NOISE AND VIBRATION PROBLEM IN THE NEIGHBOR-HOOD OF THE BUDAPEST M4 METRO LINE

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The M4 metro line has been opened to the public in the March of 2014 being 7.4 km long with 10 stations and automatized trains operating at the present. The tunnel is 13m under the ground level where the test runs began at the end of 2013. Between two of the stations inhabitants, who live in the suburban-like area, filed complaints to the operators during the test runs especially for night time metro passings. The test track can be found at a section which has special vibration mitigation measures implemented in the right track.
It must be noted that more stringent limit values were defined than the present regulations prescribe both for the metro tunnel and inside the buildings for environmental vibration and for maximum noise level as well.
The results of the many noise and vibration measurements showed that values were under the limits inside the buildings. The measured vibration values were higher though at some frequencies than the defined limits. According to this, the operator would like to find solution with a help of a vibration study.
From the results of the measurements, conclusions can be drawn corresponding to the condition of each trains. Some of the trains had old wheel profiles (K5) while som had new profiles (K6). After the measurements the metro trains were divided into three different groups corresponding to the conditions of the wheels. In the prepared study international mitigation measures, which brought trustable results, were presented as well.
Between these two stations a curve can be found. For the evaluation of the condition of the track further measurements were conducted. Three vibration accelerometers were placed on the train and measurements were performed between the two stations in both tunnels. Two meters were placed on the axes of the train, and one was placed at the middle of the train’s floor. From these measurements the critical section of the track originating from the interaction of the track and the train can be determined.
At the end of 2016, further detailed measurements were performed for the evaluation of the noise and vibration complaints which could help determine the further needed mitigation measures.

Keywords: metro, track, noise, vibration

1. Introduction

Between two of the stations inhabitants, who live in the suburban-like area, filed complaints to the operators during the test runs especially for night time metro passings.

The noise and vibration limit is the following for one passing by:

- 42dB $L_{max;}$
- 18 mm/s^2 for maximum value

2. Present vibration mitigation in the track

During the construction of the M4 metro in Hungary the following resilient rubber layers were built in at the sensitive areas the station and the tunnel sections:

- Section no. 1 layers: Zwp 377/155/10 (FF10) with rail pad
- Section no. 2 layers: DFMA-M10 under ballast mat (20mm) + Zwp 377/155/10 (FF10) with rail pad
- Section no. 3 layers: DFMA-M6 under ballast mat (30mm)+Zwp 377/155/10 (FF10) with rail pad

According to the sample cross section the under ballast mat was built under the filling concrete. The under ballast mat was protected from mechanical impacts during the construction by covering it with geotextile.

Between two stations (Bikás park and Újbuda-központ) the substructure of the right and left tracks are different. The following cross section figures (Figure 1. and 2.) show the two tracks sub-structure:

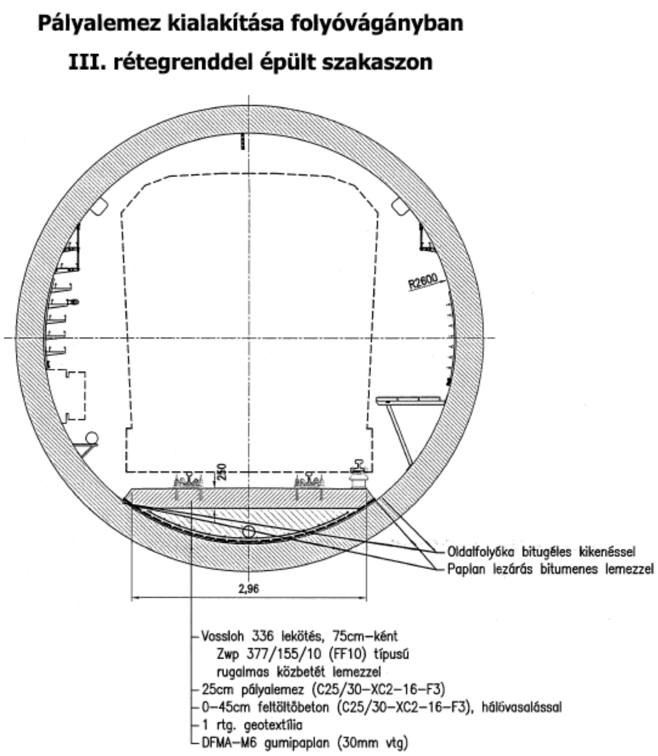

Figure 1: Cross section of the right track between 13+05,50 and 19+56,25 hm

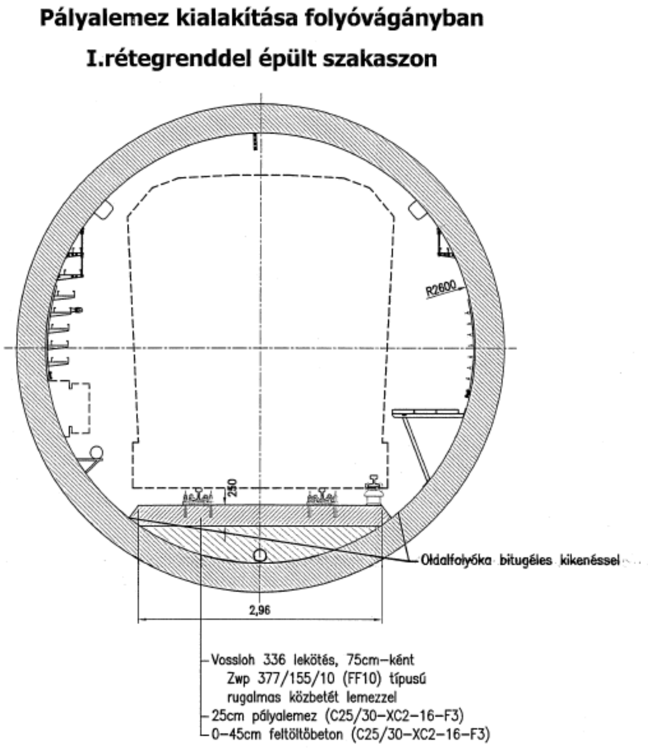

Figure 2: Cross section of the right track between 19+76,50 and 26+85,50 hm and the left track between 13+10,00 and 26+00,00 hm

3. Noise and vibration measurements

3.1 Circumstances of the noise and vibration measurements

The noise and vibration measurements were carried out at residential buildings and in the tunnel as the following:

- One tri-axial acceleration meter and one microphone was placed in the living room
- One tri-axial acceleration meter and one vertical accelerometer was placed in the tunnel

In living rooms one tri-axial acceleration meter and one microphone were placed at the center of the room. The vibration values and noise levels were measured simultaneously with a 4-channel noise and vibration meter.

Besides the above, two acceleration meters were installed in the tunnel: one tri-axial acceleration meter in the axis of the track, on the track plate and one vertical accelerometer on the tunnel's wall.

3.2 Results of vibration emission measurements

During the assessment of the individual measurement points, frequency analysis was performed for the measurements in the tunnel, in order to determine the disturbing effects of the subway passing with the highest values.

The velocity data of that passing were obtained from BKV Zrt., acquired from the ATC data.

19+50 hm left track (in the axis of the track)

