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Vibration isolation design of railroad tracks within Ankara high speed train station

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Ankara serves as the hub for high speed railway operations within Turkey. A new station building of nine stories in total, which incorporates a shopping mall and a hotel inside, is currently under construction. Need arises for controlling vibrations due to passing trains through the building. Finite element model of the building is developed by commercial software. The interaction of the building with the foundation is represented by a number of spring and damper combinations whose characteristics are obtained from the existing knowledge of soil-structure interactions. Dynamic stiffness characteristics of the isolating layer under the railway slabs are sought. The Frequency Response Functions (FRF's) between several floors of the building and the base of the track are obtained from the finite element model, to be coupled with FRF's of the train-track-isolating layer system. Vibration isolation design is carried with respect to vibration criteria in Turkish environmental noise regulations.

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INTRODUCTION

A strong impetus by the Turkish government is set forth to establish a high speed train network in Turkey. It is decided to have the capital city Ankara to serve as the hub of the network. Upon completion of MARMARAY which also involves tube crossing of Bosphorus under the sea the network included rail connection between two major cities Ankara and Istanbul, which is the extension of first leg between Ankara and Eskisehir. Another leg of the network between Ankara- Konya is currently in operation. Plans are underway to extend the network to other cities, to Bursa and İzmir in the West and to Sivas in the East in the near future. Figure 1 shows the status of high speed railroad network in Turkey as of May 2015.

This study aims to develop a methodology to design vibration isolation system under the tracks within the station building. Interactive dynamics of the station building and railroad car and track system are considered through FRF/impedance coupling. The building is modeled by finite elements to obtain FRF's between relevant locations. Soil parameters are also employed to model dynamics of the building on elastic foundations. Lumped parameter model of the car and track system is available from previous studies by Forrest and Hunt, and Alan and Caliskan [5-7].

