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CONTRIBUTION OF QUADRATIC RESIDUE DIFFUSERS TO EFFICIENCY OF TILTED PROFILE PARALLEL HIGHWAY NOISE BARRIERS

***M. R. Monazzam, P. Nassiri**

Department of Occupational Health, School of Public Health, Tehran University of Medical Sciences, Tehran. Iran

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ABSTRACT
This paper presents the results of an investigation on the acoustic performance of tilted profile parallel barriers with quadratic residue diffuser (QRD) tops and faces. A 2D boundary element method (BEM) is used to predict the barrier insertion loss. The results of rigid and with absorptive coverage are also calculated for comparisons. Using QRD on the top surface and faces of all tilted profile parallel barrier models introduced here is found to improve the efficiency of barriers compared with rigid equivalent parallel barrier at the examined receiver positions. Applying a QRD with frequency design of 400 Hz on 5 degrees tilted parallel barrier improves the overall performance of its equivalent rigid barrier by 1.8 dB(A). Increase in the treated surfaces with reactive elements shifts the effective performance toward lower frequencies. It is found that by tilting the barriers from 0 to 10 degrees in parallel set up, the degradation effects in parallel barriers is reduced but the absorption effect of fibrous materials and also diffusivity of the quadratic residue diffuser is reduced significantly. In this case all the designed barriers have better performance with 10 degrees tilting in parallel set up. The most economic traffic noise parallel barrier which produces significantly high performance, is achieved by covering the top surface of the barrier closed to the receiver by just a QRD with frequency design of 400 Hz and tilting angle of 10 degrees. The average A-weighted insertion loss in this barrier is predicted to be 16.3 dB (A).

Keywords: Tilted parallel noise barrier, Diffusion, Boundary element method

INTRODUCTION
In recent years road traffic has rapidly raised, particularly in towns and even more in large cities, thus representing, without any doubt, one of the most widespread source of noise pollution. Noise exposure reduction may be effectively achieved by the erection of an acoustic barrier which prevents traffic noise reaching the receivers located inside the shadow zone by the direct path. In case of residential and other urbanized areas located on both sides of roadways, pairs of parallel traffic noise barriers are usually erected, but the multiple reflections occurring between the barriers cause a significant degradation in the single barrier screening performance (Bowlby and Cohn, 1994; Slutsky and Bertoni, 1988; Watts, 1996).

To improve the acoustic efficiency of single noise barriers, many studies, both theoretically and experimentally, have been done and many different new types of barriers have been proposed (Hothersall, *et al*., 1991; Arenas and Monsalve, 2001; Ishizuka and Fujiwara, 2004; Monazzam and Lam, 2005).

However, little works have been reported on efforts on reduction of multiple reflection effects of various parallel traffic noise barrier configurations. Nonetheless, concern is increasing as more is achieved about the issue and greater needs for parallel traffic noise barriers are being identified.

*Corresponding author: *mmonazzm@hotmail.com*
Tel/ Fax: +98 21 88992663

A detailed examination of previous literature on parallel barrier multiple reflections has shown that most of the previous research pointed to a quantifiable degradation in insertion loss due to the second barrier (Bowlby, 1984).

With respect to traditional roadside parallel barriers, new noise barriers are essentially based on two basic principles. The first principle involves the application of sound absorbing or diffusing materials to the traffic edges and faces of the barriers. The second principle involves the adoption of new barrier shapes which substantially imply the modification of barrier angles by introducing tilted parallel barriers.

Recently numerous researches have been conducted to improve the performance of parallel traffic noise barrier by incorporating sound absorptive elements. In this case Watts and Godfrey by a field measurement study showed a fairly significant improvement by changing the barrier face from reflective to sound absorptive (Watts and Godfrey, 1999).

The idea of tilting the barriers is a principle to redirect the waves upward so that the imaging effects of the pair of barriers are reduced. However Watts examined the performance of both parallel vertical and tilted traffic noise barriers by a full scale method. It was shown that although both sound absorbing barriers and tilted barriers are improved the performance of the parallel barrier, they are still effective in degradation of single barrier performance due to unwanted reflected paths (Watts, 1996).

Another principle in parallel noise barrier that one should bear in mind is that, whenever pairs of barriers are erected at both sides of a roadway, the use of acoustically rough traffic faces of the barriers is always preferred to acoustically absorbent faces. Therefore the researchers are looking to obtain a diffusive rather than a geometrical reflection of the incident sound in the main frequency range of the traffic noise spectrum. In fact, owing to the spreading in all directions of the reflected noise by diffusing hard elements, non-negligible abatements with respect to pairs of geometrically reflecting barriers may be achieved.

In this case Fujiwara introduced the reactive barriers to suppress the edge effect of reflective noise barriers at which the efficiency of the “soft” barrier increased by more than 10 dB in the frequency range with lowest surface pressure (Fujiwara, 1990).

The acoustic performance of pairs of diffusive roadside vertical barriers was tested experimentally in a scale model, and compared with that of reflecting vertical barriers by Claudio *et al*. in 2007. Significant attenuation benefits were detected not only in the shadow zone behind the vertical barriers, but also above them, thus proving that diffusive traffic faces of the vertical barriers may effectively help in reduction of multiple reflection effects (Claudio, *et al*., 2007).

The performance of quadratic residue diffuser (QRD) on different reflective single vertical barrier profiles is also investigated by Monazzam *et al*, where the best shape for using the device was found to be a T shaped profile (Monazzam and Lam, 2005).