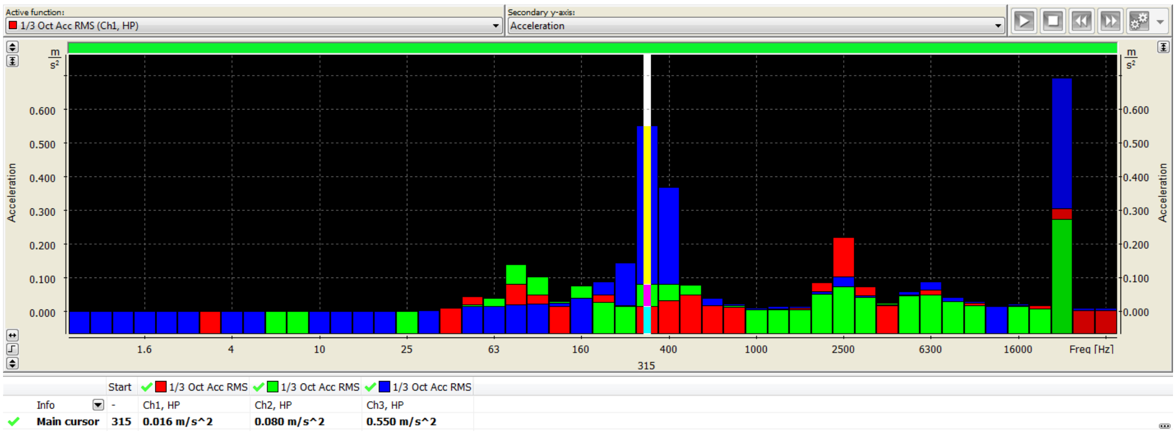

Figure 3: Frequency function of the highest vibration values measured at 19+50 hm in the axis of the left track

19+50 hm left track (on the tunnel's wall)

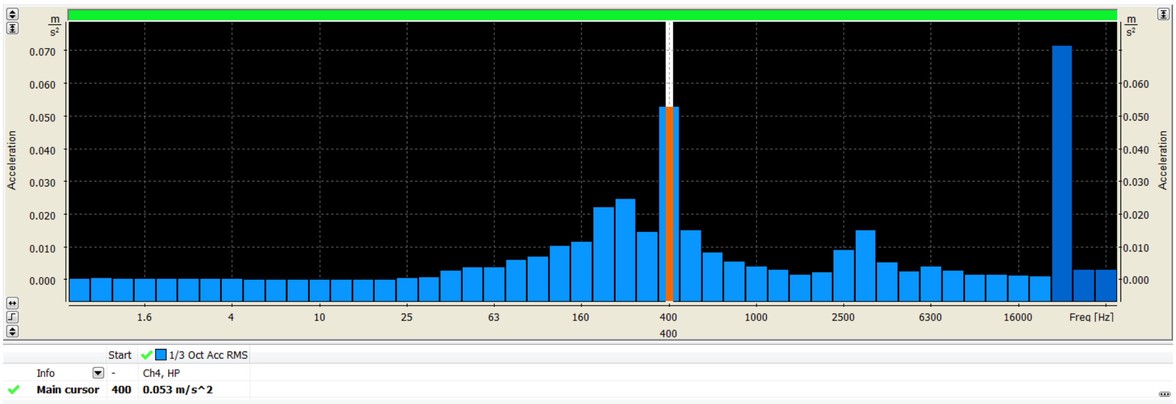

Figure 4: Frequency function of the highest vibration values measured at 19+50 hm on the wall of the left track

The trains were running at a speed of 58 km/h average. Vibration values measured on the wall are deviating in a wide range (between 63 and 630 Hz).

The weighted maximum acceleration values measured in the axis of the track and on the tunnel wall were linked to the associated average train speed according to the following table (Table 1.):

Table 1: Maximum acceleration values

Location	Maximum acceleration in the axis of the track (mm/s^2)			Maximum acceleration on the tunnel wall (mm/s^2)	Average speed (km/h)
	X	Y	Z		
15+50 hm right	19.724	21.878	231.739	4.519	70
15+50 hm left	4.677	4.121	16.406	2.317	45-50
17+01 hm left	14.962	13.964	14.962	6.026	58
19+50 hm left	7.852	13.804	31.623	6.095	58
22+25 hm right	10.000	9.886	57.544	14.791	56
22+00 hm left	5.689	6.918	52.481	12.303	70

3.3 Results of vibration immission measurements

The following tables illustrate the values of the passings with the highest noise and vibration values. The vibration measurements are indicated in the characteristic frequency range.

