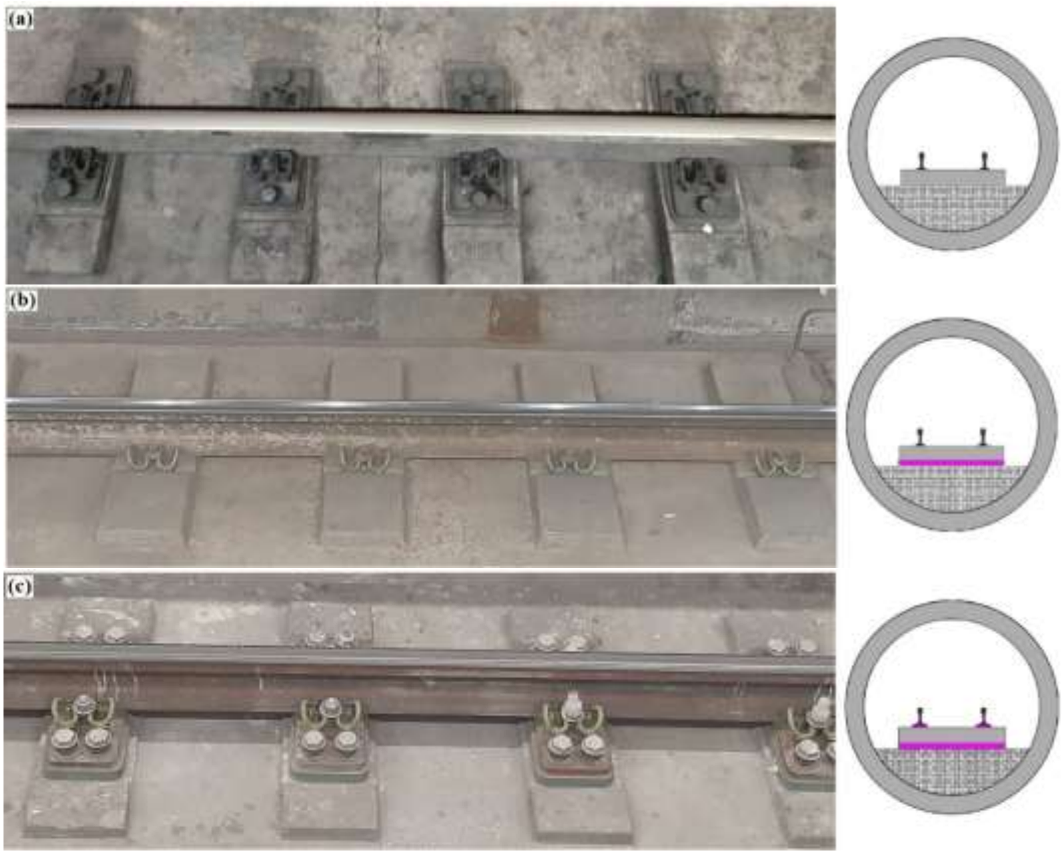

Fig. 2 Slab tracks: (a): Tehran subway: DFT, (b): Isfahan subway: FST, and (c): Isfahan subway: HRF mounted on FST.

4 RESULT AND DISCUSSION

Figure 3 shows a schematic of train-track interaction and components according to the current research [10-11].
The main purpose of investigating the vibrations created in the train and the surrounding environment due to the train running on the track is to limit it to the permissible values. If after carrying out vibration measurements or estimating the amount of vibration using predictive models, the level of vibrations is higher than the permitted values, an appropriate method should be chosen to control and reduce vibrations. As mentioned before, floating slab track, subgrade treatment, pilling building to bedrock, rail straightness, pile supported track, wave impedance barrier (WIB), use of trenches and barrier, the use of a pad under the rail, a pad under the baseplate, the use of elastic fastening, the use of seperator springs, rubber plates under the sleeper and the embedded rail system are among these methods [3], [15-24]. Acceleration-time graphs in all three longitudinal (x), lateral (y), and vertical (z) directions are presented in “Figs. 4 and 5”. Figure 4 shows the longitudinal, lateral and vertical vibrations in 15 stations of the go route (1-15) and “Fig. 5” shows the longitudinal, lateral and vertical vibrations in 15 stations of the return route (16-30). Also, “Fig. 6” shows the Fourier transition and peak-frequency in terms of time.