No works have so far done to improve the efficiency of tilted parallel barriers by hard elements. This paper investigates the contribution of welled diffusers to efficiency of profiled tilted parallel highway noise barriers. The welled diffuser used in this investigation is quadratic residue diffuser, which is the most common Schroeder diffuser.

In this paper the single reference reflective barrier is a tilted rigid T shaped barrier. In this case it has been shown by numerous papers that a rigid vertical T shaped barrier is a barrier with high performance and also the best shape for using both absorptive and diffusive elements. (Hothersall, *et al*., 1991; Monazzam and Lam, 2005). In this report the performance of different angled tilted parallel noise barrier with quadratic residue diffuser either on the top surface or on the barrier roadside faces with different frequency designs and properties, is predicted using a two dimensional boundary element method. Insertion loss at 1/3 - octave centre frequencies are calculated. The results are also compared with reflective as well as equivalent absorptive tilted parallel barrier on the rigid ground to show that it is efficient to use ribbed surfaces instead of absorptive elements on tilted parallel barrier to cancel out the effects of multiple reflections in these kinds of problems.

MATERIALS AND METHODS

Quadratic Residue Diffuser

Quadratic residue diffuser is a diffuser consisting of a series of wells of the same width and different depths. The wells are separated by thin fins. Within one period, the depths of the wells are controlled by a quadratic residue sequence. In each well, the incident wave and its reflected wave will have different phase shifts corresponding to the different path lengths they have traveled. If the phase differences are sufficiently large, the structure will produce a significant scattering of the reflected wave, with scattering characteristics depending on the depth sequence of the elements. In a best condition and design a QRD should make a uniform scattered field within its design frequency range. Many more information with more details on the design, diffusive and absorptive properties of this kind of surfaces can be found in other recent publications (Cox and D'Antonio, 2004; Monazzam and Lam, 2008).

Prediction methods

A tilted parallel noise barrier of infinite length lies on the plane, and it is assumed that the acoustical properties and the cross-section shape of the noise barriers do not vary across their length. Therefore the problem is a two-dimensional, with the z-axis parallel to the barrier length, and all the geometrical and acoustical variables remain unchanged in the z-direction. The barrier surfaces are assumed to be locally reacting with specific surface admittances. The Helmholtz wave equation is then solved by the boundary integral equation at a single frequency using boundary element method (Monazzam and Lam, 2005). In the numerical simulations, dimension of elements was taken to be less than λ/5 to give a reasonable representation of constant surface pressure over an element.

In the cases with QRD structure, the welled surfaces are represented by a box with the top surface having an admittance distribution as given by the simple phase changes due to plane wave propagation inside the wells. Using this method, it is much more convenient to do the calculations over a wide range of barrier designs. The result of this assumption on single QRD barriers is validated (Monazzam and Lam, 2005). The interference between the source and its ground image was minimized by locating the sound source very close to a rigid ground. The ground is always taken to be rigid. In this investigation a tilted T shaped profile barrier (barrier No.1 of the tilted parallel barrier) is always used for co-ordination. Distance from the source to the centre line of the barrier is 5 m in all calculations in this investigation. The sound pressure before and after barrier erection at different receiver points is predicted at 1/3-octave centre frequencies between 50 and 4000 Hz. The insertion loss at each frequency is then calculated by:

$$IL = -20\log_{10}\left|p_b / p_g\right| dB \qquad (1)$$

where p_b is the pressure when barrier is present and p_g is the pressure at the receiver with only the rigid ground present.

For the simulation of the effect of absorbent surfaces, a fibrous material is assumed and for the calculation of the characteristic impedance and propagation constant of the fibrous material, the empirical formulae of Delany and Bazley are used (Delany and Bazely, 1970).

The normalized specific impedance of the wells of quadratic residue diffuser is calculated by the method introduced by Wu (Wu, *et al*., 2001). In this method the viscous and thermal losses in the wells are also taken in account, although if the surfaces of the wells are rigid and it is sufficiently wide the viscous and thermal losses are generally ignored in the literature.

RESULTS

The performance of a few different shapes of tilted parallel noise barriers with different configurations has been studied using 2D boundary element method. he typical barrier design used in the simulation is shown in Fig. 1. Barrier No.1 is a tilted T shaped barrier and barrier No.2 is a tilted plain barrier which is sited in 40 m distance with barrier No.1. Both barriers are tilted with the same angles outward the road. As it is shown in the figure the overall heights of both barriers is 3m, which is typically used in literature. In all models the stem and cap thickness of barrier No.1 is respectively 0.1 and 0.3 m. The span of the T top in T shaped barrier is 1m. This length is mostly used because in most areas highway traffic noise has a dominant frequency of approximately 550 Hz, resulting in a wavelength approximately 2 feet long (FHWA, 1980), a 3-feet (1 m) width for T-top is used to ensure adequate performance of the top edge of barrier No1. These dimensions are similar to those used in previous studies on the performance of different environmental noise barriers (Hothersall, 1991; Crombie, *et. al.*, 1995; Fujiwara, 1998; Monazzam & Lam, 2008). In all models the stem of barrier No.2 is 0.3 m. This thickness for the stem in barrier No.2 and the cap in barrier No.1 is used to ensure enough space for utilizing different QRD designs on these surfaces.

