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Performance of Environmental T-shape Noise Barriers Covered with Primitive Root Diffusers

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There is a considerable increase in the use of noise barriers in recent years. Noise barriers as a control noise solution can increase the insertion loss to protect receivers. This paper presents the results of an investigation about the acoustic efficiency of primitive root sequence diffuser (PRD) on an environmental single T-shape barrier design. A 2D boundary element method (BEM) is used to predict the insertion loss of the tested barriers. The results of rigid and with a different sequence diffuser coverage are also predicted for comparison. Employing PRD on the top surface of T-shape barrier has been found to improve the performance of barriers in comparison with the use of rigid and QRD coverage at the examined receiver locations. It has been found that decreasing the design frequency of PRD shifts the frequency effects towards lower frequencies, and therefore the overall A-weighted insertion loss is improved. It was also found that using wire mesh with reasonably efficient resistivity on the top surface of PRD improves the efficiency of the reactive barriers; however utilizing wire meshes with flow resistivity higher than the specific acoustic impedance of air on the PRD top of a diffuser barrier significantly reduces the performance of the barrier within the frequency bandwidth of the diffuser. The performance of a PRD covered T-shape barrier at 200 Hz was found to be higher than that of its equivalent QRD barriers in both the far field and in areas close to the ground. The amount of improvement compared made by PRD barrier compared with its equivalent rigid barrier at far field is about 2 to 3 dB, while this improvement relative to the barrier model "QR4" can reach up to 4–6 dB.

Keywords: noise barrier, resistive layers, T-shape barrier, primitive root diffuser.

1. Introduction

A major portion of noise pollution is generated by transport infrastructure projects, road and rail, etc. Noise barriers prevent sound waves from reaching direct wave to the receiver in the shadow zone. To optimise this insertion loss different barrier types have been designed of which the T-shape profile is a common example. Several studies have shown that the T-shape barrier could provide valuable improvement in the barrier efficiency. Fujiwara and Nakia (1996) introduced a T-shape barrier with a reactive surface and stated a 5 dB benefit at low frequencies. They also noted improved performance at frequencies above 1000 Hz. The addition of absorptive material or diffusers has been found to further improve the barrier performance (Cox, D'Antonio, 2004). Fujiwara *et al.* (1998) has shown that a uniform series of rigid wells in the upper surface of a T-shape barrier produces insertion loss values equal to those of a soft surface over a significant range of frequencies. In respect to the use of Quadratic Residue Diffuser (QRD) to cover the top of the barrier, Monazzam and Lam (2005) has shown that a T-shape barrier design produces a higher barrier A-weighted insertion loss than using a typical fibrous absorbent material on the barrier. A similar type of examination for T-shape barriers is shown in Baulac *et al.* (2008).

The objective of this study is to investigate the performance of T-shaped noise barriers covered with primitive root sequence diffusers (PRD). For this purpose, the insertion loss should be estimated according to following stages

At first, the depth sequence diffusers of various models were compared. Then, to verify the effectiveness of PRD, the calculations at different design frequencies were done. Finally, the performance of a reactive T-shape barrier model along with different resistive layers on the top covers have been compared.

2. Methods

2.1. Absorption by QRD and PRD

Different types of diffuser were introduced by Schroeder in the 1970 (Schroeder, 1975; 1979). Quadratic residue and primitive root diffusers are the most usual ones. Their structures are made by wells with the same width and various depths.

Thin fins are used as separator in the wells. Different depths provide highly diffused reflections which can be estimated by a mathematical sequence called the quadratic residue or primitive root sequence.

For QRD, the depth of the n-th element in the diffuser (d_n) can be obtained as follows:

$$d_n = \frac{Sn\lambda_0}{2N}, \qquad (1)$$

where

$$Sn = n^2 \text{ modulo } N, \tag{2}$$

N – prime number and $n = 0, 1, 2 \ldots N$ and λ_0 is the wavelength design.

On the other hand, the depth of PRD is defined as:

$$d_n = \frac{Sn\lambda_0}{2(N-1)}, \tag{3}$$

where

$$Sn = r^n \text{ modulo } N, \tag{4}$$

$n = 1, 2 \ldots N{-}1$ (it should be mentioned that the above equation for mod 7, 0 could not be considered), r – the primitive root of N.

The sequence number (Sn) for QRD and PRD for a few different prime numbers is shown in Table 1. It is worthwhile noting that for PR diffusers with prime number above 3, there are more than one set of sequence numbers.