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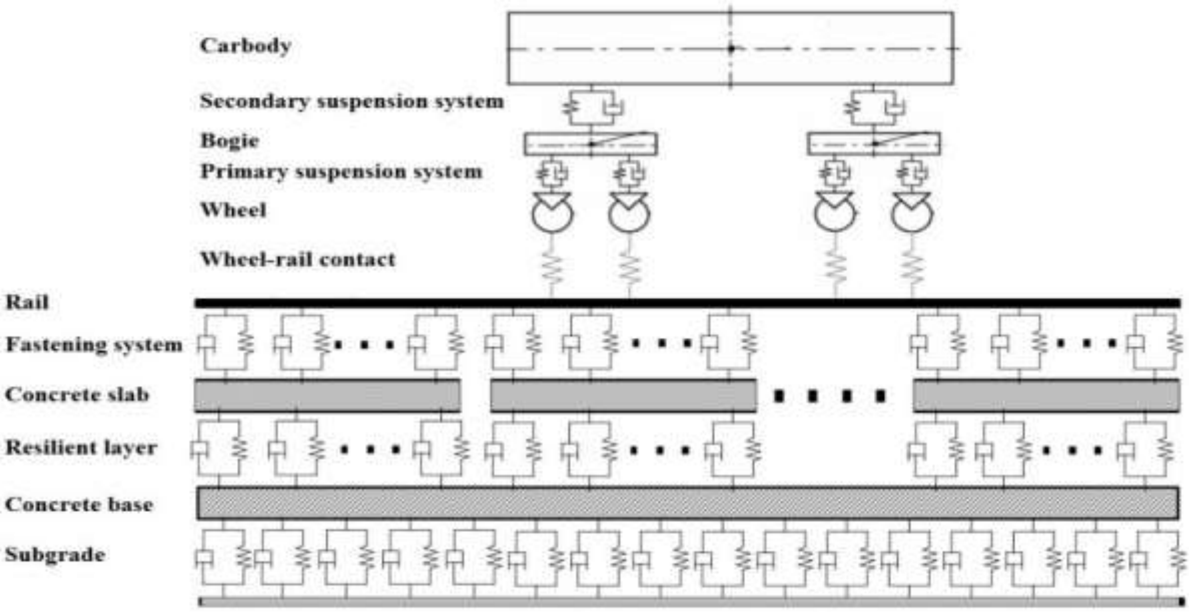

Fig. 3 A schematic of train-track interaction.