The following vibration loads were determined during vibration tests:

Table 2: Vibration loads and maximum noise levels

Location	Maximum acceleration	Frequency range	L_{Amax}	Average speed (km/h)
Budapest, Zámori str. 10.	2.6 mm/s^2	25-80 Hz	31.2 dB	left 58, right 70
Budapest, Zámori str. 16.	1.2 mm/s^2	25-100 Hz	39.9 dB	left 58, right 70
Budapest, Bártfai str. 12/b. – basement	6 mm/s^2	25-125 Hz	40.9 dB	left 58, right 70
Budapest, Bártfai str. 12/b. – groundfloor	17 mm/s^2	25-125 Hz	36.5 dB	left 58, right 70
Budapest, Fehérvári rd. 55/b	1.7 mm/s^2	25-125 Hz	34.1 dB	right 56 left 70

A typical set of vibration values in rooms of the buildings to be protected were in the range of 25 to 125 Hz. These vibration values also appear as radiated structural noise on the building walls, and ceilings.

Based on the measurements 3 groups can be distinguished in terms of the vibration acceleration between the trains.

- trains with low vibration values
  - in the axis of the track: 5,8-6,2 mm/s^2
  - on the tunnel wall: 1,6-2,6 mm/s^2
- trains with medium vibration values
  - in the axis of the track: 13,3-19,5 mm/s^2
  - on the tunnel wall: 3,7-4,2 mm/s^2
- trains with high vibration values
  - in the axis of the track: 13,3-19,5 mm/s^2
  - on the tunnel wall: 3,7-4,2 mm/s^2

Trains with low vibration values had the K6 wheel profile and 5000-28000 km mileage, while trains with medium values had both profiles and 38000-53000 km mileage.

One of the trains had outstanding vibration values compared to the others. One of the reasons was the K5 wheel profile and the 68,000 kilometers mileage.

Two other trains had K5 wheel profile but their mileage was around 40,000 km. The vibration values were similar to each other (in the axis of the track: 13.3 to 13.5 mm/s^2, and on the tunnel wall 3.7 to 4.2 mm/s^2).

The wheel profile of these two trains had been modified to the K6 profile for experimental purposes in August of 2015. Since then, their mileage was 46000 and 53000 km; their vibration values were similar on the tunnel wall.

The following conclusions can be made:

- the generated maximum noise and vibration load in buildings is strongly dependent on
  - the building's condition,
  - the track superstructure of the tunnel

  - ○ the speed of the train
  - ○ the condition of the trains' wheels
  - ○ the transfer medium (soil) type and layering
- the combined effects of the above

4. Results of the Vibration emission measurements in 2017

Besides the previous measurement points, 2 more accelerometers were placed in the tunnel on the fastening of the rails.

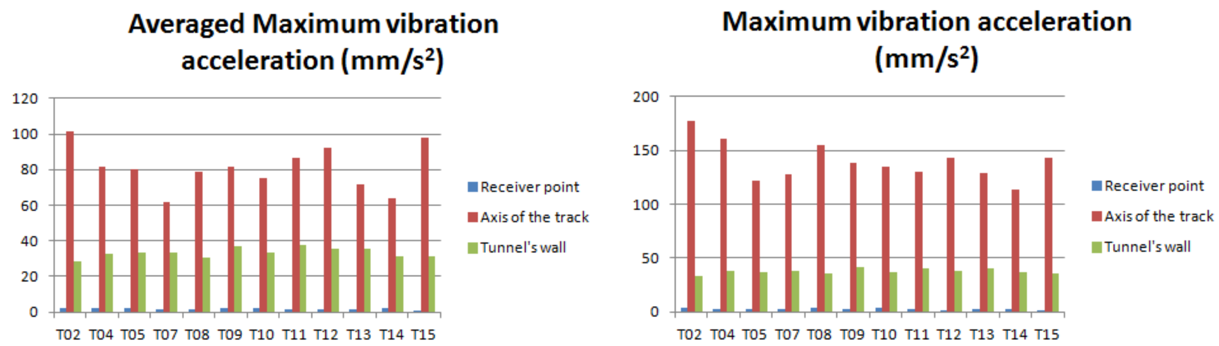

Figure 5: Averaged maximum vibration and maximum vibration acceleration values caused by the trains on the left track

At the left track on the axis of the track and on the wall of the tunnel the measured vibration load is mostly independent of the trains and changes in certain interval. At this section between the track and the wall of the tunnel vibration mitigation is not installed.