Table 1. Sequence number of two different Schroeder diffusers, a) Quadratic Residue Diffuser, b) Primitive Root Diffuser.

a)

N	Sequence
3	0, 1, 1
7	0, 1, 4, 2, 2, 4, 1
13	0, 1, 4, 9, 3, 12, 10, 10, 12, 3, 9, 4, 1

b)

B	r	Sequence
3	2	1, 2
7	2	1, 2, 4, 3
	3	1, 3, 4, 2
7	3	3, 2, 6, 4, 5, 1
	5	1, 5, 4, 6, 2, 3

A Schroeder diffuser is an important variation of the phase grating diffuser which can also absorb sound energy. The intense coupled resonance between the wells of different depth causes very large particle velocity around the edge of the well.

Therefore this intense resonance may result in very high absorption. By installation of an absorbent material, the sound pressure is restrained. Fujiwara (Fujiwara, Furuta, 1991) installed an absorber on the barrier edge and stated that because the absorber reduces the sound pressure on the edge, the barrier efficiency has been improved. Another study (Wu *et al.*, 2000) has also shown that the variable depth sequence concept can be used to improve significantly the absorption and impedance characteristics of conventional constant depth design.

They also demonstrated that by covering a QRD with wire mesh, significant increases in the absorption coefficient of constant slit diffusers, QR diffusers, were achieved and the QR diffuser design could be optimised.

2.2. Numerical modelling method

Performance of the noise barrier can be estimated by using the numerical modelling method. In this investigation, the boundary element method (BEM) was used to conduct the numerical analyses. This method enables the performance of noise barriers of arbitrary profiles and surface conditions can be calculated (Ishizuka, Fujiwara, 2004). One of the advantages of this method is the accuracy and another one is the flexibility of representation of various barrier shapes.

As shown in Fig. 1, it is a two-dimensional method which consists of two axis (x, y). The horizontal axis lies in the ground and the y axis is perpendicular to the ground plane. γ is the cross-section surface of the noise barrier on the ground.

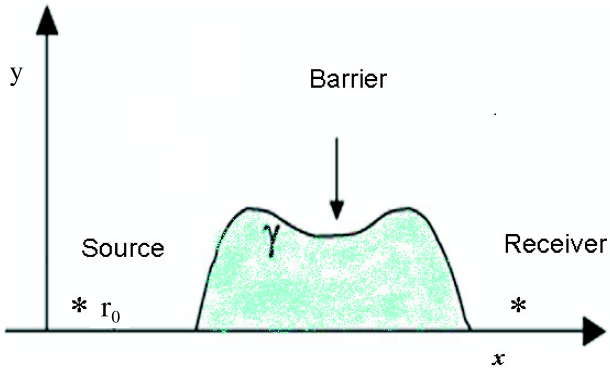

Fig. 1. The two-dimensional model.

A uniform line source is at $r_0 = (x_0,\ y_0)$ and the sound pressure at r is $p(r, r_0)$. The barrier surface is divided into a number of elements ($\gamma_1,\ \gamma_2, \dots \gamma_n$) and it is assumed that $p(r_0,\ r_n)$ is constant for each element. From this approximation, the following integral equation was introduced by Helmholtz:

$$\varepsilon(r)p(r, r_0) = G(r, r_0) + \int\limits_{\gamma} \left(\frac{\partial G(r_s, r)}{\partial n(r_s)} - ik\beta(r_s)G(r_s, r) \right) p(r_s, r_0)\partial s(r_s), \quad (5)$$

where $\partial s\,(r_s)$ – the length of an element of γ at r_s, $\dfrac{\partial}{\partial n\,(r_s)}$ – normal derivative at r_s which guide into the propagation normal, k – the wave number.

In a rigid ground plane, $G(r,\ r_0)$ is the acoustic pressure at r due to the source at r_0 which could be estimated as:

$$G\,(r, r_0) = -\frac{i}{4} \left\{ H_0^{(1)}\,(k\,|r_0 - r|) + H_0^{(1)}\,\left(k\,|r_0' - r|\right) \right\}, \quad (6)$$

where r_0' – the image of the source in the ground ($r_0' = (x_0 - y_0)$) and $H_0^{(1)}$ – the Hankel function of the first kind of zero order.

The above integral was solved numerically in FORTRAN. More details can be found in (Monazzam, Lam, 2005).