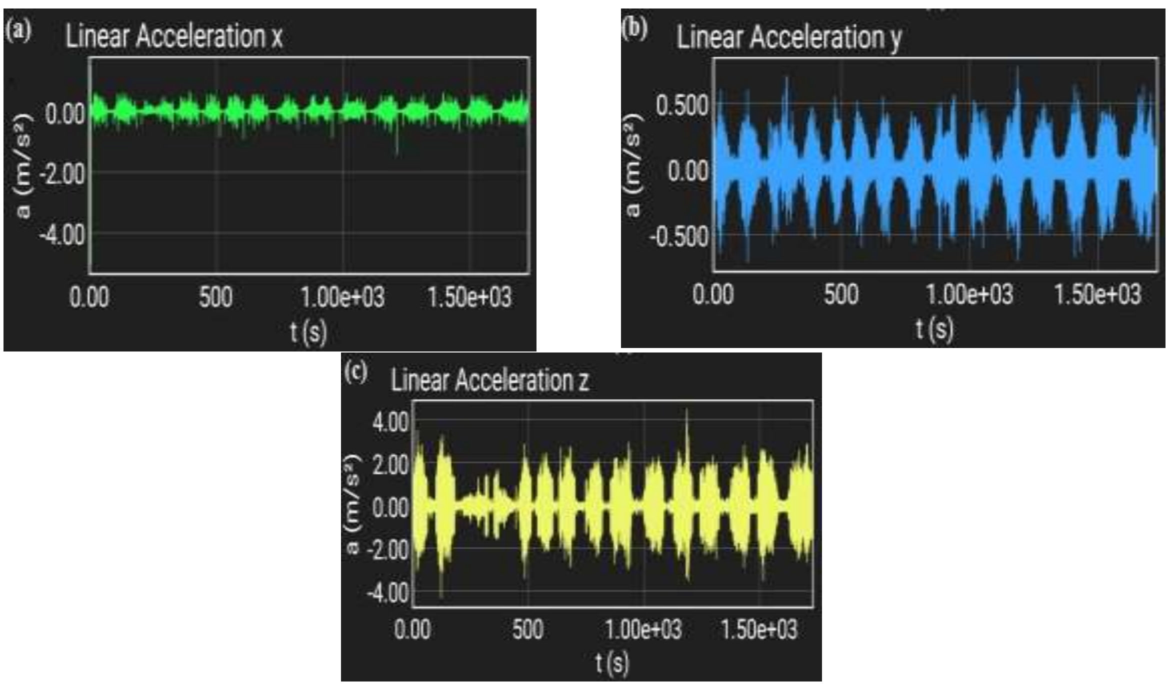

Fig. 4 Acceleration-time graphs in all three directions for 15 go stations (number 1-15).

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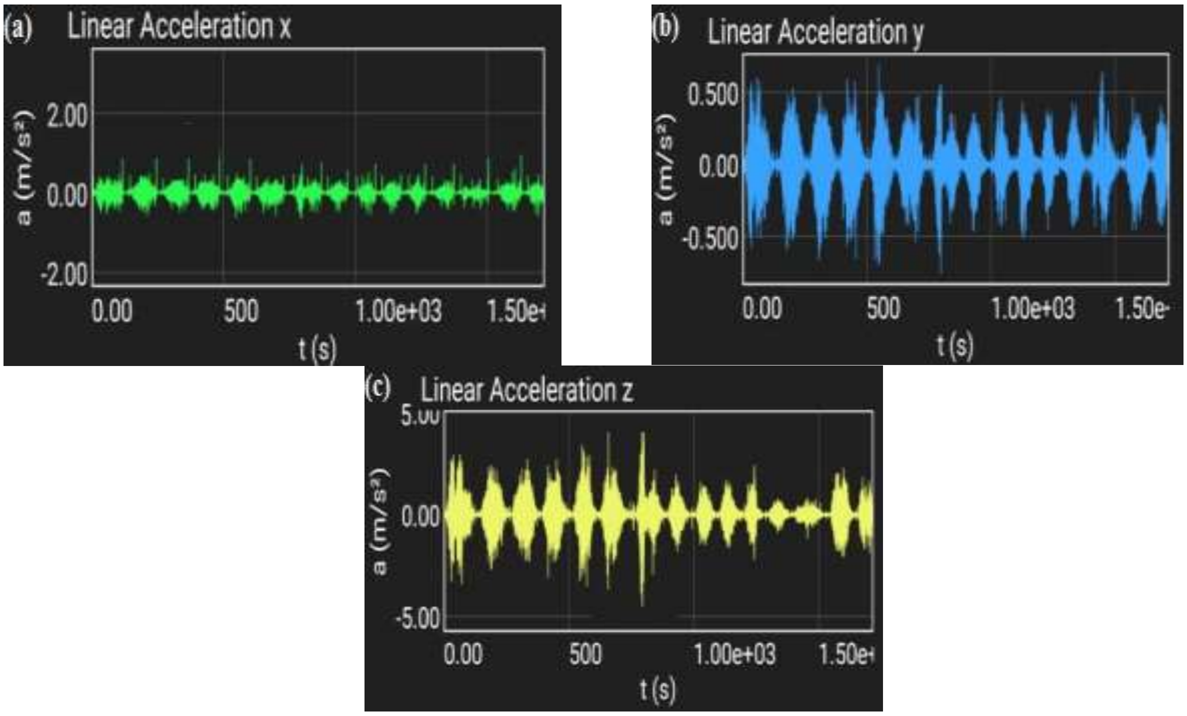

Fig. 5 Acceleration-time graphs in all three directions for 15 return stations (number 16-30).

