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Developing a New Vibration Analysis Calculative Method for Esfahan Subway Train and Railways Design, Manufacturing, and Construction

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Abstract**—**The simulated mass and spring method evaluation for subway or railways construction and installation systems have a wide application in rail industries. This kind of design should be optimizing all related parameters to reduce the amount of vibration in cities, homelands, historical zones and other critical locations. Finite element method could help us a lot to analysis such applications with an excellent accuracy but always developing some simple, fast and user friendly evaluation method required in subway industrial applications. In addition, process parameter optimization extremely required in railway industries to achieve some optimal design of railways with maximum safety, reliability and performance. Furthermore, it is important to reduce vibrations and further related maintenance costs as well as possible. In this paper a simple but useful simulated mass and spring evaluation system developed for Esfahan subway construction. Besides, some of related recent patent and innovations in rail world industries like Suspension mass tuned vibration reducer, short sleeper vibration attenuation fastener and Airtight track vibration-noise reducing fastener discussed in details.

Keywords**—**Subway construction engineering, natural frequency, operation frequency, vibration analysis, polyurethane layer.

I. Introduction

INPUT values that used in this paper are types and thickness of rails, foundation characteristics, ground modules, loading parameter and railways geometry.

For doing this approach, it is important to input all the requested information accurately. This method has two main sub approaches: Recessive approach and vibration approach. Both of the approaches can evaluate the whole system characteristics.

It is important to identify the bed reaction module accurately before starting both sub approaches. The reaction bed module identification is closed to recessive lamination module identification and that is because of using mass and weight system in subway industries. Both of these modules are a function of polyurethane layer characteristics or installation quality of polyurethane and cabin maximum allowable weight or number of passengers and quality of cabin. In addition, it could potentially create different types of frequencies. In usual city subway system with normal quality of ground soil and also acceptable cabin quality it could be supposed to be 0.0036 N/mm^2 for bed reaction module and 2600 N/mm for spring module K in the subway system with mentioned characteristics like Esfahan subway construction [1].

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The natural frequency of the railway could calculated by (1) if c' is dynamic module per N/mm calculated by (2). Furthermore, m is spring weights in Kg, E' is dynamic tensile module per N/mm^2, A is load surface per mm^2 and d is recessive layer thickness per mm. damping quantity K and power transfer I also calculate with (3) and (4) respectively if η related to damping characteristics. In addition, f and f_o are related to loading parameter [2].

$$f_0 = 1/2\pi^2 \sqrt[2]{c'/m} \quad (1)$$

$$c' = \frac{E'A}{d} \quad (2)$$

$$K = 20\log\left[\sqrt{\frac{1+\eta^2}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\eta^2}}\right] \quad (3)$$

$$I = 100\left[1-\sqrt{\frac{1+\eta^2}{\left(1-\left(\frac{f}{f_0}\right)^2\right)^2+\eta^2}}\right] \quad (4)$$

It is worthy to know that if L represents the distance between two rails (train main shaft length) and R is radius of the train main shaft then increasing of the L/R cause to increasing lateral natural frequency [3].

Controlling the train operation vibration will help us to reduce operation risks of long machine in several kilometer underground tunnels [4].

Besides, we should always control the outputs of the vibration method with bed module characteristics and make sure the displacement occur is less than allowable displacements. Then we should first identify all modules and we could perform both dynamic and static analysis. For this purpose the static vibration frequency of rail supposed to be 20 Hz.

The results of this evaluation method confirm the laboratory results and this method considering as a parallel way to evaluating the vibrational behavior of subway systems. In addition, this method is parallel to all vendor graphs in damping layers characteristics presented in all vendor technical documents and related software [5].

II. Literature Review and Significance of This Method

Methods for recording, simulation, and analysis previously have been developed to perform an assessment, which supplies track managers with arguments on track design and track maintenance.

The railway track vibration behavior for design and maintenance recently classified and investigated [6].

Several interesting investigations recently take place by assist of technical and professional data collectors and related soft wares [7].

In addition, a new vertical vibration analysis method of the periodic rail support that improves the prediction of the rail response for both low and high Frequencies introduced [8]. The model of the periodic support consists of two three-directional Kelvin-Voigt systems for the rail pad and the ballast, and a mixed Kelvin-Voigt/Maxwell system for the subgrade. This method could only present for the case of the stationary harmonic loads.

Besides, analysis of propagation of vibration wave excited by the movement of trams in the soil on which is planned to build multi-storey residential buildings is recently investigated [9].