The ribbed surface is assumed to be a box with the top edge having an admittance distribution as given by the simple phase changes due to plane wave propagation within the surface's wells. This representation has been validated on a reactive welled barrier by Monazzam and Lam (2005).

At different locations, 9 receivers were selected to predict the sound pressure at 1/3 octave frequency between 50 and 4000 Hz. In addition, it should be mentioned that the sound source is always on the rigid ground and it is fixed at a 5 m distance from the centre line of the barriers. Thus, in order to predict the insertion loss at different frequencies, the following equation is used:

$$\mathrm{IL} = -20\log 10\left|\frac{p(r, r_0)}{G(r, r_0)}\right| \;\mathrm{dB}, \tag{7}$$

where $p(r, r_0)$ – sound pressure at the receiver with presence of the both barrier and the rigid ground, $G(r, r_0)$ – sound pressure at the receiver only with the presence of the rigid ground.

The application of this method on ribbed profiled barriers was verified by a scale model by Monazzam and Lam (2008).

2.3. Impedance of a profiled absorber

In this study, to compute the impedance of the wells for the utilized Schroeder diffusers the method presented by Wu *et al.* (2000) is used. The analysis below is used to estimate the impedance of a resistive layer. In this method, z_1 is the backing impedance of the hole with a depth of l_{n1} and r is a resistance material.

$$z_w = \frac{pcz_1 \coth(jk_t l_{n1}) + (\rho c)^2}{z_1 + \rho c \coth(jk_t l_{n1})} + R. \tag{8}$$

More descriptions on this method could be found in (Wu *et al.*, 2000; 2001).

2.4. Characteristics of models

As the basis a few different T-shape profiled noise barriers are designed. In all models including reference barrier the overall height of barriers is fixed at 3 m and the cap and stem thickness are respectively 0.3 and 0.1 m. In addition, the length of the T-part of barriers in all surfaces is 1 m. The characteristics of different models are also given in Table 2. The frequency bandwidth for the QRD barrier is from 400 Hz to 1.4 kHz and the lowest frequency limits for PRD barriers depending on the frequency designs starts from 315 to 800, while the frequency cut off for all PRD barriers is around 1.25 kHz due to their similar well widths.

To examine different shapes and designs of diffuser barriers, a range of barrier models was used. The performance of each model was predicted in the one third octave band at nine receiver locations at 20, 50 and 100 m from the barrier on the ground, and at heights of 1.5 and 3 m above the ground. A sound source was

Table 2. Characteristics of different barrier models.

Models	Diffuser types	(N)	Design frequency fr [KHz]	Well width w [cm]	Sequence	Description
T	–	–	–	–	–	Rigid
QR4	QRD	7	0.4	12	{0 1 4 2 2 4 1}	"Q" with wells
PR4	PRD	6	0.4	14	{3 2 6 4 5 1}	"P" with wells
PR5	PRD	6	0.5	14	{3 2 6 4 5 1}	"P" with wells
PR10	PRD	6	1	14	{3 2 6 4 5 1}	"P" with wells
PWL	PRD	6	0.4	14	{3 2 6 4 5 1}	"P" with wire mesh (R = 5.7 Rayls (MKS))
PWM	PRD	6	0.4	14	{3 2 6 4 5 1}	"P" with wire mesh (R = 55 Rayls (MKS))
PWH	PRD	6	0.4	14	{3 2 6 4 5 1}	"P" with wire mesh (R = 550 Rayls (MKS))

placed at the coordinate (5, 0), so that it could not be influenced by interferences between the source and its ground image.

For all of these model types, the fin thickness is assumed to be negligible and for rigid barriers, where the viscous and thermal effects in the wells are taken in account, by the method introduced in (Wu *et al.*, 2000). In this study the dimension of the elements was taken to be less than $\lambda/5$ to give a reasonable representation of constant surface pressure over an element (Hothersall *et al.*, 1991). The dimension of a T-shape barrier which is introduced by barrier model "PR4" is presented in Fig. 2.

