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EXPERIMENTAL AND NUMERICAL ANALYSIS ON ACOUSTIC PERFORMANCE OF FULLY-ENCLOSED BARRIER IN URBAN RAILWAY TRANSIT

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Abstract

Nowadays, the increasing number of urban railway lines has gradually become one of the major environmental annoyances in cities. Noise barrier, as the most effective method to control the impact of noise, are widely applied as an engineering application in urban railway transit. Compared with the conventional and multiple-edged profiles, fully-enclosed barriers can reduce railway noise much more effectively. Aiming at understanding the acoustic performance of fully-enclosed barriers, a series of experiments have been carried out in Ningbo, China. It can be seen from experimental results that the fully-enclosed barrier shows good performance in the frequency range of the main source of urban railway noise. However, low frequency noise has not been controlled effectively and the pressures at low frequencies are even larger than those in the test field without barriers. In order to make clear the cause of the negative effect at low frequencies, a two-dimensional model of a fully-enclosed barrier on a boxed girder simulating the actual conditions of the experiments has been established. With a simulated point source on the side of the track closed to the barrier, the model can be developed and solved using the Boundary Element Method (BEM). The numerical results from the BEM analysis show that sound pressures at many low frequencies are amplified excessively and these peaks of sound pressure are sharp and high. Since the appearance of sound level distribution at the frequencies of these peaks seems to be the natural frequency responses of acoustic resonance, the acoustic resonance of the air cavity formed by the fully-enclosed barrier is highly suspected to be the cause. Therefore, the acoustic modes of the air cavity were solved by the Finite Element Method. Compared with the results of the BEM model, several frequencies of the acoustic modes approximately coincided with those of the peaks, and the corresponding distributions of sound pressure inside the barrier were in good agreement with those of the BEM model. Hence the peak values of sound pressure at low frequencies in the model with the fully-enclosed barrier are mainly caused by the acoustic resonance of the air cavity. In conclusion, the acoustic mode of the air cavity formed by a fully-enclosed barrier can be excited by the source inside the barrier to amplify the sound pressure in the vicinity of urban railways, which results in unsatisfactory performance of the fully-enclosed barrier at low frequencies.

Keywords: Noise barrier, railway, BEM, acoustic resonance, experimental analysis

1. Introduction

As the development of the economy, the increasing number of private cars appear on the traffic road in China. In order to reduce the gas pollution emitted from the vehicles, effectively mitigate urban traffic congestion and low efficiency, the government of China devotes major efforts to developing urban rail transit. However, the contact between steel wheel sets and the track can induce significant noise, which needs to be considered into the urban environment governance as well. Noise barrier, as the most effective way to mitigate the propagation of sound, are widely applied as an engineering application in urban railway transit. Since the performance of a barrier is supposed to be improved with the increasing height and the barrier cannot be ultimately high, a new type of the traffic barrier is introduced ^[1, 2] as shown in **Figure 1**. Obviously, all the tracks and trains would be surrounded by the enclosed barrier so that there is almost no chance to transmit wheel-rail noise to the ears of the residents living around. The attenuation of the enclosed barrier is estimated to be more than 20 dB (A) in the laboratory ^[1, 2] which the performance of other barriers on the market cannot reach. Nevertheless, the noise reduction effect of the enclosed barrier has better to be experimented in the field so as to evaluate its effect during the operation period of urban rail transit. Many countries in the world have established the relevant standards as their guidance for doing the field experiments ^[3, 8]. ISO 10847-1997 ^[3] proposes that the performance of a barrier in the field test can be represented by the difference in sound pressure levels at a specified receiver position before and after the installation of a barrier provided that all the relevant parameters have not changed, which is called the insertion loss or the attenuation. Besides, it also states that the sound pressure levels at the receivers “before” and “after” barrier installations can be measured by the direct measurement method when the barrier has not yet been installed, or the indirect measurement method when the barrier installed cannot be readily removed. Though many researchers and scholars ^[4, 5 and 6] followed this standard to measure and evaluate the acoustic effect of barriers, it still has some demerits. The receiver positions are not given specifically, only determined by two conditions: hemi free-field conditions and on reflecting surfaces. Because of its vague definition, the receivers are defined as being located at the area which is the most sensitive to the noise in the Chinese standard ^[7]. However, there are no universal receiver positions for evaluating the barrier performance, which may lead to a confusion of the noise reduction abilities of the barriers on the market. Aiming at clarifying this, European Committee for Standardization has done something relevant recently. PD CEN/TS 16727-7^[8] provides nine locations to place the receivers, forming a grid, in order to measure the attenuation of a given noise barrier at a given site including given meteorological conditions. More specifically, the nine positions are at a distance from the nearest track center of 7.5 m, 12.5m and 25 m and at a height above the mean rail head height of the nearest track of 3.5 m, 6.0 m and 9.0 m, respectively. As referred in the standard, this approach is suitable for comparing attenuations of different types of barriers at the same site under the same meteorological conditions. Hence by utilizing various definitions from the different standards, in consideration of the scene of the actual situation, the receiver positions can be put forward and applied into the in-situ experimental study of noise reduction by the enclosed barrier.