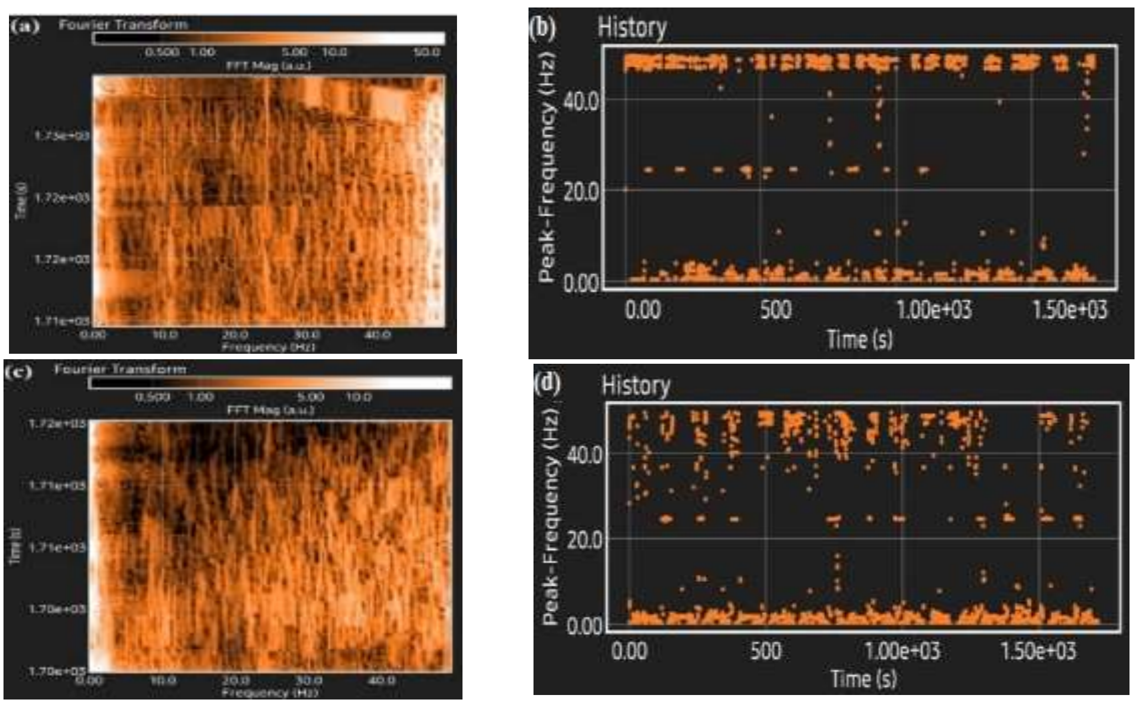

Fig. 6 Fourier transform and frequency: (a, b): 15 go stations (1-15), and (c, d): 15 returning stations (16-30).

As can be seen, the lowest vibration amplitude in the graphs is related to the acceleration in the longitudinal direction (x). Due to adhesion at the wheel-rail interface, the train acceleration is low in this direction (the nature of longitudinal dynamics). The vertical acceleration on the way (1-15) is fluctuating in the range of ±3 in all stations except for two stations. In stations No. 3 and 4, between Si-O-Se-Pol and Imam Hossein Square, the structure of the track is different from the rest of the stations. The same thing happened in the opposite stations (27-28) on the return route. As mentioned earlier, in this area of the train route, due to the number of historical buildings and adjacent to the subway track, the type of track with the least transmitted vibrations should be considered. Therefore, in this area, under special conditions, the HRF mounted on FST system has been used, and in other stations, FST with low stiffness has been used ("Fig. 2"). It is clear that the acceleration values, especially the vertical acceleration (a_z), change significantly depending on the type of track structure and it is consistent with the reference [12]. The maximum, minimum, average, and RMS (root-mean-squre) values of acceleration at each station (1-6) are compared in the "Fig. 7".