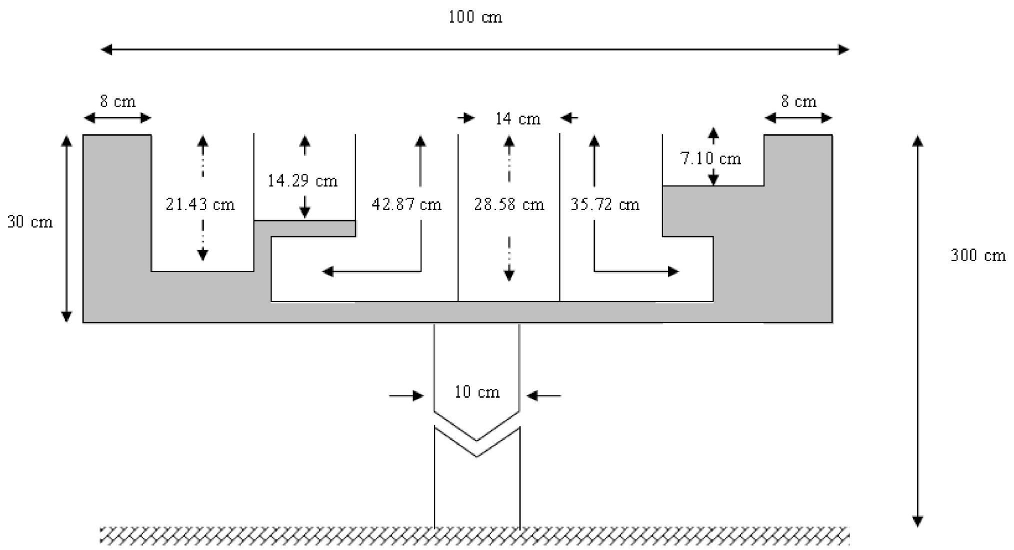

Fig. 2. Schematic diagram of side view of barrier model "PR4".

2.5. A-weighted traffic noise insertion

To provide a single broadband performance for the designed barriers, the British standard method is used to calculate the A-weighted traffic noise insertion loss of barriers (BS EN, 1998).

3. Result and discussion

3.1. Sequence effect

At first, the performance of the primitive root diffuser on T-shape barriers is compared with that of the quadratic residue diffuser in Fig. 3. It has been shown that the performance of barrier models "PR4" and "QR4" in a low frequency range (50–160 Hz) are almost the same. At frequencies between 160 Hz till 2000 Hz the primitive root diffuser demonstrates some higher improvement compared with that of the quadratic residue diffuser, although its efficiency is lower at three frequencies (i.e. 315, 1000 and 1250 Hz). In fact, the performance improvement is started from lower frequencies in the barrier model "PR4" compared with that of the barrier model "QR4". This is why the results of the A-weighted traffic noise spectrum for these models at the receiver point (−50, 0) also shows a PR4 increase the insertion loss by further 0.7 dB(A). This could be explained by higher well depths in "PR4" compared with that in "QR4". Although both barriers are diffusive barriers, the barrier with the primitive root sequence diffuser is less frequency dependent. This is likely because the primitive root diffuser has every possible sequence from 1 to 6, while the quadratic residue diffuser has only three sequences: 1, 2 and 4.

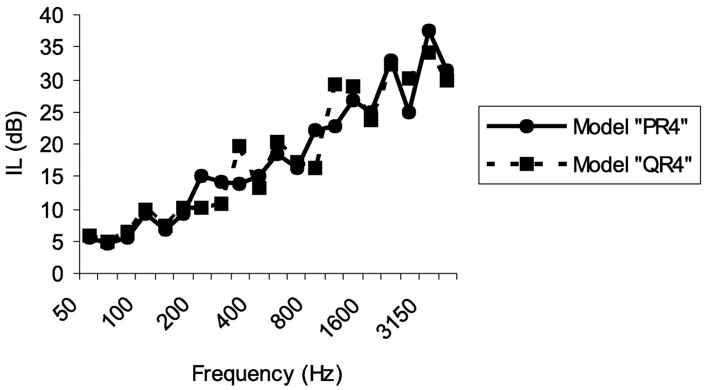

Fig. 3. Comparisons between a T-shape QRD barrier (Model "QR4" and a T-shape PRD barrier (Model "PR4") at the receiver point (−50, 0). Both diffusers have the same frequency design of 400 Hz.

The performance of these models is compared with a simple T-shape barrier as a reference model in Fig. 4. This shows that at frequencies lower than 315 Hz the effect of both diffusers is lower than their equivalent rigid barrier. According to Fig. 4, which illustrates the achieved improvements utilising QR and PR diffusers on the rigid T-shape barrier, it can be concluded that at four distinct frequencies of 200, 250, 400 and 800 Hz the barrier model "PR4" has better performance than the barrier model "QR4". It should be also noted that at the receiver (−50, 0), the barrier model "QR4" enhances the A-weighted insertion loss of the "Ref" barrier by 2.5 dB(A), while the barrier model "PR4" improves the A-weighted insertion loss of the "Ref" barrier at the above mentioned receiver point by 3.2 dB(A).