2. In-situ experimental study of noise reduction by the enclosed barrier

2.1 Field experiments procedure

The enclosed barrier has mounted on the elevated section of Metro 1 in Ningbo city, between the station Liangzhu and the station Lugang. The whole length is 420 m, which is longer than the highly protected area. **Figure 1** shows the simplified structure of the enclosed barrier. Its main components are sound-absorbing panels with the material of glass wool and open cell aluminum foam, sound insulation

panels (PMMA panels and PC panels) and steel frames. In addition, there is an opening with two meters width. Since the barrier cannot be removed during the period of operation, an alternative site has to be found in order to test the pressure for the “before” measurement. At the site between the station Gaoqiao and the station Liangzhu of Metro 1 in Ningbo, the type of the viaduct and the environmental conditions are almost the same with that for the “after” measurement and no barriers are installed on the viaduct. Thus that, the in-situ experiment can be conducted on these two sites for the “before” and “after” measurement. On the left side of the site, there is a river between the factories and the metro lines; on the right side is a four-lane road separating the most sensitive area from the lines. The source in the experiment is the naturally occurring railway traffic, the passenger trains which has six vehicles with each length of 19 meters. Because of the experimental sites located in the middle of two stations, we are prevented from considering the brake mode of the trains. The train travels with the speed of around 40-50 km/h when passing the test field and its noise is mainly concentrated on a certain frequency range from 800 Hz to 2500 Hz [9].

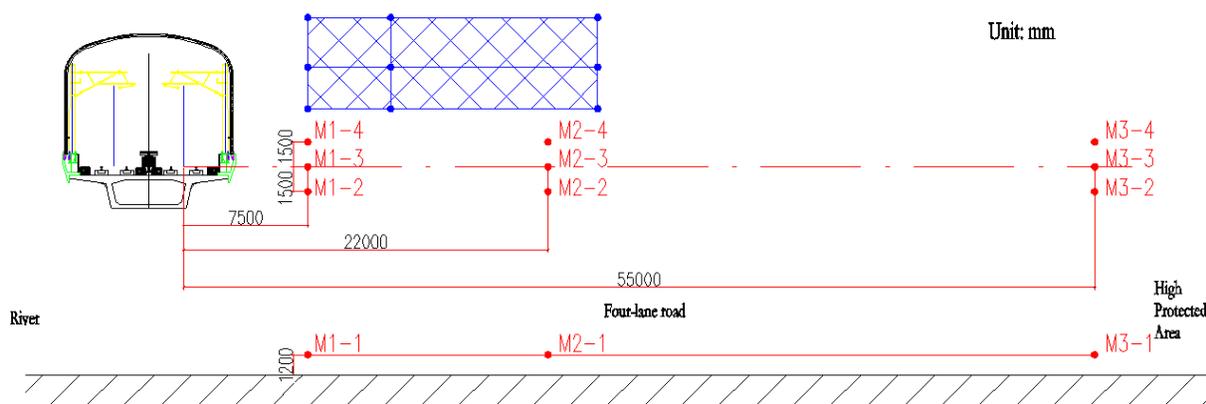


Figure 1. Configurations of the in-situ experiments by the enclosed barrier

In terms of the residential building far away from the lines, by considering the recommended locations of the standards (the blue points in Figure 1), the receiver positions are eventually determined and shown as the red points in Figure 1. With the grid forming method, the nine positions are determined at a distance from the nearest track center of 7.5 m, 22 m and 55 m and at a height above the mean rail head height of the nearest track of -1.5 m, 0 m and 1.5 m, respectively. The recommended receivers are located at three heights above the track so as to reveal the noise reduction effect of the barrier to bright zone, transition zone and shadow zone, respectively. However, the bright and transition zone of the enclosed barrier are too high to reach and the most sensitive areas are largely in its shadow zone. In addition, the microphone cannot be fixed stably as the disturbances can be easily occurred at the top of the long support. Thus the receivers cannot be located very high, better to be settled close to the height of track. The positions of the receivers are above and below the rail head height 1.5 meters in order to experiment the influences of the secondary noise caused by the bridge vibration and barrier vibration, respectively. While the receivers on the mean rail head height are measured to realize the performance of the barrier purely without any disturbances. The distance from the receiver to the source are much longer than the recommendations due to the residential buildings located far away from the lines. With the grid forming method, the three distances from the source are settled immediately. Besides, the receivers near the ground are selected to simulate human ears of pedestrians as the barrier installed on the viaduct. The microphone at each receiver position are omni-directional and protected by the windscreens, and the corresponding response frequency range are from 20 Hz to 20 kHz [10]. The sampling frequency of the sound pressure signals was intended to be 51.2 kHz, based on the Nyquist Theorem, more than twice the maximum frequency component of the audio frequency (20-20 kHz), to avoid the message distortion. The microphones are mounted in the grazing position on the standing poles due to the signal contamination caused by the microphone safety