The developed method allows determining the wave vibration in the ground without necessity to perform complex measurements of soil vibration but the rail and train cabin could not be evaluated in this system. In this paper a new calculative method for case of both rotary and stationary harmonic loads investigated in rail, train cabin and the foundation for the first time. This method successfully performed for the Esfahan rail ways design, manufacturing and construction.

III. Experimental details

The mentioned method used in subway train construction of Esfahan and at the end the results compare with other traditional evaluations about all different parameter in this field. The polyurethane layer with 25 millimeter thickness covered completely or surrounding by 12 millimeter thickness two concrete. The live stress due to the train motion tested between 0 and 0.025 N/mm^2 for the rail material and geometry and also all ground characteristics (found in technical document of this kind of train and rail way vendor).

The wide of the rail is 2.6 meter with checking the polyurethane technical documents tables we could loading up to 0.75 N/mm^2 in operation time. The system base whole on mass and spring completely used both in semi deep and deep constructions.

The Esfahan subway construction engineering has 40 cm depth for rail system, 70 cm traverse gap and slope is 30/1000. In addition, types of rail are S49. There is also a critical path in this construction engineering. That is because of several historical zone located between Takhti and Azadi square some of them have more than 500 years old. These buildings and bridges are so sensitive to vibration because of their special paintings, arts and architecture then the group decided to design some kind of light weight and spring damping system in this area.

Several different variant tested for a purpose. The results will explain in the next sections. The mentioned method used for modeling, simulating and evaluation of the subway construction in Esfahan. For elasticity module of recessive layers evaluation under dead loads group used vendor graphs and it was estimated 0.012N/mm^2 and for dynamic module estimation the frequency supposed to be 20 Hz. The density supposed to 200kg/m3 all above parameter adjusted to limit static displacement less than 4 mm and dynamic displacement less than 3 mm. The lateral share recessive module should be evaluated by the height of lateral recessive profile. Two standard scenarios tested in this matter plan A. 250mm plan B. 360mm [10].

IV. Result and discussion

Tables I to VII represented the results of vibration and recessive evaluations. Table I and II showed the recessive and reactionary evaluations of the system. The dynamic and static displacement reduced by increasing the thickness from 40 to 45cm this phenomenon have two main reasons, the height 5cm increased and changing in polyurethane layer characteristics.

TABLE I
Linear Displacement and Other Subway Instruction Characteristics of Deep Tunnels - Polyurethane Layer Thickness Equal to 25mm

Upper thickness cm	Spring coefficient lateral elastic layer KN/mm	Bed module static N/mm^3	static Spring coefficient KN/mm	Dynamic Basic bending index mm	Static Basic bending index mm	Dynamic Rail displacement mm	Static Rail displacement mm	Static pressure on recessive Layer N/mm^2 Operation condition	Static pressure on recessive Layer N/mm^2 Only rails	Axial load Ton
40	1.433	3650	2.85	3476	3639	2.94	3.39	0.0243	0.012	12.5
45	1.433	3790	2.96	3762	3937	2.65	3.08	0.0237	0.012	12.5
40	1.433	3500	2.73	3515	3679	3.41	3.93	0.0257	0.012	14
45	1.433	3550	2.77	3824	4002	3.13	3.65	0.025	0.012	14

TABLE II
LINEAR DISPLACEMENT AND OTHER SUBWAY INSTRUCTION CHARACTERISTICS OF SEMI DEEP TUNNELS - POLYURETHANE LAYER THICKNESS EQUAL TO 25MM

Upper thickness cm	Spring coefficient lateral elastic layer KN/mm	Bed module static N/mm^3	static Spring coefficient KN/mm	Dynamic Basic bending index mm	Static Basic bending index mm	Dynamic Rail displacement mm	Static Rail displacement mm	Static pressure on recessive Layer N/mm^2 Operation condition	Static pressure on recessive Layer N/mm^2 Only rails	Axial load Ton
40	2.006	3650	2.85	3476	3639	2.94	3.39	0.0243	0.012	12.5
45	2.006	3600	2.91	3742	3995	2.55	3.13	0.025	0.012	12.5
40	2.006	3500	2.73	3515	3679	3.41	3.93	0.0257	0.012	14
45	2.006	3550	2.77	3824	4002	3.13	3.65	0.025	0.012	14

The results of natural frequency calculation presented in Table III. The two main factors in such calculation are dynamic module of recessive layer and the weight of the spring system. By increasing in spring system weights the natural frequency decrease considerably. That is why the natural frequency decrease in operation condition comparative to rail natural frequency without train loading.