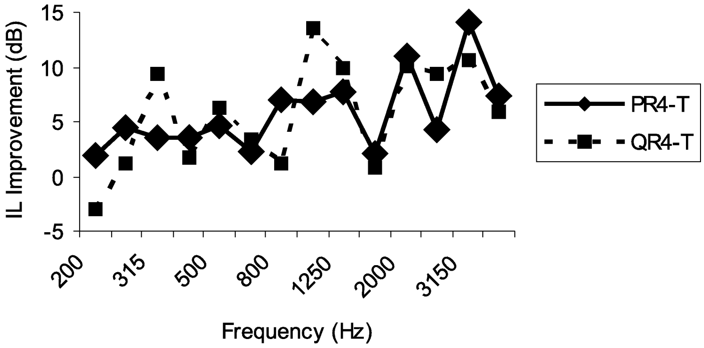

Fig. 4. Insertion loss improvement made by barrier models "PR4" and "QR4" over "Ref" barrier at the receiver point (−50, 0).

The details of the far and near field improvements of the presented primitive root diffuser edge barrier over its equivalent quadratic residue diffuser edge and rigid T-shape barriers at 200 Hz are shown in Fig. 5 and Fig. 6. To provide these results, the predictions are made over 2500 receiver points from 2 to 250 meter distances from the centre line of the barriers on the ground extents to 10 meter above rigid ground. One of the main objective of most researchers on barrier performance optimisation is to improve the low frequency attenuation of the barrier, and thereby to improve the overall A-weighted performance. In this case both figures of 5 and 6 are presented at 200 Hz to show the effectiveness of the primitive root sequence effect at low frequencies.

Three distinctive areas are clearly seen in both the Figs. 5 and 6 including the near field close to ground, near field at higher heights and the far field. The best improvement is made by barrier model "PR4" in the near field close to the ground. The amount of improvement relative to the "Ref" barrier at these regions can reach up to 3.5–4 dB.

The least effect of the barrier model "PR4" is seen in the near field with heights above 3 meter. This was already explained for quadratic residue diffuser edge barrier by Monazzam and Lam (2005). It seems that the diffuser surface redirects some of the sound wave upward, hence the low performance of the diffusive barrier is expected at these zones. This was observed in the primitive root diffuser edge barriers as well. This phenomenon is more visible in Fig. 6 where

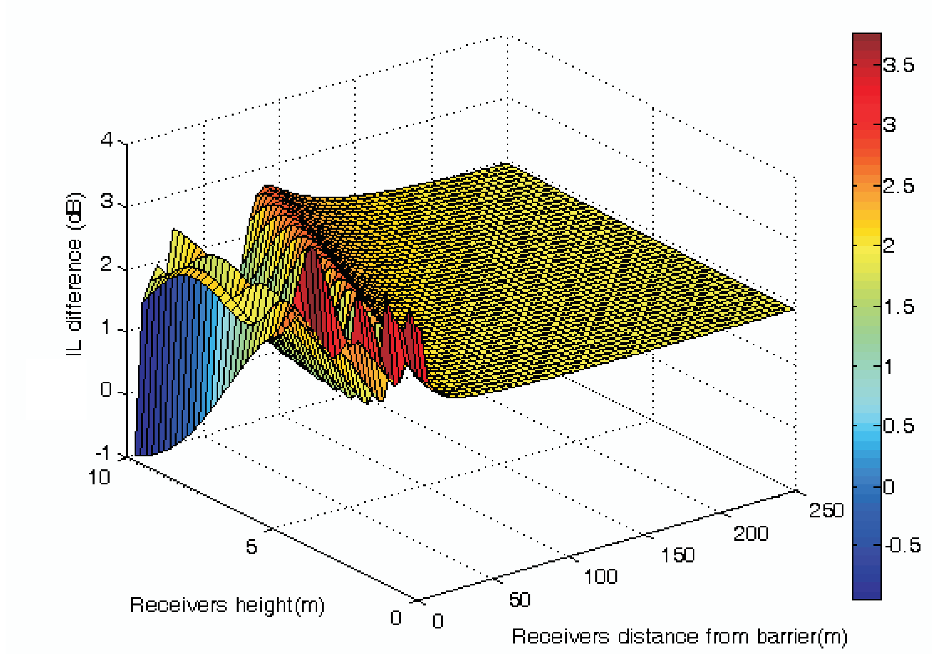

Fig. 5. Surface plot of differences of insertion loss of barrier model "PR4" relative to "Ref" barrier at 200 Hz.