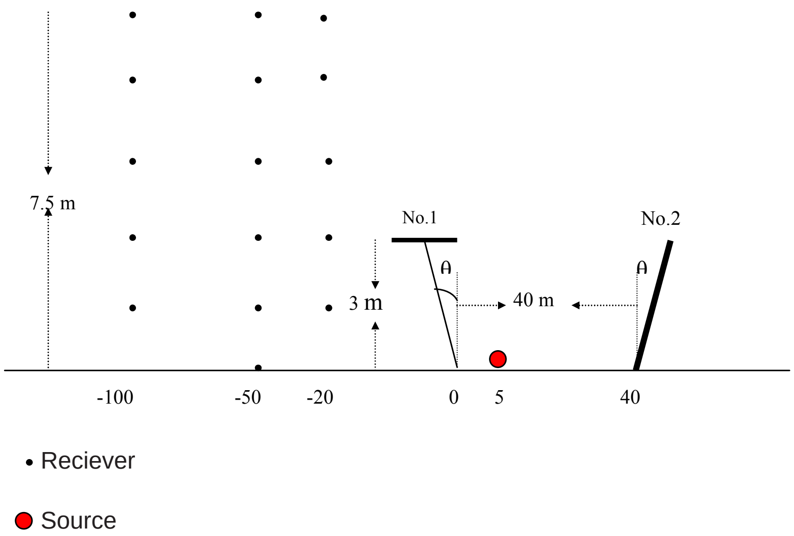

Figure 1: Schematic setup of the tilted parallel barrier
(Source and receivers locations are also included, dimensions are in m)

The 16 receiver points model a wide field behind barrier No. 1 from 20 to 100 m on ground extended to height of 7.5 m. The source is located at coordinate (5, 0.02).

Three different surfaces were used on the barrier including:

Rigid surface: All surface admittances are zero, which is the Neumann boundary condition.

Absorbing surface: The upper surface of the cap in barrier No.1 and roadside of barrier No.2 is covered with fibrous absorptive material. The flow resistivity of the fibrous material is taken to be 20000 N.s/m^4. The thickness of the fibrous material is fixed at 0.245 m (the same as the thickness of the QRD).

QRD barrier: A Quadratic residue diffuser with frequency design of 400 Hz and well width of 12 cm is fixed to the surface of barrier No.1 and 3 Quadratic residue diffusers with frequency design of 1 kHz and well width of 12 cm covers the roadside face of barrier No. 2 as shown in Fig.1.

Different designs are used to examine how diffusers affect the performance of tilted profiled parallel barriers. The different designs and their model names are introduced in Table 1.

Table 1: Design model names and corresponding configurations

Model	Barrier 1	Barrier 2	Tilted angle (θ)
RS	Rigid	Absent	5
PRS	Rigid	Rigid	5
PAS	T part is covered with fibrous material	Rigid	5
PAAS	Roadside is covered with fibrous material	Roadside is covered with fibrous material	5
PGS	QRD edged	Rigid	5
PGGS	QRD edged	3 QRDs at the roadside	5
RST	Rigid	Absent	10
PRST	Rigid	Rigid	10
PAST	T part is covered with fibrous material	Rigid	10
PAAST	Roadside is covered with fibrous material	Roadside is covered with fibrous material	10
PGST	QRD edged	Rigid	10
PGGST	QRD edged	3 QRDs at the roadside	10

Note: The overall surface and thickness of fibrous material in absorptive barrier models is the same with those of in their equivalent diffusive barrier models.

The dimension of one of the tested QRD designs in the top surface of barrier No.1 and the vertical barrier No. 2 having 3 QRDs (labeled model ‘‘PGGS’’ here) are shown in detail in Fig. 2.

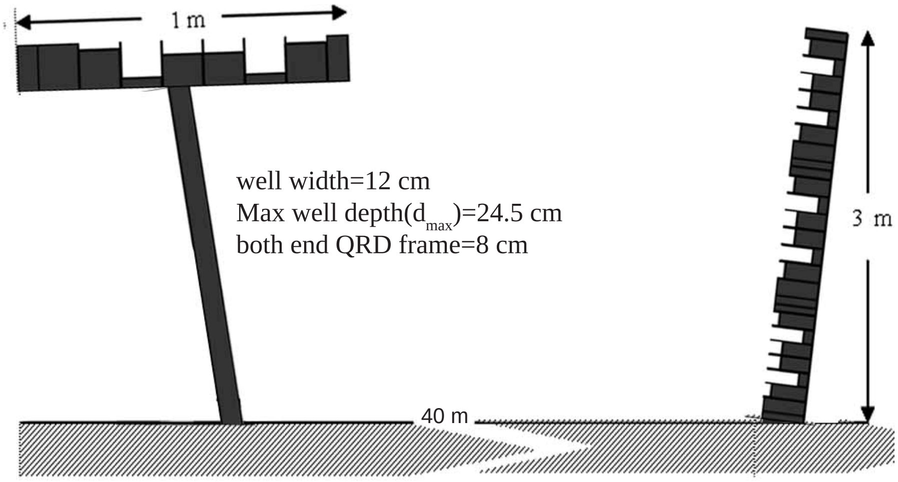

Fig. 2: Dimensions of the T-shape barrier (barrier No.1) having a QRD (N = 7* and fr = 400 Hz) and the vertical barrier No.2 having 3 QRDs (N = 7 and fr = 1kHz) in parallel barrier model “PGGS”

In order to investigate to what extent the QRD tilted barriers reduce the degradation effect of multiple reflection effect of reflective tilted parallel barrier, the results are compared against an equivalent tilted rigid parallel barrier.