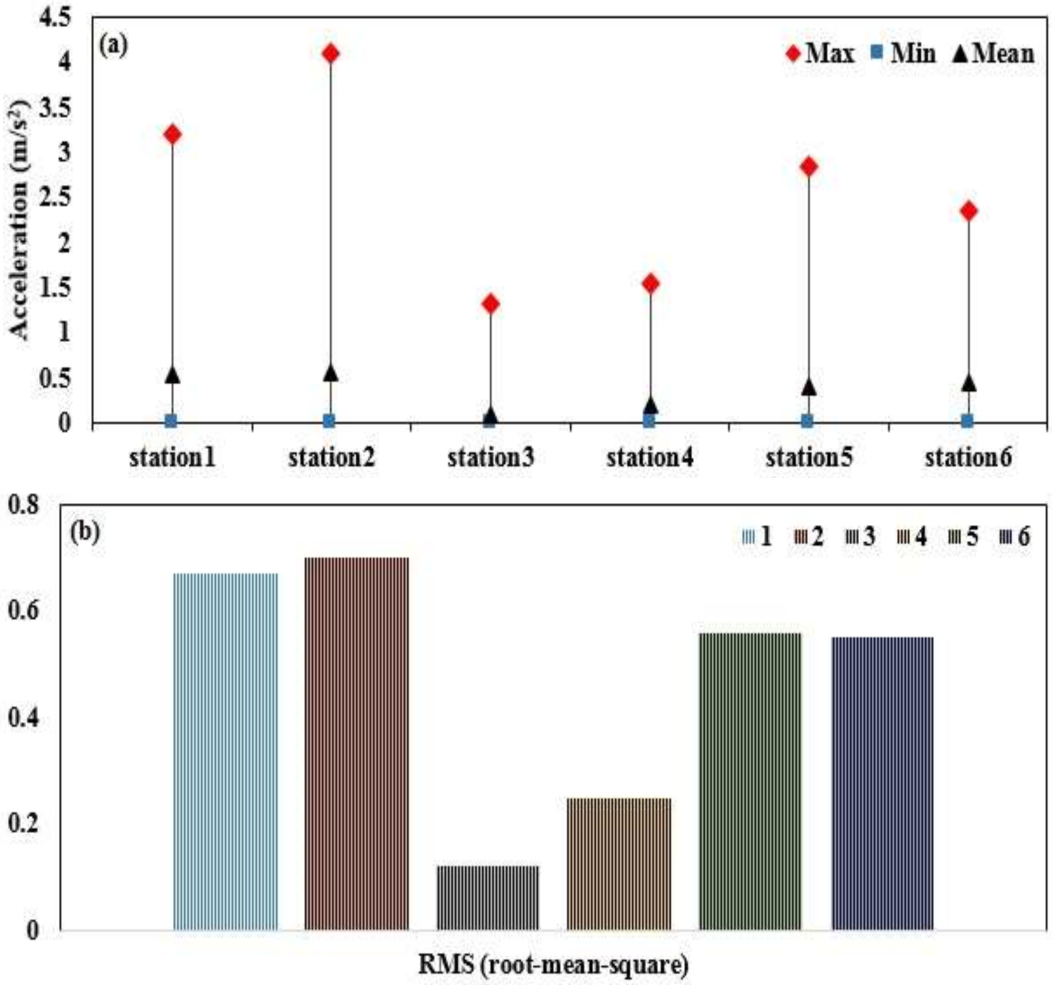

Fig. 7 Value of acceleration: (a) maximum, minimum, and average and (b) RMS.

Stations 3 and 4 have lower maximum and average in comparison to other stations. Also, RMS acceleration as effective values of acceleration shows that stations 1, 2, 5, and 6 due to different track structure from station 1 and 2 have higher values and it is obvious that they have higher vibration amplitude and lower ride comfort. The measurement and evaluation of ride comfort often focus on obtaining vertical and lateral accelerations (a_z and a_y) [31-33]. A comparison of the results of vertical accelerations in 30 studied stations is presented for further investigation ("Fig. 8").