Then it is strongly recommended to adjust dynamic characteristics of recessive layers to fix the rail natural frequency of rail system. We should always keep this important item less than 18 Hz. increasing in lateral profile dimension cause slight increase in rail line natural frequency. That is because of increasing in effective bed dynamic module of the system due to such dimension changings. Table III shows that with increasing axial load from 12.5 to 14 ton there is no considerable changing in natural frequency of the system and this item almost constant during this increasing in axial load.

The vibration damping criteria in operation frequency is 60 Hz and indicates in Table III. Vibration damping criteria is almost 20 decibel for mentioned historical zone. The results will confirm the suitability of mentioned items adjusting for construction condition in this critical subway rail line [11].

TABLE III
NATURAL FREQUENCY AND VIBRATION DAMPING CRITERIA IN 60 HZ ESFAHAN SUBWAY CONSTRUCTION CHARACTERISTICS

considerations	Vibration reduction dB	Natural frequency Hz for dynamic train	Natural frequency Hz for static train	Dynamic Rail displacement mm	Static rail displacement mm	Axial load Ton
Lateral profile height equal to 350mm	-20.2	17.7	20.8	2.65	3.08	12.5
Lateral profile height equal to 250mm	-20.6	17.2	20.4	2.65	3.08	12.5
Lateral profile height equal to 350mm	-20.0	17.9	20.8	3.13	3.65	14
Lateral profile height equal to 250mm	-20.2	17.6	20.4	3.13	3.65	14

Damping vibration system also shown in Tables IV-VII between the frequency band 0-200 Hz. damping criteria calculated by formula 4 mentioned before. Damping characteristics increased by increasing in frequency. In the natural frequency range the vibration amplitude increasing considerably by increasing in train loading. These phenomena continue up to resonance frequency that is equal to 1.414f° but fortunately decreased after passing resonance and damping. The line frequency always should be passing the natural frequency in an extremely short period of time [12] and also line frequency should be much far away than natural frequency to avoid resonance in any further train condition as well as possible.

Due to the results explained in Tables IV-VII. It is strongly recommended that the line and train natural frequency keep under 18 Hz in any subway application in Esfahan subway construction (it is also possible to keep this parameter around 15 Hz) [13].

As mentioned before the line and train operation frequency is around 25 Hz that is much far than the designed natural frequency (15 Hz); therefore, we could adopted all the operation criteria like displacements and stresses with vibration criteria like natural frequency, operation frequency and damping in railway system using polyurethane layer [14].

In addition, it is strongly recommend increasing the polyurethane layer up to 37 millimeter in critical historical zone between Takhti and Azadi square to protect harmful effects of subway vibration transfer to historical bridges and buildings as well as possible [15].

One of the new patent and innovation in subway industries is Suspension mass tuned vibration reducer introduced by china railways construction 2011. Suspension mass tuning shock absorber, has lower suspension spring connected with main piston that is connected with main piston lug, and cylinder body comprising discontinuously penetrating box wall that is filled with damping liquid.

The utility model has the beneficial effects. The suspension mass tuned vibration reducer has a simple and compact structure and low cost good effects of vibration reduction and insulation can be achieved, and adjustment can be facilitated and expansion can also be facilitated, the effect of vibration reduction can be promptly adjusted through an external hydraulic or gas pressure control system, and the suspension mass tuned vibration reducer has good stability [16].

Construction technology of short sleeper vibration attenuation fastener with improved structure replacing elasticity short sleeper developed in recent years. The invention belongs to the technical field of rails, and particularly relates to a construction technology of a short sleeper vibration attenuation fastener with an improved structure replacing an elasticity short sleeper. The construction technology is simple and rapid, low in maintenance and construction cost [17].

Moreover Airtight track vibration and noise reducing fastener for railway track, has bolt hole provided between support plate and airtight bases corresponding to support plate, and anchor bolt fixed with sleeper through bolt hole, developed in China 2010.

The utility model has the advantages that vibration isolating rubber material works in a closed space to prolong the service life, and when the performance is reduced after long-term use, only the rubber pad plate needs to be replaced to save maintenance cost and when the higher vibration isolating effect is provided, the higher torsional stiffness of the track and the traffic safety are ensured [18].