Multiple reflection effect on a tilted T shaped barrier

One of the most common recommended methods for reduction of multiple reflection effects on plain parallel barriers is to tilt the contributed surfaces by different angles toward receiver points. In this case, many efforts have been done to describe the effect of multiple reflection on tilted plain parallel barriers by many investigators (Watts, 1996), but this effect on tilted profiled barrier has yet to be tested. This is why in this investigation the effect of a plain tilted barrier when is erected in front of a tilted T shaped barrier with different tilted angles and 40 m distance is studied.

Firstly a comparison on the performance of two different conditions including a tilted T shaped barrier with no multiple reflection degradation effect (barrier model RS) and its equivalent condition with the multiple reflection reduction effect (barrier model PRS) in 1/3 octave center frequencies is made in Fig. 3. In barrier model RS the surface condition and source position is kept exactly the same as barrier model PRS, the only difference is the possible multiple reflection effect resulting from barrier No.2. It is worth remembering that in this condition the tilted angle is 5 degrees. As it is clearly seen from the figure the multiple reflection between two screens reduce the performance of tilted profiled parallel barrier compared with that of equivalent single profiled barrier in frequencies between 80 to 100 Hz.

The frequency selectivity in tilted barrier is not very dominant within the tested frequency ranges, although some ups and down are visible in the figure. In this case the constructive effect of incident and reflected waves in this special geometry made the minimum performance in 125 Hz and the deconstructive effect of them introduces the highest performance in 1250 Hz for the tilted parallel barrier while the performance in single profiled barrier increases almost smoothly as the frequency increase, which is due to lack of multiple reflection degradation effect.

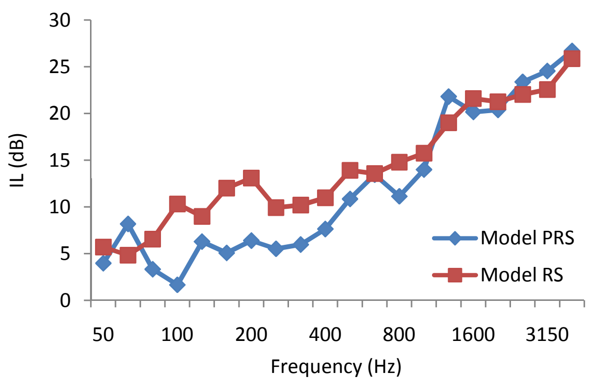

Fig. 3: Predicted spectra of Insertion Loss for single 5 degrees tilted T shaped rigid barrier (barrier model RS) along with its equivalent parallel barrier (barrier model PRS) at receiver point (-50, 0)

This is to some extent predictable that with changing the geometry and receiver position the performance of both barrier configurations will change but tilted parallel barrier is fairly more dependant to the geometry. To test this, 16 receiver points are examined in this investigation. The results for the 16 receivers showed that the performance of tilted parallel barrier compared with that of equivalent single tilted T shaped barrier is getting worse in most frequencies in far field especially above barrier's height.

In order to average the interference effects achieved at single frequencies, and allow smoother trends to be identified more easily, the A-weighted road traffic noise spectrum (BS EN 1793-3:1998) is calculated by combining the results for insertion loss at one-third octave band centre frequencies over the range 50–4000 Hz and assuming a suitable source spectrum.

The A-weighted mean reduction of insertion loss by multiple reflections which is created by barrier model PRS at 16 receivers is brought in Table 2. The average 4.63 dB (A) reduction in overall performance behind the tilted profile parallel barrier is a significant reduction which is presented in the table. In the receiver lower than the barrier's heights the overall reduction of performance increases as the distance of receiver from center line of barrier No.1 increases but in the receivers higher than barriers height the situation is reverse.

Referring to previous investigation and this result, one can conclude that any attempt for improving the performance of a single rigid tilted profile barrier can be removed in parallel installations, if nothing done for absorbing or diffusing the reflections from different surfaces of both barriers. The most contributing surfaces in the problem raised in this investigation are the top surface of barrier number 1 and roadside surface of barrier number 2.

Table 2: The A-weighted mean reduction of insertion loss of barrier model PRS compared with that of in barrier model RS

Receiver No.	The A-weighted mean reduction of insertion loss(dB(A))	Receiver No.	The A-weighted mean reduction of insertion loss(dB(A))
1	3.52	9	3.64
2	2.87	10	4.77
3	4.33	11	6.74
4	4.65	12	5.30
5	3.25	13	4.90
6	4.1	14	5.04
7	5.0	15	6.32
8	4.8	16	4.86
Average (App.)		4.63	

In this part of the study assuming the dominant frequency of around 500 Hz for highway traffic noise a set of calculations in a wide area (400 receiver points) for the reduction of performance of tilted parallel barrier in both far and near field is also done and the result is shown in a 3D graph. The studied area was from 2 to 50 meter distance from barrier number 1 from ground extended to the height of 7 meter. The reduction of performance in tilted parallel barrier model PRS compared with the single equivalent tilted T shaped barrier is shown in Fig. 4.