grid^[11]. Moreover, the omnidirectional characteristics can be also improved in the grazing position though the sensitivity is higher in the normal position. Generally the equivalent continuous A-weighted sound pressure level or 1/3 octave band sound pressure level are introduced to calculate the attenuation of a barrier. The difference of the equivalent A-weighted sound levels in the field with and without barrier is a single-number rating of the attenuation, which is the most common indicator to evaluate the noise reduction ability of a traffic barrier. However, the performance of barrier at each frequency band cannot be assessed intuitively merely by this single-number rating and that is why the 1/3 octave band sound level is also necessary to compute. Besides, the use of A-weighting tends to devalue the effects of low frequency noise in particular^[12-15] so that the 1/3 octave band of attenuation without any frequency weightings should be taken into consideration. The equivalent A-weighted sound level is selected to quantify the level during the pass-by, but the time period of integration has to be determined. In order to evaluate the reduction noise effect more accurately, the measurement time interval of sound pressure level must be enforced strictly according to the train pass-by period. As the passing time of each train on the bridge are realized less likely by the observation of the naked eyes and it is even impossible to measure in the field with the enclosed barrier, an approach was introduced to obtain precisely. A piezoelectric acceleration sensor was adhered on the rail foot to monitor the variation of the vertical acceleration, which can detect whether the train passing or not in real-time (shown in Figure 2(a)). Nevertheless, at the beginning, the sound pressure signals in the practical measurement were better recorded by the observation of the naked eyes from the moment when the train nose travelled close to the measured cross-section to the time the tail of the train had already left for several seconds. The measured period of sound would be updated by the vertical acceleration of the rail in the post processing procedure. The experiments on the “before” and “after” sites are conducted on the sunny days just several days apart. As such, we can consider the meteorological conditions have no evident change which are not necessary to measure. However, an acoustic amplifier, an electrical charge amplifier, a sound pressure collecting equipment, an A/D data collection card and a computer which can run a data collecting program must be prepared. All the instruments has met the requirements of EN 61672-1 and the equipment of microphones are complied with IEC 61672 class 1. Due to the limitation on the number of the instruments, the pressure signals at each distance from the line were recorded successively and the valid train pass-by measurements at each distance are repeated 10 times or more to ensure the statistical representativeness of the sample^[8]. In addition, the measurement must be made with little road traffic to avoid the disturbance of road noise as possible.



(a) The piezoelectric acceleration sensor adhered on the rail foot (b) The microphones mounted on a standing pole

Figure 2. Experimental set up for the in situ measurement of the attenuation of the enclosed barrier

2.2 Experimental analysis

Figure 3 shows the acceleration time history of the rail closed to the barrier on both the “before” and the “after” sites. It can be seen the magnitude of the acceleration level increases gradually when the train was coming whereas decreases when the train was leaving as well. Once the wheel rail contact occurs, the rail vertical acceleration would be in response to the force. Since every train has twelve wheelsets and their locations are fixed on the train, twelve sharp peak responses would be found in the time history and with the length of vehicle and wheelbase, the times corresponding to the beginning and end of the train pass-by time interval therefore are easy to calculate. Then the sound level in the period of pass-by can be intercepted by the times, for the example framed by two dash lines in Figure 4. Obviously at the same time when the train pass-by, the valid increase and decrease of the sound level occurred synchronously almost with that of the rail acceleration. Hence it is indicated that the method for determining the time interval of train pass-by is reasonable and effective which would be employed into the measurement analysis. The train speed is also an important parameter in pass-by sound pressure level which can be calculated as well. However, the speed of the train passing the measured cross-section at both sites are almost 40-50 km/h with little variation, which means this parameter can be ignored in this experimental study. According to the relevant standards [3, 7, 8], the equivalent continuous A-weighted sound pressure level can be represented as follow,

$$L_{pAeq,T_{pass}} = 10 \log_{10} \left[\frac{1}{T_p} \int_{t_1}^{t_2} \frac{p_A^2(t)}{p_0^2} dt \right] = 10 \log_{10} \left[\frac{1}{N} \sum_{n=1}^N \frac{p_A^2(n)}{p_0^2} \right] \quad (1)$$

where T_p is the train pass-by time interval, p_A the A-weighted instantaneous sound pressure, p_0 the reference sound pressure (20 μ Pa). In the post processing procedure, the sound pressure signals were filtered by the bandpass of audio frequency range and A-weighting filter firstly, and then by utilizing the time interval of train pass-by, the equivalent continuous A-weighted sound level $L_{pAeq,T_{pass}}$ would be solved.

Since the valid pressure signals at each position are measured at least 10 times, the equivalent levels must be the average of them and the average method is given as,

$$L_{Aeq} = 10 \log_{10} \frac{1}{n} \sum_{i=1}^n 10^{0.1 L_{AE,i}} \quad (2)$$

where L_{Aeq} is the sound level used to calculate the attenuation of the barrier and $L_{AE,i}$ is the i th pass-by level computed by Eq.(1). Hence the single-number rating of attenuation for evaluating the performance of the barrier would be easily to resolve.

Identically, the 1/3 octave band level can be acquired in the same way. However, to simplify the method for calculation, the attenuation of each 1/3 octave band would be obtained by the ratio of sound energy in the field with and without the barrier, giving by

$$Att(f_{oct}) = 10 \log_{10} \left(\frac{\sum_i^N p_{wo}^2(f_i)}{\sum_i^N p_w^2(f_i)} \right) \quad (3)$$

where $p(f)$ is the sound pressure with respect to a certain frequency calculated by the implementation of Fast Fourier Transform, f_{oct} the center frequency of 1/3 octave band.