The maximum vibration accelerations were

- between 110 and 180 mm/s^2 at the axis of the track
- between 33 and 40 mm/s^2 on the wall of the tunnel
- between 1.7 and 3.4 mm/s^2 at the receiver point

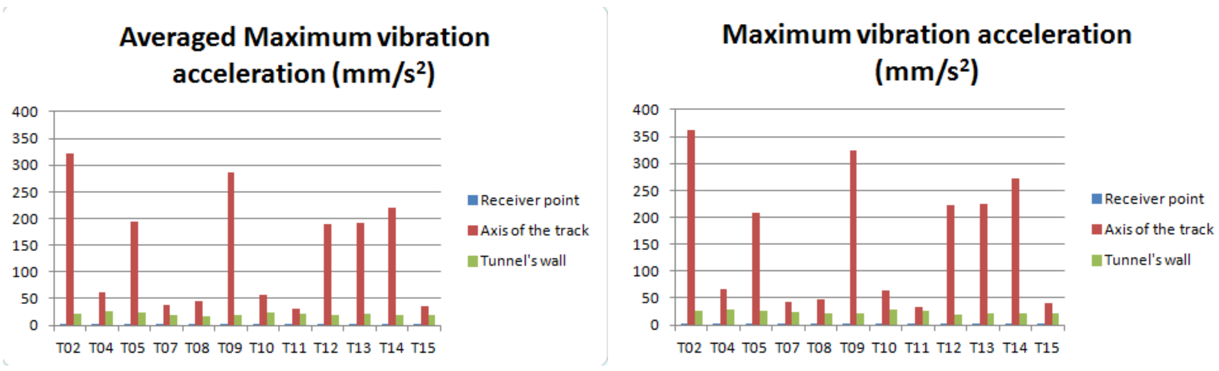

Figure 6: Averaged maximum vibration and maximum vibration acceleration values caused by the trains on the right track

At this section between the track and the wall of the tunnel vibration mitigation is installed.

The maximum vibration accelerations were

- between 32 and 363 mm/s^2 at the axis of the track
- between 20 and 29 mm/s^2 on the wall of the tunnel
- between 1.6 and 3.6 mm/s^2 at the receiver point

The measured vibration acceleration values on the wall of the tunnel and at the receiver point of both tracks are showed on the following figure.

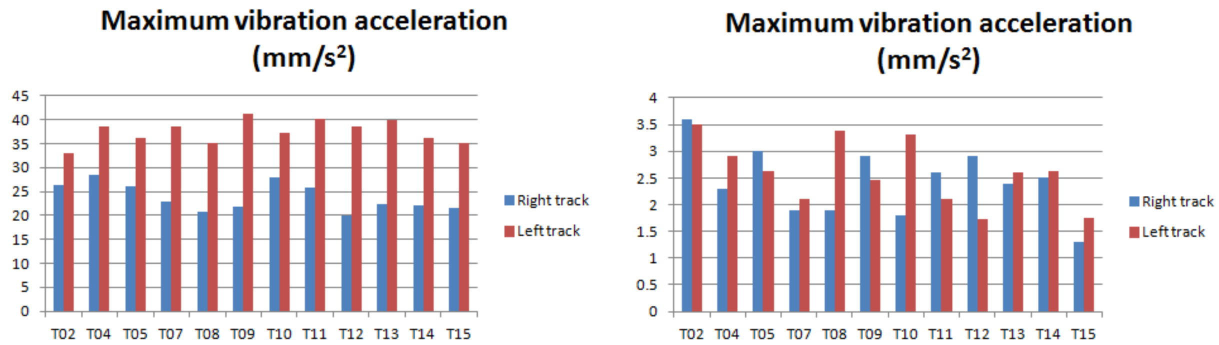

Figure 7: Maximum vibration acceleration values on the wall of the tunnel and at the receiver points

The maximum acceleration values on the wall of both track have a difference of 7-8 mm/s^2 average by trains which means 2.0-5.5 dB(v) difference. It can be stated that the two tracks don't have considerable difference in terms of vibration acceleration by the different trains.