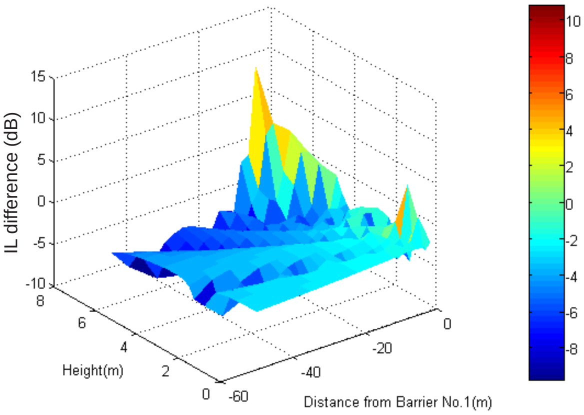

Fig. 4: The amount of reduction in insertion loss of barrier model PRS compared with that of in barrier model RS at 500 Hz in the wide field behind barrier number 1

As it is clearly seen from the graph the amount of reduction increases when height and distance increases, some thing that is also true for the overall performance of the 5 degrees tilted profile parallel barrier. There is a very narrow field in the illuminated zone that the destructive effect of the reflective waves from the top surface of barrier number 1 and waves coming from the roadside of the barrier number 2 is made a significant improvement in the performance of the 5 degrees tilted profile parallel barrier. The average reduction of acoustic performance of the tilted parallel barrier is more than 3.7 dB at 500 Hz compared with the single equivalent T shaped barrier. With increase in tilted angles from 5 to 10 degrees in parallel barrier model PRST lower degradation effect exists, as it is shown in Fig. 5, this is due to increase in the angle of reflection waves which leads to reduction of multiple reflection effects.

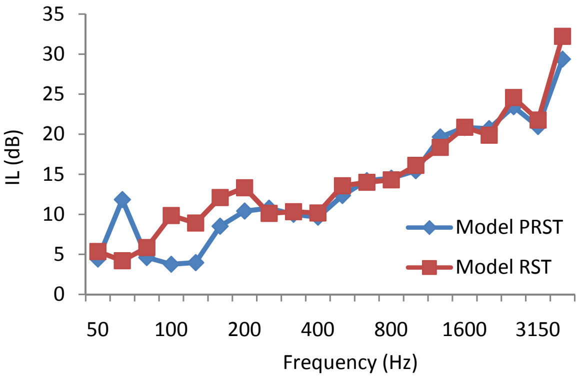

Fig. 5 : Predicted spectra of Insertion Loss for single 10 degrees tilted T shaped rigid barrier(barrier model RST) along with its equivalent parallel barrier(barrier model PRST) at receiver point (-50,0)

In this case with tilted angle of 10 degrees the average reduction of acoustic performance in parallel tilted barrier is above 1.6 dB at 500 Hz compared with the single equivalent T shaped barrier, which is of course significantly lower than that of in 5 degrees tilted highway traffic noise barrier.

Absorption effects on tilted profiled parallel barrier

It has been both theoretically and experimentally showed that using absorbent materials on tilted plain barriers are the utmost method to remove the multiple reflections between two simple parallel barriers. Since the tilting method redirect most of the reflected waves upward and the remaining are taken by the absorbent elements of both barrier surfaces. However this study is used the absorbent elements to investigate the reflective wave absorption effect on the tilted profiled parallel noise barrier. In this case two different methods are introduced.

Firstly the reflected wave from the top surface of 5 degrees tilted T shaped barrier is removed by covering just the top surface by fibrous materials (barrier model PAS) and secondly the reflective waves of both the top surface of barrier number 1 (the 5 degrees tilted T shaped barrier) and also the roadside face of barrier number 2 (the 5 degrees tilted plain barrier) is vanished by utilizing absorbent elements on this surface as well as top surface of barrier number 1(barrier model PAAS). To investigate the effect of top surface reflection of barrier number 1, a comparison between barriers models PRS and PAS is made in Figure 6.

Removing the top surface reflections by fibrous materials improves slightly the performance of the barrier model PAS just above 1.25 kHz compared with the rigid tilted barrier model PRS. Bellow 1.25 kHz no improvement is made by fibrous material of the top surface of barrier number 1. Improving the performance on high frequencies is predicable but lack of efficiency on low frequencies could be explained by both the tilting configuration of screens and the small absorbent surface. It can be predicted that by increasing the top surface dimension, the benefit of absorbent materials will be shifted toward lower frequencies and the overall performance gets to some extent higher than that of the designed cap span. This is beyond the purpose of this investigation and will not be presented here.

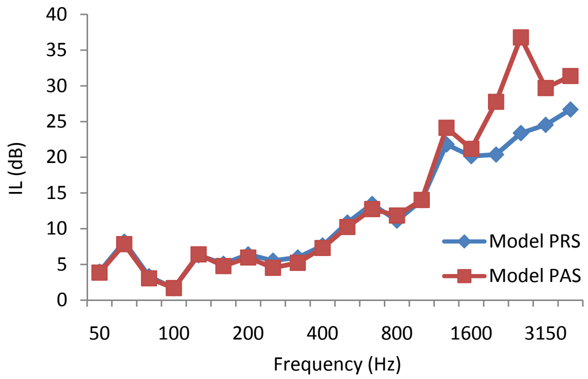

Figure 6: Predicted spectra of Insertion Loss for 5 degrees rigid tilted profile parallel barrier (barrier model PRS) along with its equivalent partially absorbent parallel barrier (barrier model PAS) at receiver point (-50, 0)

The A-weighted mean insertion loss of partially absorbent 5 degrees tilted parallel barrier is compared with its equivalent rigid barrier as well as single T shaped barrier and it is found that almost at entire receiver points no significant improvement is visible, the small improvement in some receiver points is achieved by the improvement in frequencies above 1.25 kHz as it was shown in Fig. 6. The small improvement is also limited to the high receiver points, because the waves reflected upward from barrier number 2, which is a tilted screen.