Since the receivers closed to the sensitive area are located far from the lines which might be affected by road noise and other meteorological factors, this article primarily analyzes sound pressure from the microphones near the track in order to study the individual effect of the enclosed barrier in the field. The article mainly focused on the entire field performance of the enclosed barrier will be published later. The attenuations at the receivers 7.5 meters horizontally from the source (M1-4, M1-3, M1-2 and M1-1) are illustrated in Table 1. Obviously, all the attenuations of the barrier at the receivers closed to the source are

above 10 dB (A), which is indicated the enclosed barrier has a good performance in the field during the operation period of urban transit. The attenuation at the receiver M1-3 is 11.81 dB (A), nearly consistent with that at M1-2 (11.92 dB (A)) though the position of M1-3 is much closer to the source. Covered by the top flange at the site with and without the enclosed barrier, both of the receiver M1-3 and M1-2 are located in the shadow zone whether the barrier is installed or not. So the enclosed barrier would make the additional effect identically on the sound pressure at the receiver M1-3 and M1-2. As such, the bridge seems to be the equivalent of a barrier for M1-3 and M1-2. Compared the attenuation at the receiver M1-4 with M1-3, it was larger evidently. From the schematic diagram of the cross-section (Figure 1), it can be found the position at the receiver M1-4 is not covered by the bridge on the site without the barrier whereas both the receiver M1-4 and M1-3 are almost in the same situation on the “after” site. Hence the attenuation at the receiver M1-4 is more significant due to the high sound level on the “before” site. The attenuation at M1-1 is 5.79 dB (A), which is the lowest value among these four receivers since it is located far from the source. Nevertheless, the enclosed barrier seems to be useful somehow to the sound level at the positions closed to the ground.

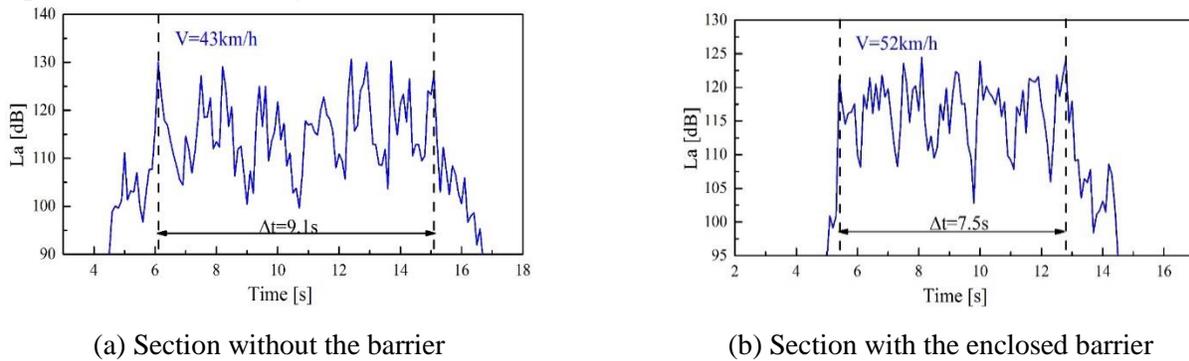


Figure 3. Time history of the rail vertical acceleration level on both sites

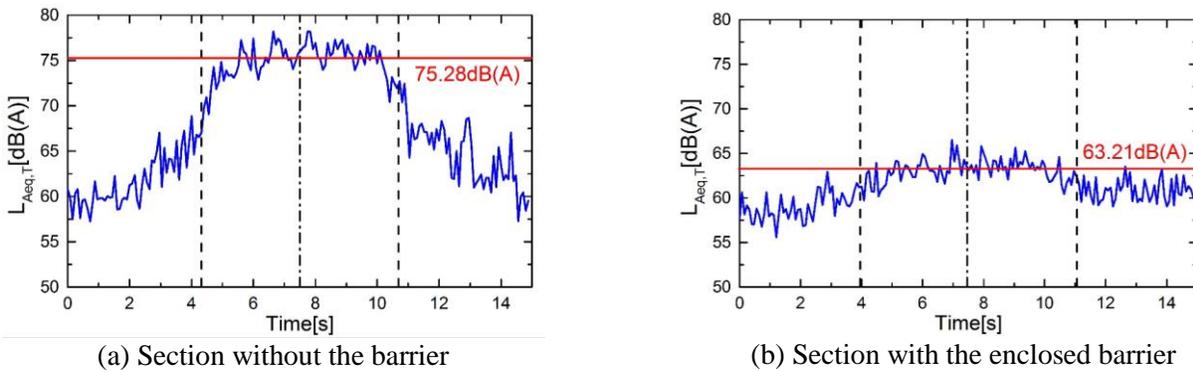


Figure 4. Time history of A-weighted equivalent level at the receiver M1-3

Table 1. The attenuations at the receivers 7.5 meters horizontally from the source (unit: the equivalent continuous A-weighted sound pressure level, frequency range: 20-20kHz)