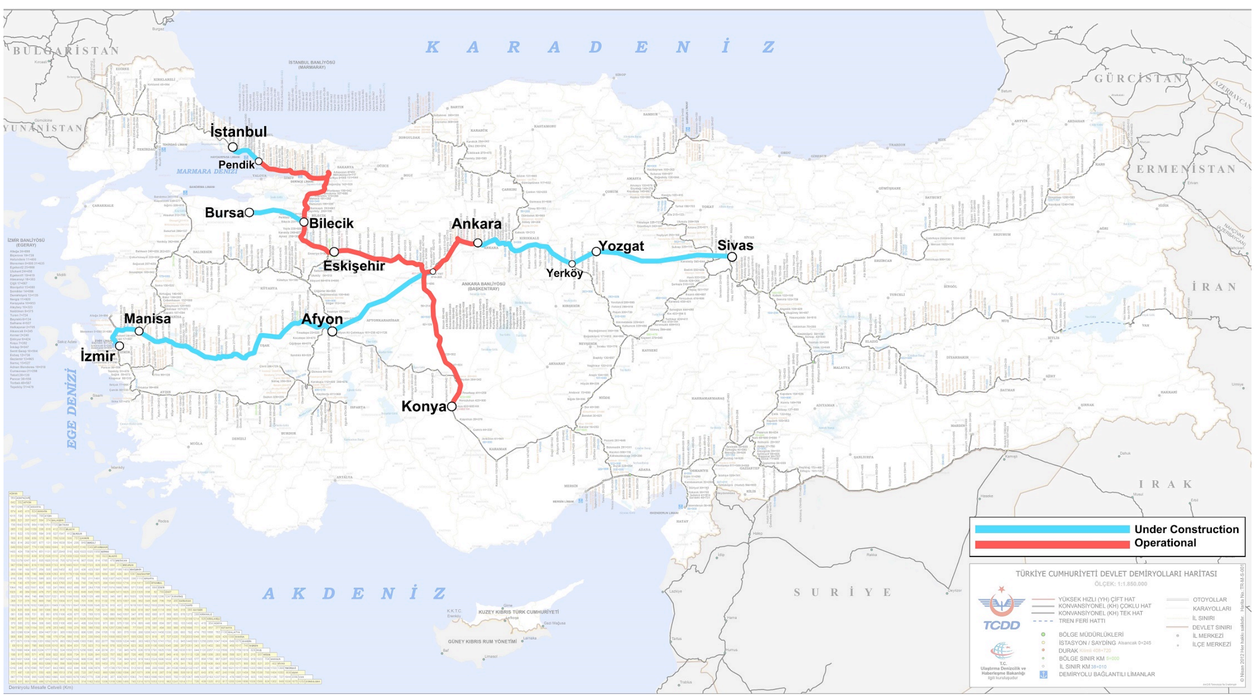

Figure 1: Map of high speed lines in Turkey

VIBRATION ASSESSMENT CRITERIA

In similar analyses in Turkey, two assessment criteria are applied: Turkish Environmental Noise Regulation (TENR) and Federal Transit Administration (FTA) criteria [1-3]. TENR first enforced in 2005. It has been revised twice since then. The latest revision appeared in April 2011. The vibration measures introduced in 2005 remained unchanged through the revisions. In TENR, vibration criteria are specified for residential and office uses, and other land uses are not covered. The usual practice in the projects in Turkey is to employ Turkish version of ISO 2631-2 standard unless otherwise specified [4]. FTA criteria are also used for land uses other than residential and office uses when specified at the tender stage. In Figure 2, the vibration criteria by TENR and FTA are compared.

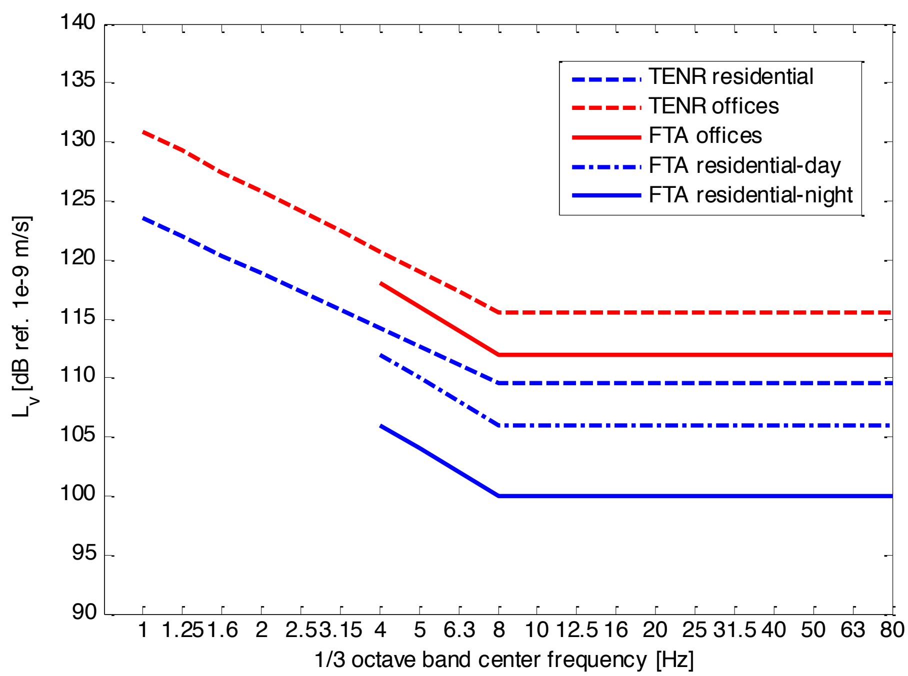

Figure 2: Comparison of assessment criteria

MODELING

Interactive dynamics of the car and track work with that of the building needs to be considered in the study of environmental vibrations originating from train movements on the tracks within the station building where maximum speed of travel is limited to 50 km/h. An analytical model can be devised for the car and track work (Figure 3) [5-7]. A finite element model is needed to study structural dynamics of the station building.