Covering the roadside face of barrier number 2 as well as the top surface of barrier number 1 by fibrous material in 5 degrees tilted parallel barrier model PAAS improves the performance of its equivalent rigid barrier model PRS. The effective frequency is shifted toward frequencies lower than 250 Hz as one can see in Fig. 7. This is because of the large absorbent elements used in this model. In fact increasing the area of absorbent material widens the effective frequency bandwidth.This model is also made a significant overall A-weighted improvement.

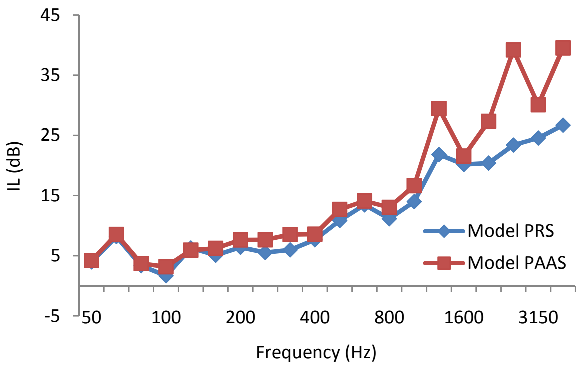

Fig. 7: Predicted spectra of Insertion Loss for 5 degrees rigid tilted profiled parallel barrier (barrier model PRS) along with its equivalent absorbent barrier (barrier model PAAS) at receiver point (-50, 0)

An interesting result in absorbent 5 degrees tilted parallel barrier model PAAS is its almost regular improvement in performance at 500 Hz in a wide field behind barrier number 1. The mean insertion loss improvement in this frequency in the wide tested area behind barrier number 1 is 2 dB. The benefit of absorbent material is higher in far field than that of in near field with high heights.

Effect of QRD on tilted profiled parallel barrier

The main scope of this investigation is to study the contribution of QRD surfaces on different parts of tilted profiled barriers. Therefore the methods of utilizing absorbent elements are similarly applied but this time by QRD surfaces. In this case in the first model the top surface of barrier number 1 is covered by QRD (barrier model PGS) and in the second model both top surface and roadside face of barrier number 2 are covered by QRDs (barrier model PGGS). In both above presented models the tilted angle is kept at 5 degrees. Fig. 8 shows the performance of partially diffusive parallel barrier model PGS compared with the fully absorptive parallel barrier model PRS in receiver number 1.

The improvement is started from frequencies above 315 Hz, which a 1/3 octave band lower than that of the diffuser's frequency design. The advantage of using this receiver point is that the effect of image of receiver is omitted, therefore better comparison is provided.

Employing the designed QRD on model "PGS" increases the insertion loss of the barrier compared with the rigid profiles parallel barrier (model PRS) at a wide frequency range above 315 Hz. The Fig. clearly shows that the peaks of insertion loss gained by model "PGS" at 630, 1000 and 2000 Hz. Increases at 315, 500 Hz, 1.25 kHz are also significant. At frequencies lower than 315 Hz and above 2 kHz (outside the QRD frequency bandwidth) the performance start to decline and go even slightly lower than rigid shape at very low frequencies. In 800 and 1600 Hz which are the function of frequency design of the utilized diffuser, the performance of the partially diffusive tilted parallel barrier is reduced. The reason behind this phenomenon on QRD surfaces as well as single QRD barriers is explained in detail by Monazzam (Monazzam, 2005). In this investigation the findings for QRD surfaces and single QRD barriers are seen in parallel QRD barriers too.

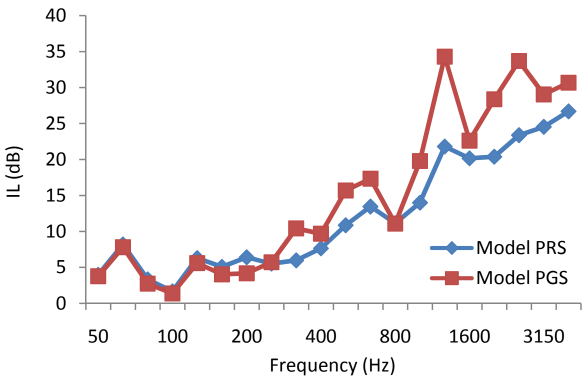

Fig. 8: Predicted spectra of Insertion Loss for 5 degrees rigid tilted profiled parallel barrier (barrier model PRS) along with its equivalent partially diffusive barrier (barrier model PGS) at receiver point (-50, 0)

Overall performance of the partially diffusive tilted parallel barrier in dB (A) is also compared and a significant improvement is achieved. The reason behind this improvement lies on the low frequency performance improvement, which is achieved by the designed diffuser. The very interesting result here is that the overall improvement increases as the distance and heights of receivers increases. It is worth remembering that all tilted parallel barriers suffer form low performance in far field and high height. It is also predictable that with lowering the design frequency in this barrier configuration, higher overall performance is achievable due to shifting the effective frequencies to the lower frequencies by using QRDs with lower design frequency.