Receiver Position	M1-4	M1-3	M1-2	M1-1
Attenuation/ dB(A)	16.14	11.81	11.92	5.79

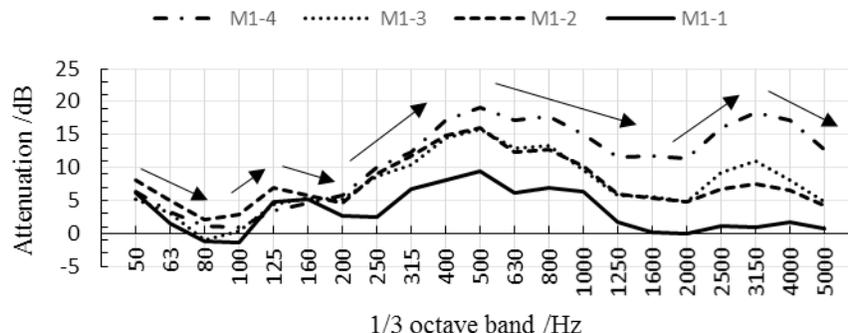


Figure 5. The attenuation in 1/3 octave bands from 50 Hz to 5 kHz at the receivers 7.5 meters horizontally from the source (unit: dB without any weightings)

Without any frequency weightings, the attenuations in each 1/3 octave band are presented in [Figure 5](#). The attenuations decrease slightly from 50 Hz to 100 Hz and then increase to the local maximum values at the frequency of 125 Hz. From 125 Hz to 200 Hz, they are almost invariable. When the frequency increases from 200 Hz to 500 Hz, the attenuation increase considerably to the global maximum values. The curves subsequently show a slow decrease till 1.6 kHz, keeping a slight upward and downward tendency at last. These four curves of attenuations show the same variation trend with respect to the increase of frequency since the receivers are located at same distance from the source, but to different extents. Among these four receivers, the attenuation at M1-4 varies most significantly, the next are M1-3 and M1-2, and the last one is M1-1. At the receiver M1-4, the attenuations above 10 dB are occurred at the frequency range from 250 Hz to 5 kHz which covers the predominant frequency range of the source. The attenuations at M1-3 and M1-2 are higher than 10 dB from 250 Hz to 1 kHz as well. As a result, the enclosed barrier is effective enough to attenuate the sound from the rail transit source during the operation period. However, the attenuations at each receiver at low frequency range are ultra-low, even negative at the 1/3 octave band of 80 Hz and 100 Hz. That means the enclosed barrier had bad performance at low frequency below 250 Hz in the test field, of which the reason is necessary to study by other approaches.

3. Numerical simulation analysis

The correlation between the in-situ attenuations of the barrier and frequency are complicated and the environmental conditions are also poorly controlled. Moreover, the ultra-low attenuations at low frequencies are difficult to interpret. Meanwhile, the time and cost required to prepare and do the in-situ experiments again are also expensive. For these reasons, the numerical approach would be useful somehow to explain the bad performance of the enclosed barrier below 250 Hz. By the numerical simulation, the noise reduction effect of the barrier can be analyzed from the source type, the barrier shape, the absorption ability of the barrier material, etc. Typically, the Boundary Element Method is the top-most used among all the numerical methods [\[16-18\]](#). The numerical model of a sound problem has two components: sound source and boundary condition. The sound source in this article was simplified as a point source in two dimensions which is also called coherent line source in three dimensions. As the length of train is much larger than the distance between the train and the position of the receiver of interest, the coherent line source was preferred to standing for traffic noise of the passing train. The point source must be located on the center line of the track at the height of wheel-rail contact according to the relevant national standards in Europe [\[19-21\]](#). The amplitude and the angle of the source are supposed to be constant in the models with and without the barrier since the numerical results of concerned are the differences of sound levels between these two models. The boundary condition in the numerical model also has two parts:

the geometry of barrier and the bridge, and the ground. The geometry of the barrier and the bridge are constructed based on the section drawing of the enclosed barrier and the box bridge. Considering that the large profile of a railway vehicle might affect the sound attenuation of the barrier, the geometry of the metro car was added into the boundary condition as the train services in the test field were operated with CNR stock (Type B) in 6-car sets. The track structure systems and other additional structures closed to the top flange might have influence on the attenuation, especially at high frequency. In order to simulate the actual situation of sound propagation more accurately, they are added into the models as well. All the surfaces of the geometry are supposed to be rigid without any absorption material attached at first, which can be regarded as Neumann condition on the boundary. Identically, the ground is supposed to be rigid as well. The problem with a rigid ground can be converted into a symmetrical problem for a half-space with a rigid boundary condition. Supposing that the image source and the image receiver symmetrically about the ground, the total pressure at the receiver should be the summation of four propagation paths from the source to the receiver. Since the source must be located at the exterior of the boundary conditions in this case, the position of source had to be shifted from the central line of track to the side of track closed to the receivers, shown with white lines in [Figure 7](#).