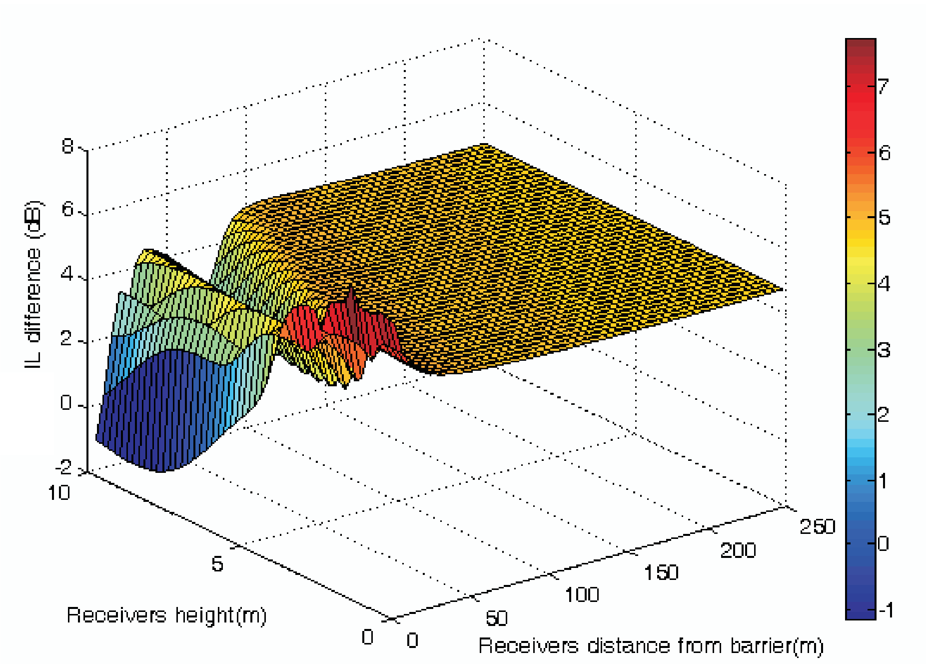

Fig. 6. Surface plot of differences of insertion loss of barrier model "PR4" relative to barrier model "QR4" at 200 Hz.

two different diffuser edge barriers are compared. As one can see, the primitive root sequence diffuser shows more diffusive effect in this frequency at the zone close to the barriers with high heights. This is due to the fact that the sequences in the primitive root diffusers allow the diffuser to have a higher well depths tuned to the lower frequencies. Therefore at this frequency a more diffusive effect is seen at the top surface of the introduced barrier. Finally, as one can see in both plots, the barrier model "PR4" has a better performance in a wide area in the far field. The amount of improvement made by the barrier model "PR4" compared with its equivalent rigid barrier in these areas is about 2 to 3 dB, while this improvement relative to the barrier model "QR4" can reach up to 4–6 dB. In fact, at this frequency the quadratic residue diffuser has less performance than a rigid surface, but the primitive root sequence could cover the weakness of both the rigid and QRD edge barriers at these areas.

3.2. Design frequency effect

In this stage, the effect of different design frequencies on the acoustic performance of the T-shape barrier with PRD covers is investigated. In this case, three different models named "PR4", "PR5" and "PR10" with design frequencies of 400, 500 and 1000 respectively were designed. The features of designed models are shown in Table 2. As can be seen in Fig. 7, PR4 with small difference to PR5, has the highest efficiency at low frequencies. By increasing the design frequency, it seems that the efficiency of the diffuser at low frequencies has been compromised because the effective frequency leads to higher frequency effects. In addition, the overall A-weighted insertion loss of these models at the receiver point (−50, 0) shows that the performance of the PRD barrier with the design frequency of 400 Hz is higher than that of both the PRD barriers with the design frequencies of 500 and 1000 Hz by 0.2 and 2.2 dB(A), respectively. In fact, shifting the effective frequency to high frequencies in the barrier model "PR10" reduced the overall A-weighted efficiency of the barrier.