Railway wheel sensor developed recently in rail industries. Railway vehicle for example subway train, wheel sensor for streetcar, has magnet producing magnetic field in Hall Effect detectors, and vibration sensor sensing vibrations caused by railway vehicle and producing vibration indicating signal a sensor for detecting the presence of wheels of a rail vehicle is disclosed.

The sensor comprises first and second Hall Effect devices, a magnet for supplying a magnetic field to the first and second Hall Effect devices, means for mounting the first and second Hall Effect devices and the magnet adjacent to the rail, whereby a railway vehicle wheel changes the magnetic field in the Hall Effect devices to produce wheel indication signals, and a processing circuit for receiving the wheel indication signals from the first and second Hall Effect devices and for producing an output signal in response to the wheel indication signals. A method of detecting the presence of a wheel is also provided [19].

TABLE IV
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 250 MM WITH AXIAL LOAD EQUAL TO 12.5 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-101	6.1	12.5	17.2	20.4
-299	12	16	17.2	20.4
-137	7.5	20	17.2	20.4
9	-0.9	25	17.2	20.4
55	-7	31.5	17.2	20.4
75	-12.2	40	17.2	20.4
85	**-16.5**	**50**	17.2	20.4
91	**-20.6**	**63**	17.2	20.4
94	**-24.5**	**80**	17.2	20.4
96	-28	100	17.2	20.4
97	-31.3	125	17.2	20.4
99	-40.8	250	17.2	20.4

TABLE V
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 250 MM WITH AXIAL LOAD EQUAL TO 14 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-103	6.2	12.5	17.6	20.4
-306	12.2	16	17.6	20.4
-130	7.2	20	17.6	20.4
11	-1	25	17.6	20.4
56	-7.1	31.5	17.6	20.4
76	-12.3	40	17.6	20.4
85	**-16.6**	**50**	17.6	20.4
91	**-20.7**	**63**	17.6	20.4
94	**-20.6**	**80**	17.6	20.4
96	-28.1	100	17.6	20.4
97	-31.4	125	17.6	20.4
99	-40.8	250	17.6	20.4

TABLE VI
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF SEMI DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 360 MM WITH AXIAL LOAD EQUAL TO 12.5 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-93	5.7	12.5	17.2	20.4
-271	11.4	16	17.2	20.4
-167	8.5	20	17.2	20.4
2	-0.1	25	17.2	20.4
52	-6.5	31.5	17.2	20.4
74	-11.7	40	17.2	20.4
84	**-16.1**	**50**	17.2	20.4
90	**-20.2**	**63**	17.2	20.4
94	**-24.1**	**80**	17.2	20.4
96	-27.7	100	17.2	20.4
97	-31	125	17.2	20.4
99	-40.5	250	17.2	20.4

TABLE VII
NATURAL FREQUENCY AND VIBRATION REDUCTION AS A FUNCTION OF SEMI DEEP TUNNEL FREQUENCY AND LATERAL PROFILE HEIGHT EQUAL TO 360 MM WITH AXIAL LOAD EQUAL TO 14 TON

I(equation 4)%	K(equation 3)dB	frequency	System natural frequency in operation condition	System natural frequency only rails
-95	5.8	12.5	17.6	20.4
-278	11.5	16	17.6	20.4
-159	8.3	20	17.6	20.4
4	-0.3	25	17.6	20.4
53	-6.6	31.5	17.6	20.4
74	-11.8	40	17.6	20.4
84	**-16.2**	**50**	17.6	20.4
90	**-20.3**	**63**	17.6	20.4
94	**-24.2**	**80**	17.6	20.4
96	-27.7	100	17.6	20.4
97	-31.1	125	17.6	20.4
99	-40.5	250	17.6	20.4

V. CURRENT AND FUTURE DEVELOPMENT

In this paper a calculative method introduced for subway construction engineering vibration analysis. Related formulations and equations introduced (I or K=f(f(Hz)). Furthermore, a case history related to Esfahan subway construction and its critical line (historical zone vibration considerations) explained in details. Finally the adaptation of these results with other commercial methods discussed and the calculative method successfully performed.

Both results confirmed that with suitable design of rail ways dimension, materials, control the loading condition of cabins (with cabins quality and dimensions), polyurethane layer thickness and characteristics, we could keep the subway natural frequency around 18 Hz .

These kind of process parameter optimization could protects all historical buildings and bridges from any potential harmful vibration generated by subway trains in any further operation times. These results only consist of vibration generated by subway operation and the vibration generated by construction machinery or any possible explosive activity should be design and limits by parallel investigations.

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