Based on the principle of BEM, only the boundaries of the model need to be meshed. The mesh size has to be increased with a given frequency in order to meet the requirement of the calculation accuracy and analysis accuracy due to the strong dependence of acoustic analysis on frequency. The length of element in the article was defined less than one sixth of the minimum wavelength as the element type was the quadratic order element. The precision of numerical model was controlled less than 6% of sound pressure when less than 0.5 dB of sound level. After the numerical model of the enclosed barrier was established and calculated at low frequency range, the pressure at any positions in the vicinity of the barrier could be solved by the post-processing calculation. [Figure 6](#) presents the frequency domains of sound level at the receiver M1-4, M1-3, M1-2 and M1-1, respectively. The sound levels are much larger than those of experimental results probably due to the different types of the source in the numerical simulation and the in-situ experiment. Nevertheless, a mass of peaks are appeared at low frequencies in [Figure 6](#) visually with the red circles. These peaks are sharp and high even the receiver M1-1 is so far away from the source, which might be highly suspected to be the cause of the bad performance of the enclosed barrier at low frequencies. At the frequencies of these peaks, all the pressure in the nearby of the barrier are amplified exaggeratedly. Since the sound level at several local positions are difficult and not enough to interpret why the barrier model would cause the amplification of sound pressure, the distribution of sound level around the barrier at the frequencies of these peaks are obtained and some of them are presented in [Figure 7](#). The appearance of sound level distribution inside the barrier seems to be the natural frequency response of acoustic resonance. As the acoustic resonance commonly occurs in the cavity of air when it is closed, the opening of the enclosed barrier seems make little effect on eliminating the resonance. Therefore, the acoustic modes of the air cavity inside the barrier would be analyzed by the Finite Element Method which is common used to perform. The results of the modal analysis are distributed in good agreement with the contours of the BEM model at the frequencies of the peaks, shown in [Figure 8](#). Meanwhile, several frequencies of the acoustic modes approximately coincided with those of the peaks and all the differences between natural frequencies and the peak frequencies are less than 1 Hz. It is indicated that when the frequency of sound suddenly approaches to the value which is approximately coincided with the natural frequencies of the air cavity, the distribution of sound pressure in the field will follow the acoustic mode and the sound level at any positions around the barrier can be amplified significantly to become the local maximum at low frequency range, for the example highlighted by red circles in [Figure 6](#). As a consequence, the peak values of sound pressure at low frequencies in the BEM model of the enclosed barrier are mainly caused by the acoustic resonance of the air cavity inside the barrier.