Analytical Model of the Car and Track Work System:

Physical model of the railroad car and track system is demonstrated in Figure 3. It should be noted that the track floor is not rigid and can be viewed as an integral part of the station building.

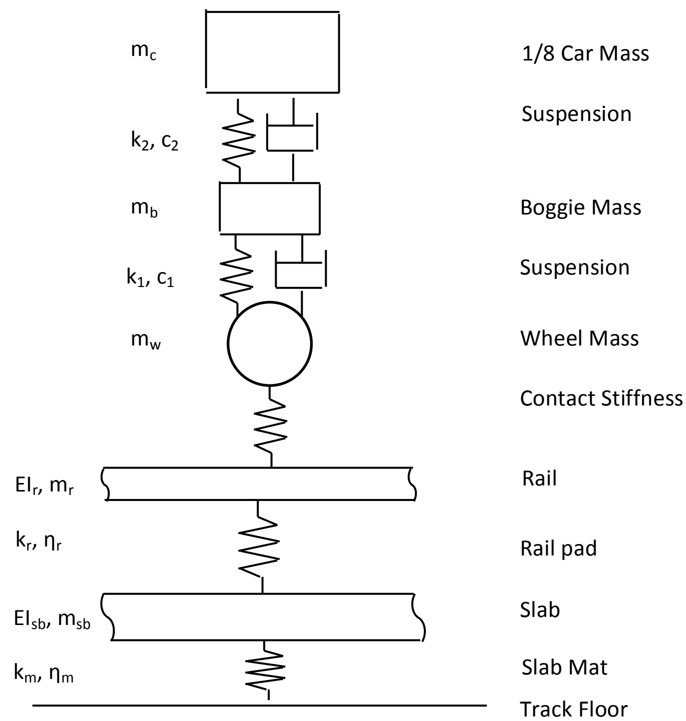

Figure 3. Physical Model of the Car and Track Work

The following procedural steps are followed in the modeling process:

1. Frequency response functions between displacement responses of a point on any floor (retail, hotel etc.) of the station building due to unit force applied on the track work floor are obtained from the finite element model of the building.
2. Frequency response function representing the displacement of the track floor due to the unit force applied on the same location can be obtained. Loads developed due to rail and wheel irregularities on the track floor can be calculated analytically from the model illustrated in Figure 3. Displacement as well as velocity response for the most critical location, that is, hotel floors, due to these forces applied on the track floor is determined by the corresponding FRF's.
3. Excitation due to rail and wheel irregularities is taken as the main forcing mechanism on the car-track system. It is assumed that rail and wheel irregularities have a spectrum in terms of frequency, f and car speed, v as given by [5,8]:

$$S_0(f) = a/[v(b + f/v^3)] \tag{1}$$

Table 1. Parameters of Rail and Wheel Irregularities [8]

	$a\left(mm^2 \cdot (1/m)^2\right)$	$b(1/m)$
Worst	9.39e-1	6.89e-2
Average	1.31e-2	2.94e-2
Best	1.90e-4	9.71e-3

4. Wheel spacing of the cars are considered in the analytical modeling. Figure 4 displays the wheel configuration on two sequential cars.

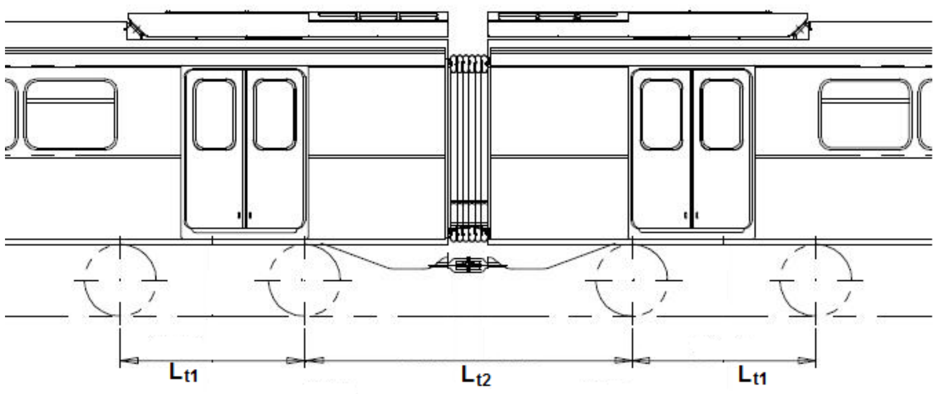

Figure 4. Wheel Configuration for Two Consecutive Cars

Finite Element Model of the Station Building:

Station Building shown in Figure 5 is designed by A-Architectural Design Inc. of Ankara, Turkey. The contractor is the joint venture of CLK (Cengiz-Limak-Kolin) of Turkey. It has 9 stories and covers an area of 336 m by 93 m. The height of the building from ground is 45 m and 53 m from the basement floor level. Car parking facility is provided in the two basement floors. It houses a shopping mall and a 5-star hotel in its upper floors (Figure 5).

A finite element model is developed for the station building in ANSYS platform. The model consists of 26.792 beam elements and 20.186 shell elements. Equivalent springs and dampers are assigned to represent soil-structure interaction at the boundary in horizontal and vertical directions. The stiffness and damping values for such spring-damper combination (COMBIN14) elements are determined by following the procedures outlined in [9]. Mechanical properties of the soil, bearing area and embedment height of the building along with its weight are taken into account in this soil-structure interaction model (Figure 6).

Figure 5. Render of High Speed Train Station in Ankara

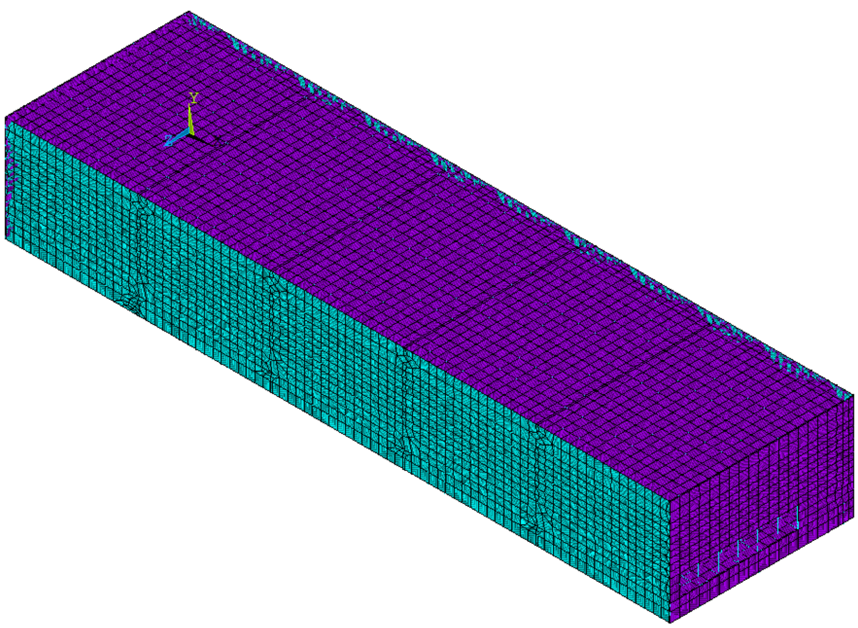

Figure 6. Finite element mesh for the building

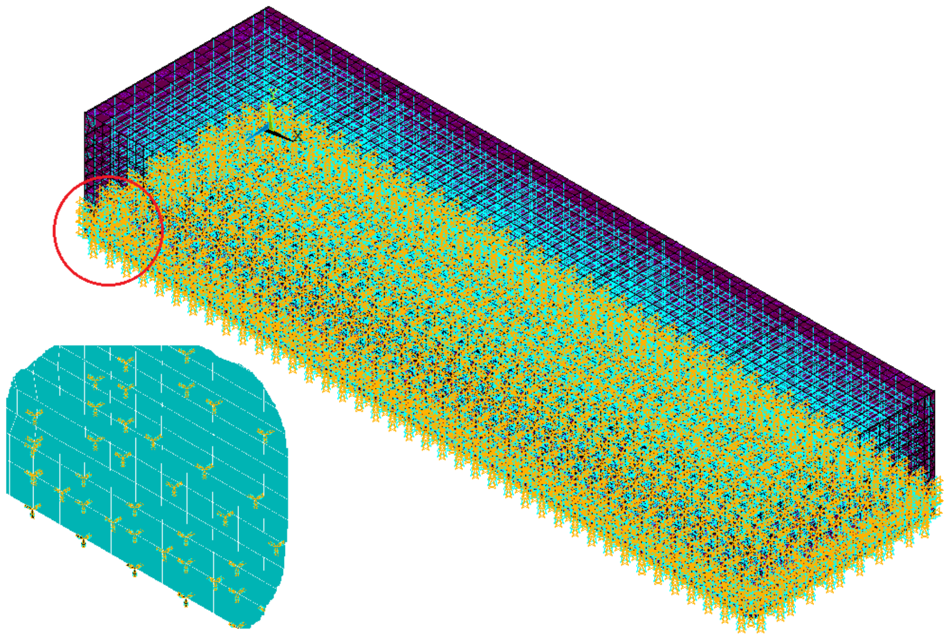

Figure 7. Soil structure interaction model

The equation of motion for the rail-slab beam system can be written in wavenumber domain as:

$$\begin{bmatrix} EI_r\beta^4 - \omega^2 m_r + k_r & -k_r \\ -k_r & k_r + EI_{sb}\beta^4 - \omega^2 m_{sb} \end{bmatrix} \begin{Bmatrix} u_r(\beta) \\ u_{sb}(\beta) \end{Bmatrix} = \begin{Bmatrix} P_r(\beta) \\ P_{sb}(\beta) \end{Bmatrix} \quad (2)$$

The FRF matrix in wavenumber domain is obtained by inverting the coefficient matrix:

$$\begin{bmatrix} H_{r,r}(\beta) & H_{r,sb}(\beta) \\ H_{sb,r}(\beta) & H_{sb,sb}\ (\beta) \end{bmatrix} = \begin{bmatrix} EI_r\beta^4 - \omega^2 m_r + k_r & -k_r \\ -k_r & k_r + EI_{sb}\beta^4 - \omega^2 m_{sb} \end{bmatrix}^{-1} \quad (3)$$

Inverse Fourier transform is used to obtain the FRF's in the space domain:

$$H(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty} H(\beta) e^{i\beta x} d\beta \quad (4)$$

Following the configuration in Figure 4, FRF's in space domain are calculated between four wheel locations on rail and corresponding location on the slab beam using Equation (4). Impedance coupling is used to couple the track floor dynamics to the rail-slab beam system. For the cases with and without the application of the mat, respectively:

$$[K_{r,sb,tf}] = [K_{r,sb}] + \begin{bmatrix} 0 & 0 \\ 0 & H_{tf,tf}^{-1} \end{bmatrix} \quad (5)$$

$$[K_{r,sb,tf}] = \begin{bmatrix} [K_{r,sb}] & \begin{matrix} 0 \\ 0 \end{matrix} \\ \begin{matrix} 0 & 0 \end{matrix} & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & k_m & -k_m \\ 0 & -k_m & k_m + H_{tf,tf}^{-1} \end{bmatrix} \quad (6)$$

$$[K_{r,sb}] = \begin{bmatrix} H_{r,r} & H_{r,sb} \\ H_{sb,r} & H_{sb,sb} \end{bmatrix}^{-1} \quad (7)$$