The amount of improvement at 500 Hz is also significant almost in entire field including far field at higher heights. However in near field close to ground some performance reduction is visible. The best performance is achieved in higher heights in the regions with angles between 45 to 60 degrees. It is worth noted that this high performance region depends on barrier shape and configuration along with the source/ receiver geometry, some thing is already described for single barriers in detail by Monazzam (Monazzam, 2005). The basic principle is the deconstructive effect of the incident and reflected waves, which provides the high performance in the above mentioned region. Identification of these regions is very important in barrier designs and installations. In fact paying attention to this behavior of noise barriers reduces the barrier's construction cost.

In a separate attempt the acoustic performance of the diffusive tilted parallel barrier having diffusive surfaces on both top surfaces of barrier number 1 and the roadside face of barrier number 2 is also compared with its equivalent rigid barrier in Fig. 9. The frequency design of QRDs used in the roadside of barrier number 2 is 1 kHz while the frequency design used on the top surface of barrier number 1 is 400 Hz. This is done to have a mixture of frequency designs in the diffusive parallel barrier and the selection of these wasn't by design. The optimization of this frequency designs could be an interesting future work for further improvements of the QRD parallel barriers.

In this barrier the performance starts to improve from 250 Hz, which is lower than the designed frequency of the QRD used at the top surface of barrier number 1. On the other hand the minima in the performance spectra are appeared to be at 400 Hz and its integer. The above two findings both maxima and minima indicates that in this barrier configuration the influence of diffuser surface in top surface of barrier number 1 is more that of in barrier number 2. In fact the wide angle of incident wave providing by the slopped barriers in this configurations effects on the ideal performance of QRD with vertical position. The benefit of the wide surface of the diffuser used in barrier number 2 is shifting the effective frequency toward lower frequencies which leads to higher overall performance for this barrier model.

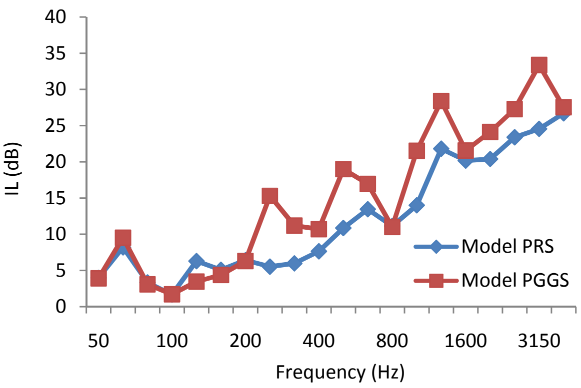

Fig. 9: Predicted spectra of Insertion Loss for 5 degrees rigid tilted profiled parallel barrier (barrier model PRS) along with its equivalent diffusive barrier (barrier model PGGS) at receiver point (-50, 0)

The average increase in overall performance by introducing QRD with different design frequencies to both components of the tilted parallel barriers improves by 2 dB (A). And the average improvement by introducing the diffuser surfaces to the rigid profiled tilted parallel barriers at 500 Hz in a wide area behind barrier number 1 (400 receiver points) is 8 dB.

Effect of tilted angle on diffusive parallel barrier

In this part of the investigation the effect of leaning the components of both partial and fully diffusive parallel barriers are also studied. Therefore three different screen's angles including 0, 5 and 10 degrees are applied. In this case firstly the performance of a vertical partially diffusive parallel barrier (tilted angle zero), which is called barrier model PG, barrier model PGS (tilted angle 5 degrees) and barrier model PGST (tilted angle

10 degrees) in 1/3 octave bands are predicted and they are presented in Fig. 10. The only difference in the above three models is just the sloping angles. With increase in the tilting angles, the performance of the partially diffusive barriers is improved above 200 Hz. The high frequency effect is more dominant in the tilted model than that of vertical model. The mean overall improvement by 5 degrees tilting diffusive barrier compared with the vertical diffusive barrier is 7 dB (A) while that is 9.7 dB (A) for 10 degrees tilting.

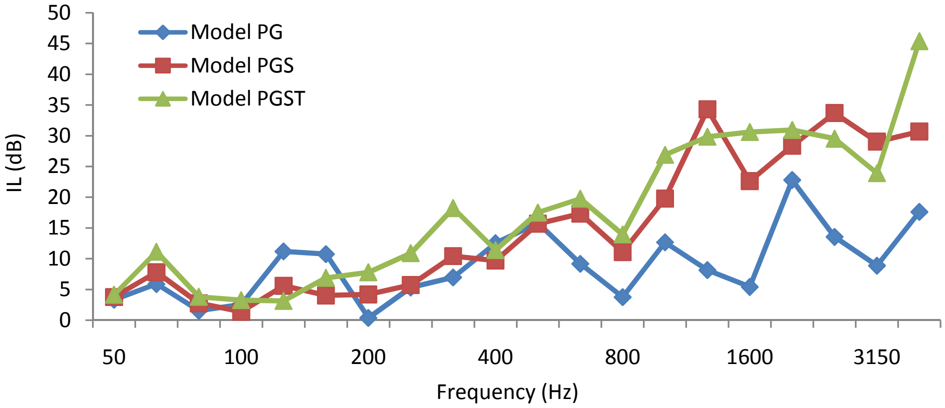

Fig. 10: Predicted spectra of Insertion Loss for three different profiled partially diffusive parallel barriers including barrier model PG, PGS and PGST at receiver point (-50, 0)

Another study is bout the tilting angle effects of diffusive parallel barrier. Thus the performance of a vertical diffusive parallel barrier (tilted angle zero), which is called barrier model PGG, barrier model PGGS (tilted angle 5 degrees) and barrier model PGSST (tilted angle 10 degrees) in 1/3 octave bands are predicted and they are presented in Fig. 11. It is worth noting that the only difference in the above three models is just the tilting angles. As one can see from the figure, the performances of all above three models get close to each other. This means the utilized diffuser surfaces could to high extent overshadow the tilting effect on parallel performances. This can be interpreted that the large diffuser surfaces which are used in these models can successfully cancel out the multiple reflection effect between parallel screens.