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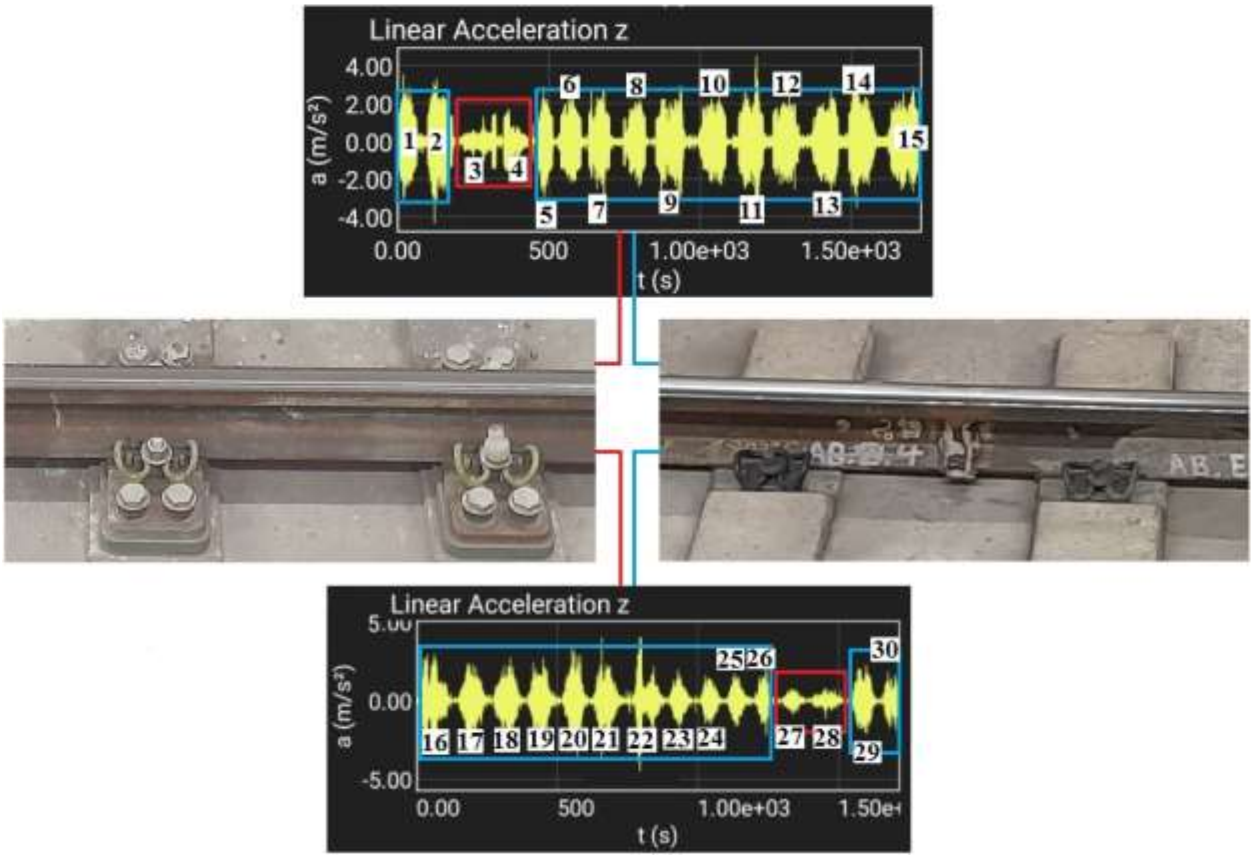

Fig. 8 Comparison of the vertical acceleration range with two different types of fastening systems.

As can be seen in the “Fig. 8”, the range of vertical vibrations in all stations except stations 3 and 4 are almost equal, but in these two stations the acceleration values are much lower (due to the difference in fastening system). There is an elastic pad between the slab track and the rail in the super-elastic system, which is also a kind of stress distributor. If the fastening system is properly designed, the impact loads are greatly reduced and the uplift of the track is controlled. Providing elasticity in the system will be the responsibility of two components. The first and most important element is the fastening system and the second is the resilient layer installed under the slab track. By ensuring the proper connection of the resilient layer, stress reduction occurs from top to bottom. In the Isfahan subway track and stations 3 and 4 (around Si-O-Se-Pol to Imam Hossein Square), there are two elements to ensure the elasticity of the system, which are fastening system and resilient layer under the slab track. According to the proper performance of both elements, the results of “Figs. 5 and 6” show that the vibrations amplitude is in a suitable range. It should be noted that the rest of the stations are within the appropriate and acceptable range from the point of view of comfort and safety. This significant difference in the acceleration values is due to the significant changes in the stiffness of the track in the test locations [12]. Even though subway tracks increase transportation and tourism development by reducing traffic load, but the damage to cultural and historical structures is always caused by vibrations from the concerns of organizations such as UNESCO.

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5 CONCLUSIONS

One of the important challenges in the construction and operation of subway tracks is the amount of damage to nearby structures, especially historical monuments. Although railway tracks are a safe, economical and fast transportation system and can lead to the developing of the tourism industry, the vibrations can damage historical structures in the long-term. Nowadays, slab track systems are used in modern railway tracks in the world for many reasons. The main purpose of a fastening system is to provide strength and reliability to connect the rail to the sleeper and ultimately prevent the rail from moving and disrupting the track. By using the proper fastening system in railway tracks, the elasticity of the slab track superstructure is significantly increased and less damage is done to the track components (increasing useful life). Also, by significantly reducing noise and vibration, they protect sensitive structures and systems next to railway tracks. Reduction of vibrations and noise caused by wheel and track irregularities ensures ride comfort and ride quality. The results of this research showed that if a super-elastic fastening system is used in the desired and sensitive areas, a strong reduction in vibrations and ride comfort will be guaranteed. The results clearly showed that the type of track structure significantly affects the vibrations of the vehicle, passengers, and finally the vibrations transmitted to the environment and ride comfort and safety.

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