The dynamic stiffness of the rail beam is the first component of the matrix$[K_{r,sb,tf}]$. Along the rail beam these components can be written as:

$$[K_r] = \begin{bmatrix} K_{r,r}(0) & K_{r,r}(L_{t1}) & K_{r,r}(L_{t1}+L_{t2}) & K_{r,r}(2L_{t1}+L_{t1}) \\ K_{r,r}(L_{t1}) & K_{r,r}(0) & K_{r,r}(L_{t2}) & K_{r,r}(L_{t1}+L_{t2}) \\ K_{r,r}(L_{t1}+L_{t2}) & K_{r,r}(L_{t2}) & K_{r,r}(0) & K_{r,r}(L_{t1}) \\ K_{r,r}(2L_{t1}+L_{t2}) & K_{r,r}(L_{t1}+L_{t2}) & K_{r,r}(L_{t1}) & K_{r,r}(0) \end{bmatrix} \quad (8)$$

The dynamic stiffness components, k_{ij}, of the rail beam are coupled with the dynamic stiffness term for the vehicle as:

$$\begin{bmatrix} k_{11} & k_{12} & k_{13} & k_{14} & k_v \\ k_{21} & k_{22}+k_v & k_{23} & k_{24} & 0 \\ k_{31} & k_{32} & k_{33}+k_v & k_{34} & 0 \\ k_{41} & k_{42} & k_{43} & k_{44}+k_v & 0 \\ -1 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_v \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \Delta \end{Bmatrix} \quad (9)$$

The dynamic stiffness term,k_v, for the vehicle is obtained by using the vehicle parameters [10]. In equation (9) at position of the first wheel, the surface roughness displacement, $\delta = \Delta e^{i\omega t}$, is applied between the wheel, Y_v, and rail, Y_1, displacements. Solving equation (9), the displacement vector, Y_r, on the rail is obtained. The corresponding loading, P_r, can be obtained on the rail by :

$$\{P_r\} = [K_r]\{Y_r\} \quad (10)$$

The response of the track floor at the location of the train and the response at the different locations of the building can be calculated by using the dynamic loading obtained in (10).

RESULTS

Stiffness characteristics of slab mat in the track work needs to be determined in such a way that the resulting vibration levels in the floors of the building comply with the specified vibration criteria. Values of parameters used in the design are tabulated in Table 2. The specified slab mat characteristics in the table belong to the design that complies with the vibration criteria. Figure 8 and 9 present the vibration velocity prediction and the comparison with the related criteria, for a hotel room and a shop floor in retail area, respectively.

Table 2. Parameter Values in Analytical Model

1/8 Car Model	Soil
m_c=6919 kg	E_s=35 MPa
m_b=2273 kg	ν_s=0.35
m_w=742 kg	ρ_s=19 kN/m^3
k_1=8.75 x 10^5 N/m	G_s=12.96 MPa
k_2=3.04 x 10^5 N/m	**Track (Rail:UIC60)**
c_1=8.7 x 10^3 Ns/m	EI_r=6280000 Pa m^4
c_2=2.1 x 10^4 Ns/m	m_r=60.21 kg/m
L_{t1} = 2.5 m	EI_{sb}=4.79 x 10^9 Pa m^4
L_{t2} = 4.28 m	m_{sb}=3330 kg/m
Slab mat	**Rail pad**
k_m= 30 x 10^6 N/m^3	k_r=136 x 10^6 N/m
η_m=0.3	η_r=0.174