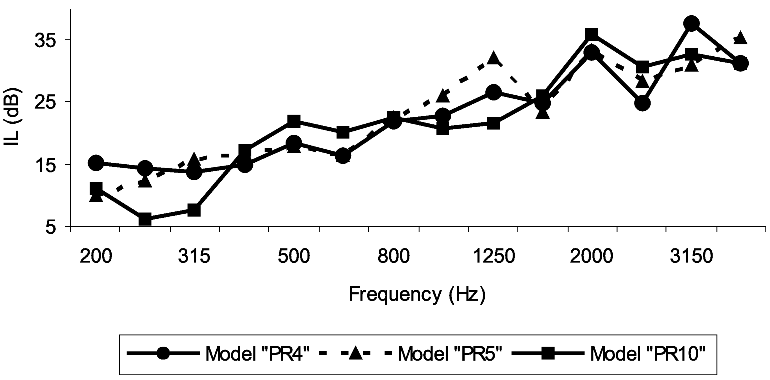

Fig. 7. The effect of primitive root diffuser with different frequency design on a single T-shape barrier at the receiver point (−50, 0).

3.3. The resistive layers effect

Many researchers have investigated the resistive layers effect on the diffuser surface using either scale models or computational studies (Mechel, 1995; Cox, D'Antonio, 2004; Monazzam, Lam, 2008). They demonstrated that by changing the wire meshes with different resistive layers, it is possible to obtain a significant absorption ability over a wide variety of frequencies.

This section proposes an improved absorption ability of reactive surfaces by putting a resistive layer on the profiled PRD barriers. Three wire mesh layers with different flow resistively, 5.7, 55 and 550 Rayls (MKS) are used respectively on the barrier models "PRL", "PRM" and "PRH". Figure 8 shows the improvement made by a layer of wire mesh with flow resistivity of 5.7 MKS Rayls on a primitive root diffuser edge barrier. In fact, the figure shows the differences of insertion loss of the barrier model "PWL" relative to the barrier model "PR4". As clearly seen from the graph, a significant improvement is achieved in wide frequency ranges by using a very low resistive layer. The use of a resistive layer could improve the overall performance by promoting the absorption ability of the surface. This is why the overall A-weighted insertion loss of barrier model "PR4" is increased by 0.8 dB(A) in this receiver location. This improvement can even become higher by increasing the resistance of the layer from 5.7 to 55 MKS Rayls. In this case the A-weighted insertion loss of the barrier model "PWM", which employs a wire mesh with resistance of 55 MKS Rayls, at the receiver point (−50, 0) is 1 dB(A) higher than that of the barrier model "PR4". Of course, increasing the resistivity above the specific acoustic impedance of air can reduce the effect of the well in resonance and shows a negative effect on the performance of reactive barriers.

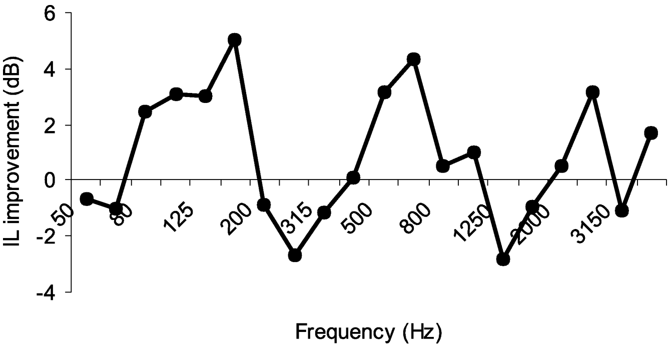

Fig. 8. Insertion loss improvement made by utilizing a layer of wire mesh ($r = 55$ MKS Rayls) on barrier model "PR4" at the receiver point (−50, 0).

3.4. Broad band insertion loss

Table 3 shows the logarithmic mean A-weighted insertion loss dB(A) of all design models and their differences with the reference T-shape barrier over 9 mentioned receivers (Named by ΔIL). As illustrated in Table 3, the A-weighted mean insertion loss of all designed models is higher than the reference T-shape model. By comparing the overall results of two different utilized Schroeder diffusers on the profiled barrier, it is proved that increasing the number of sequences in PRD compared to that in QRD provides more impedance changes on the top surface. This leads to higher performances of its relevant barrier compared to the overall efficiency of the QRD edge barrier by 0.7 dB(A). Moreover, reactive T-shaped barriers with a resistive material are more efficient than those with only a reactive top surface (e.g. PR4 and QR4). In case of wire mesh layers with different flow resistivity very similar trends are observed.

Table 3. The insertion loss of various shapes at 9 receivers.