On the other figure it is show that it does not ensure vibration protection that the right track has vibration measures because the measured vibration load is higher from all trains than on the left track.

5. Results of the vibration emission measurements on the trains

Compared to the earlier measurements and the results of the performed vibration emission measurements on the trains it can be summarized that values do not correlate between the system made of the train, track, tunnel and residential house components as the peak of the vibrations have occurred at different points in time. Therefore a single section of the track cannot be isolated with great confidence where vibration occurs on all trains.

Because the performed vibration measurements on the trains do not give clear conclusions, relations between the measurements on the axis of the track, on the wall of the tunnel and the receiver points were assessed. For the accurate investigations the assessment included frequency analysis as well. Two spectrums are showed for example on the following figure

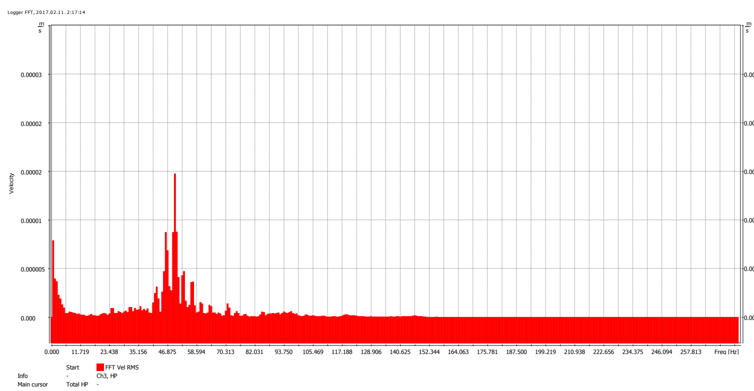

Figure 8: Characteristic spectrum of one passing at the receiver point

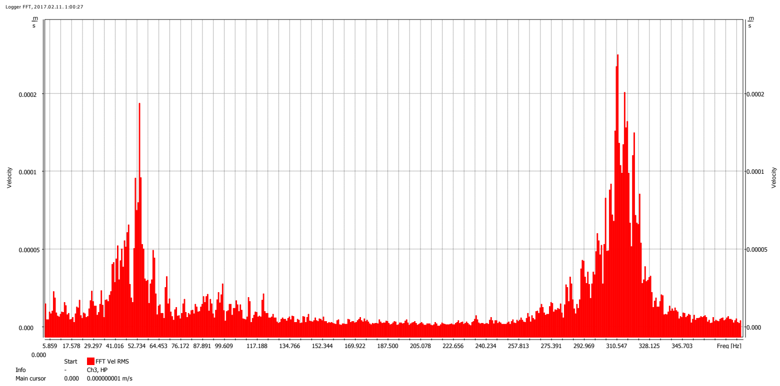

Figure 9: Characteristic spectrum of one passing at the axis of the left track

On the Figure 8 and 9 it can be seen that two components are dominant at the axis of the track:

- 30-50 Hz and
- Around 300 Hz

However the latter frequency range does not appear in the residential building during each pass-by because the propagation medium, the soil itself attenuates that range. It is important that the pass-bys had similar values on the left or right track and the 50 Hz component always dominated.

Based on the above it can be stated clearly that the problematic vibration load is not caused by the different elements of the system (train, track, tunnel, residential house) but one of the eigenfrequencies of the given system could be in this interval. This property helps the 50 Hz component propagate with much lower attenuation in the soil so it reaches the receiver points at the buildings.

Beside the 50 Hz component, the 300 Hz component is dominant too but this did not appear at any of the passings in the buildings. The 50 Hz is particularly problematic in terms of human perception because the vibration also appears as structural noise in the building.

6. Conclusions

Based on the measurements it can be stated that the problem which is causing the vibration is created by the joint effect of a whole system. The 50-Hz range, which appears in the residential building, is the system's natural frequency – thus it passes through the soil with much lower attenuation to the receiving points. The solution could be a new component, which could enable the detuning of the system. Vanguard Pandrol rail fastener is a widely used vibration-reducing method. With the proper design it can be ensured to reduce the vibration generated in the system itself, eliminating the problem of vibration load in residential buildings as well.