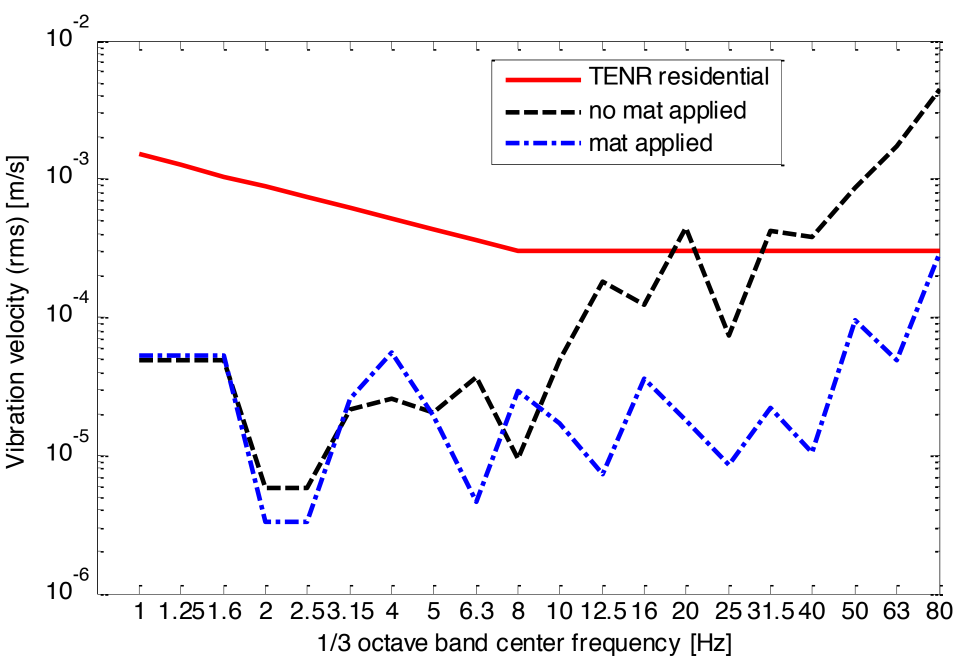

Figure 8. Vibration velocity prediction for a hotel room in the 8th floor

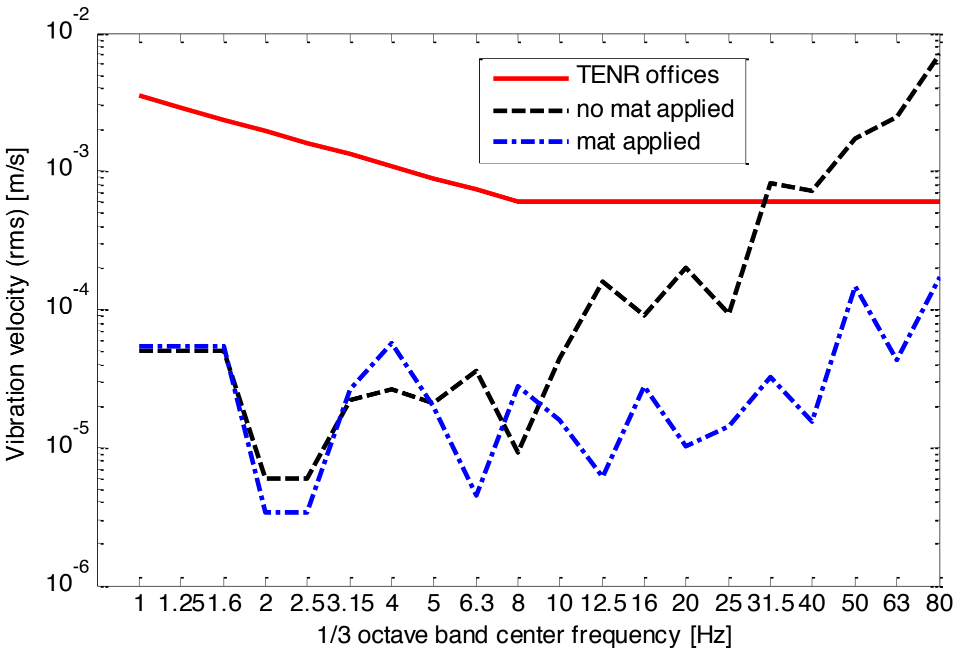

Figure 9. Vibration velocity prediction for retail in the 5th floor

CONCLUSIONS

It is demonstrated that the vibration isolation design can be optimized for compliance of any specified criteria by integrating a lumped parameter model of the car and track system with the numerical model of the building structure through impedance coupling. Unknown stiffness characteristic of the slab mat is calculated as 30 MN/m^3 to comply with two different criteria arising from two different functions, namely, retail and hotel uses. A powerful tool of FRF/impedance coupling is proven to be very convenient and effective in such a design activity.

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