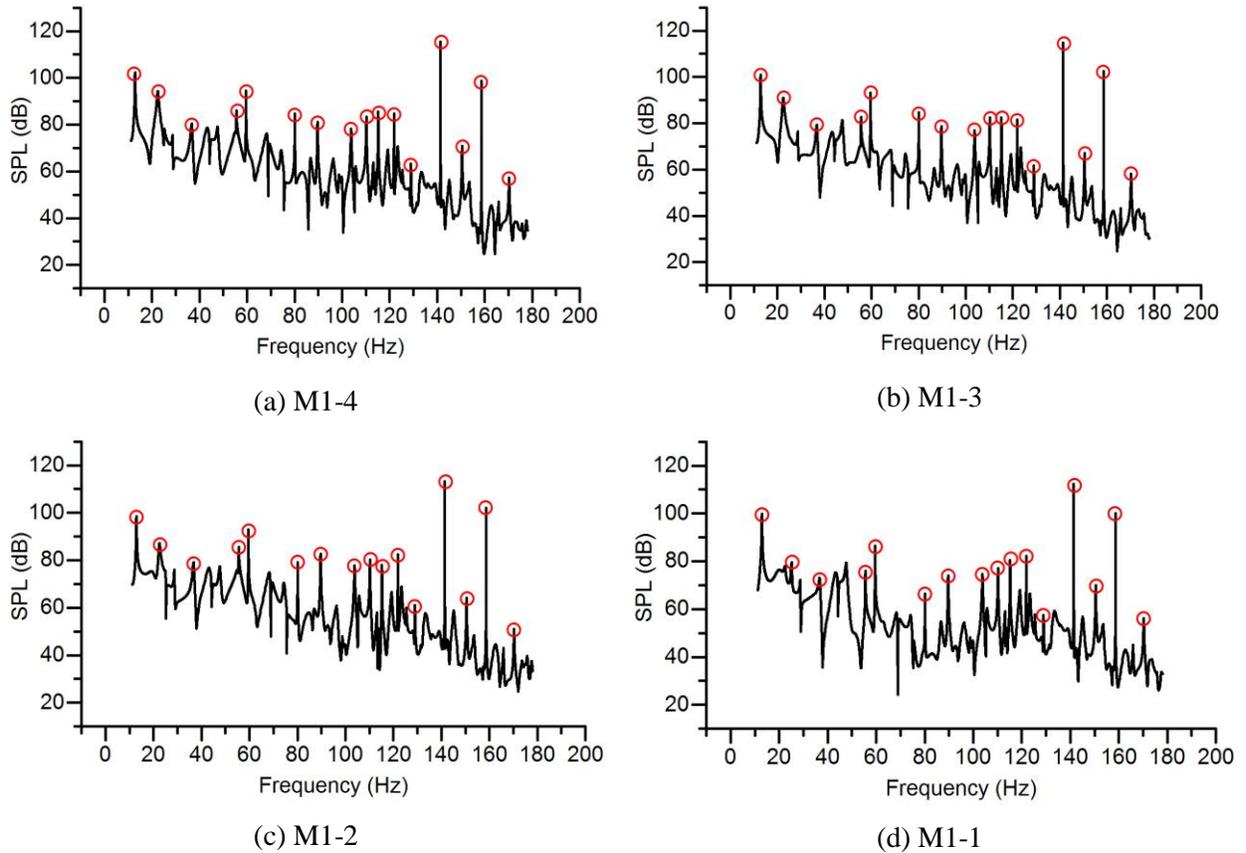


Figure 6. Frequency domains of sound level at several receivers by the numerical simulation

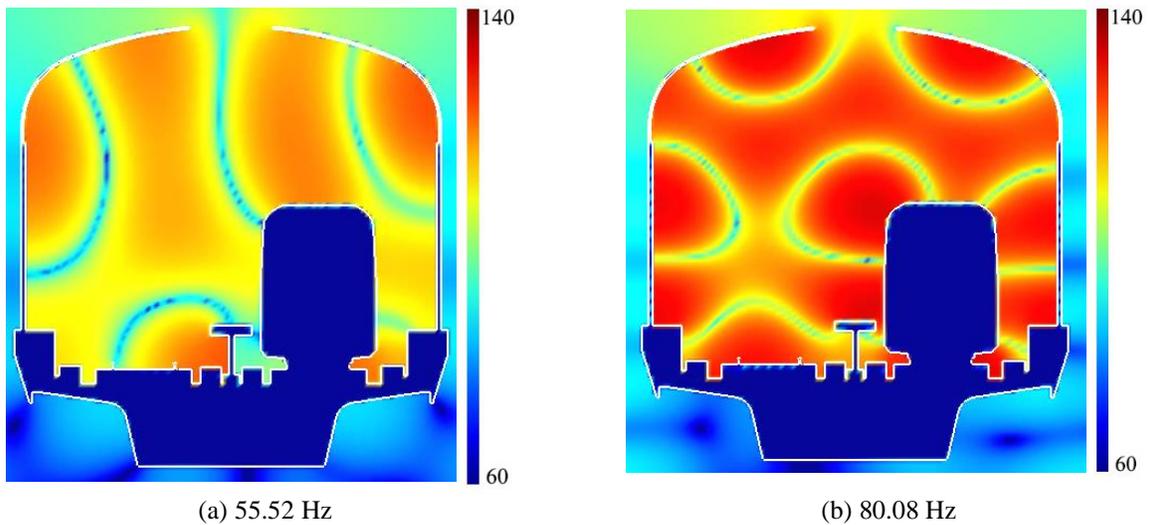


Figure 7. Sound level distribution around barrier at the frequencies of the peaks

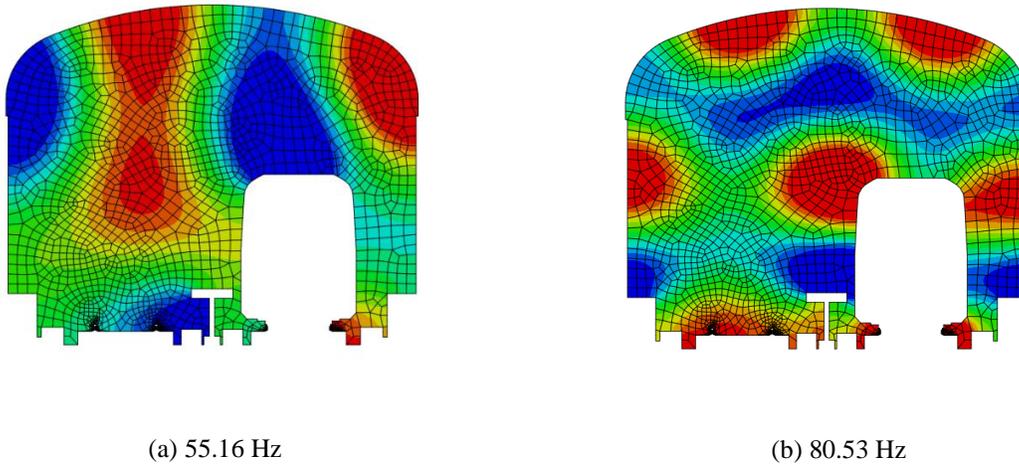


Figure 8. Acoustic modes of the air cavity inside the enclosed barrier

4. Conclusion

This research was motivated by the need to evaluate the in-situ performance of the enclosed barrier, which was well at the predominant frequency range of rail traffic noise, whereas relative poor at low frequency below 250 Hz in particular. Without the indicator of 1/3 octave band sound pressure level, only the single-number rating, A-weighted sound pressure level is difficult and not enough to realize the bad performance of the barrier at low frequency range. Besides, the use of A-weighting tends to devalue the effects of low frequency noise that the 1/3 octave band of attenuation without any frequency weightings should be taken into consideration. In order to evaluate the reduction noise effect more accurately, an approach was put forward to determine the time interval of train pass-by. By employing the rail vibration measurement into the experiment, the time interval of train pass-by was obtained reasonable and effective. The acoustic resonance of the opened cavity was found by accident in the numerical simulation of the enclosed barrier, which has a significant meaning to study the noise reduction of the barrier. The acoustic mode of the air cavity formed by a fully-enclosed barrier can be excited by the source inside the barrier to amplify the sound pressure in the vicinity of urban railways, which results in unsatisfactory performance of the fully-enclosed barrier at low frequencies. In order to eliminate the negative effect of the acoustic resonance, we can attach some absorption material on the inner surface of the barrier, or make the opening much wider in the further study.