Barrier type	IL (Min) [dB(A)]	IL (Max) [dB(A)]	IL Mean [dB(A)]	ΔIL
T "Ref"	14.8	19.54	16.9	0
QR4	17.35	21.3	19	2.1
PR4	17.96	22.14	19.7	2.8
PR5	17.87	22.63	19.5	2.6
PR10	15.88	21.77	17.5	0.6
PWL	18.7	23.69	20.5	3.6
PWM	**18.85**	**24.2**	**20.7**	**3.8**
PWH	18.57	23.84	20.4	3.5

As seen in Table 3, PWM with a wire mesh ($R = 55$) compared with other resistive cover barriers has a slight better overall performance. Increasing the frequency design of the PRD shifts its performances toward higher frequencies, which leads to a lower mean A-weighted insertion loss.

4. Conclusion

The acoustic performance of PRD edge single traffic noise barriers on rigid ground has been investigated employing a 2-D boundary element method. Broadband insertion loss of some surfaces with different well design sequences, designed frequencies and absorption abilities has been predicted over 9 receiver locations using a A-weighted traffic noise spectrum from 50 to 4000 Hz at 1/3 octave band frequencies. The performances of PRD barriers have been compared with their equivalent rigid and QRD edged barriers. The results can be summarised as follows:

1. As already introduced in previous works, using constant slits and a QRD structure on the top surface of T-shape barrier improves significantly the overall performance of the barrier. This investigation showed that using Schroeder diffusers with more sequences, which causes more impedance changes on the

top surface of the profiled barriers, provides higher overall performances in the PRD barriers. In this case a PRD barrier with the frequency design of 400 Hz improves the mean A-weighted performance of its equivalent QRD barrier by 0.7 dB. It is worthwhile noting that according to the previous finding, the QRD edged barrier with 400 Hz was the most efficient model for traffic noise control (Monazzam *et al.*, 2005). The reason behind the high efficiency of the PRD barriers can be explained by having more impedance changes on the surface and allowing higher well depths in the structure. The high impedances change provide a wider frequency effect of the devices and the high well depth shifts the first effective frequency toward lower frequencies.

2. By keeping the frequency design fixed at 400 Hz, every single designed PRD barrier could increase the overall performance of the QRD barrier of the same designed frequency.
3. Although employing PRD on the T-shape barrier was found to produce a frequency dependent barrier, the spectra of the insertion loss are smoother compared to that of the QRD edged barrier. This was explained by the number of impedance changes, which is higher in PRD than that of QRD.
4. It was also found that the increase in the frequency design of the utilized PRD surfaces while keeping the upper cut-off frequency constant, shifts the frequency effect of the diffuser toward higher values, which consequently leads to lower overall performances. In case of the barrier model "PR10", which employs a PRD with design frequency of 1000 Hz, has a 2.2 dB(A) lower overall A-weighted performance than the barrier model "PR4" in which a PRD with design frequency of 400 Hz is used.
5. According to the previous findings (Monazzam, Lam, 2008; Wu *et al.*, 2001), implementing wire mesh could increase the absorption ability of the Schroeder diffusers substantially. However, a wire mesh with high resistivity (e.g. PWH) reduces the effect of wells in resonance. Hence using wire mesh with mild resistivity on the top surface of PRD improves the overall performances of the reactive barriers by enhancing the absorption ability of the surface, while the effect of wells in resonance is still significant. It was shown that the barrier model PWM with a wire mesh ($R = 55$) has a better efficiency than the barrier model PWH with a wire mesh ($R = 550$). However putting high resistivity wire meshes on the PRD top of a diffuser barrier reduces significantly the performance of the barrier within the frequency bandwidth of the diffuser despite the large increase in absorption. This is due to the reduction of the effect of well resonances, which is the main factor contributing to the high efficiency of a PRD barrier.
6. The low frequency performance of the PRD covered T-shape barrier (Model "PR4") was found to be higher those of its equivalent QRD barriers in both the far field and in areas close to the ground. The efficiency of the "PR4" model is lower than its equivalent QRD barrier (Model "QR4") in near field above the ground.

The investigation presented in this paper on the effect of utilizing primitive root sequence on T-shape barriers has clearly shown that the utilized sequence in the diffuser could cover the weakness of the quadratic residue sequence in environmental noise control applications, therefore a further investigation on the combination of these sequences for the enhancement of the current dip on the insertion loss spectrum of the Schroeder diffuser barriers is recommended.

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