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References

1. NA, Ma. Design of Fully-closed Noise Barrier in Shanghai Rail Transit Line 6. *Modern Urban Transit*, 2010, Vol. 5, p. 013.
2. JIAN, Wang Tingfo1 Feng Miaofeng1 Xu. THE DESIGN AND CONSTRUCTION OF A SEALED SOUND BARRIER FOR URBAN VIADUCT. *Environmental Engineering*, 2012, Vol. 3, p. 033.
3. ISO 10847:1997: Acoustics -- In-situ determination of insertion loss of outdoor noise barriers of all types
4. JAGNIATINSKIS, Aleksandras, FIKS, Boris, et MICKAITIS, Marius. Determination of Insertion Loss of Acoustic Barriers under Specific Conditions. *Procedia Engineering*, 2017, vol. 187, p. 289-294.
5. YOON, Je Won, JANG, Kang Seok, et CHO, Yong Thung. Acoustic Performance Evaluation and Prediction for Low Height Noise Barriers Installed Adjacent To Rails Using Scale Down Model. *Journal of the Korean Society for Railway*, 2016, vol. 19, no 2, p. 124-134.
6. CLAIRBOIS, Jean-Pierre et GARAI, Massimo. The European standards for roads and railways noise barriers: state of the art 2015. In : *Proc Euronoise*. 2015.
7. HJ / T 90—2004: Norm on Acoustical Design and Measurement of Noise Barriers
8. PD CEN/TS 16272-7:2015: Railway applications. Track. Noise barriers and related devices acting on airborne sound propagation. Test method for determining the acoustic performance. Extrinsic characteristics. In situ values of insertion loss
9. DJ Thompson. Wheel-rail noise generation, part i: introduction and interaction model. *Journal of sound and vibration*, 161(3):387-400, 1993.
10. <https://www.bksv.com/en/products/transducers/acoustic/microphones/microphone-preamplifier-combinations/4189-A-021>
11. VOROPAYEV, Sergey I., OVENDEN, Nicholas C., FERNANDO, Harindra JS, et al. Finding optimal geometries for noise barrier tops using scaled experiments. *The Journal of the Acoustical Society of America*, 2017, vol. 141, no 2, p. 722-736.
12. PAWLACZYK-ŁUSZCZYŃSKA, MAŁGORZATA, DUDAREWICZ, A. D. A. M., WASZKOWSKA, MAŁGORZATA, et al. Assessment of annoyance from low frequency and broadband noise. *Int J Occup Environ Med*, 2003, vol. 16, p. 337-43.
13. LEVENTHALL, H. G., et al. Low frequency noise and annoyance. *Noise and Health*, 2004, vol. 6, no 23, p. 59.
14. BRONER, N. et LEVENTHALL, H. G. A criterion for predicting the annoyance due to higher level, low frequency noise. *Journal of Sound and Vibration*, 1982, vol. 84, no 3, p. 443-448.
15. KUWANO, Sonoko. Advantages and disadvantages of A-weighted sound pressure level in relation to subjective impression of environmental noises. *Noise Control Eng. J.*, 1989, vol. 33, p. 107-115.
16. TOLEDO, R., AZNÁREZ, J. J., MAESO, O., et al. Optimization of thin noise barrier designs using Evolutionary Algorithms and a Dual BEM Formulation. *Journal of Sound and Vibration*, 2015, vol. 334, p. 219-238.
17. BORDÓN, J. D. R., AZNÁREZ, J. J., et MAESO, O. A 2D BEM–FEM approach for time harmonic fluid–structure interaction analysis of thin elastic bodies. *Engineering Analysis with Boundary Elements*, 2014, vol. 43, p. 19-29.
18. KOUSSA, Faouzi, DEFRANCE, J., JEAN, Philippe, et al. Acoustic performance of gabions noise barriers: numerical and experimental approaches. *Applied acoustics*, 2013, vol. 74, no 1, p. 189-197.
19. BUNDESBahn, Deutsche. Richtlinie zur Berechnung der schallimmissionen von schienewegen, schall03/Akustik03. München: Bundesbahn Zentralamt, 1990.
20. VAN VOLKSHUISVESTING, Nederland Ministerie. Reken-en Meetvoorschrift Railverkeerslawaa. 1996.
21. DES TRANSPORTS TERRESTRES, Guide du Bruit. Pr évision des niveaux sonores. Ministère de l'Environnement et du Cadre de Vie/Minsitère des Transports/CETUR, 1980.