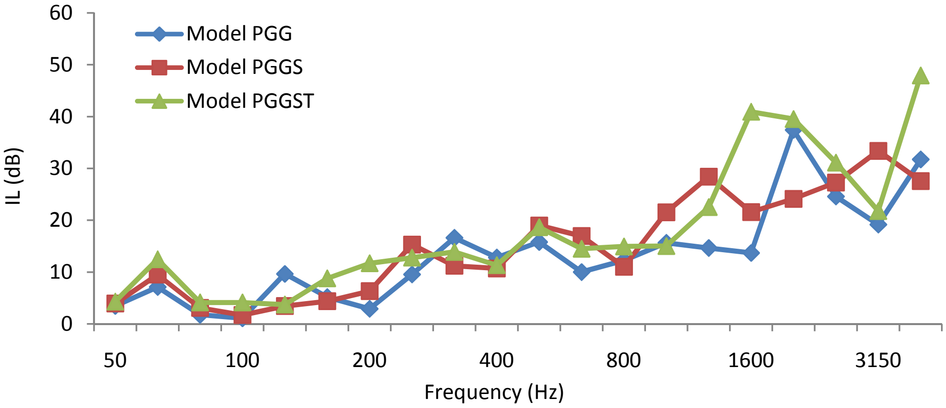

Fig. 11: Predicted spectra of Insertion Loss for three different profiled diffusive parallel barriers including barrier model PGG, PGGS and PGGST at receiver point (-50, 0)

Finally to give a clear picture of the entire designed profile tilted parallel barriers, their overall acoustic performance for 5 and 10 degrees tilting are also compared. From the results, as it is expected, none of the designed barriers could totally remove the multiple reflection degradation effect of parallel barriers and the performance of single profiled barrier with no multiple reflection effects is the highest among all tested models. However among the designed 5 degrees tilted barriers the best overall performance is achieved by introducing barrier model PGGS. Using this parallel diffusive barrier the overall performance of the rigid tilted parallel barrier model PRS improves by 1.9 dB (A). The lowest improvement is made by barrier model PAS.

By comparison the overall performances of the barriers with 10 degrees sloping, it is found that all designed barriers improve the performance of the equivalent rigid parallel barriers while the best performance is achieved by diffusive models.

DISCUSSION

The attenuation of sound by QRD edged tilted parallel noise barriers have been investigated using a two-dimensional boundary element model. Broadband insertion loss has also been predicted over a range of representative receiver positions using a A-weighted traffic noise spectrum in 1/3-octave band from 50 to 4000 Hz. The performance of three different top surfaces; rigid; absorptive; and QRD on a set of tilted parallel profile barriers with different tilted angles have been evaluated.

The performances of tilted QRD parallel barriers have been compared with their equivalent absorbent and rigid barriers. The results can be summarized as follows:

The multiple reflection effect in the tilted profile parallel barrier reduces the acoustic performance of the barrier within 80 to 1000 Hz significantly. Although by slopping the screens in parallel barriers, the frequency selectivity of the rigid parallel barriers is reduced, some constructive effects of incident and reflective waves cause the tilted parallel barriers to be frequency selective in high frequencies. Despite the fact that the degradation effect in tilted parallel barriers is not as much as that of in vertical parallel barriers, the complete contradiction of the multiple reflections is yet to be achieved. This is why the mean overall acoustic performance of the rigid 5 degrees tilted profile parallel barrier is less than its equivalent 5 degrees tilted single profile barrier by 4 dB (A).

Implication of absorbent element on just top surface of barrier number 1 in the 5 degrees tilted parallel barriers don’t make a significant improvement on low frequencies but slight improvement on high frequencies is achieved. This leads to slight overall improvement compared with the rigid one, which is just 0.1 dB (A). The reason behind this low effectiveness is the small treated surface, which is just 1 meter. The improvement in far field and higher height is more significant due to wave reflection upward by the utilized tilting angles.

With increase the treated surfaces by absorbent materials in 5 degrees tilted parallel barrier model PAAS the effective frequencies shifted toward lower frequencies, which leads to higher overall performance. The mean A-weighted improvement in performance of the absorbent barrier is predicted to be 1.6 dB (A), which is significantly higher than that of the partially absorbent tilted parallel barrier. In this model the amount of improvement in far and near filed from ground extended to higher height is almost even.

Applying a QRD with frequency design of 400 Hz on top surface of barrier number 1 in model PGS, which is a 5 degrees tilted parallel barrier, improves the performance of barrier in some frequencies started from 315 Hz. The performance is low at design frequency of the used QRD and its integer especially 800 and 1600 Hz. The benefit of the diffuser surface by shifting the frequency effect toward lower frequencies raised the overall performance of the partially diffusive parallel barrier compared with its equivalent rigid shape by 0.9 dB (A). However by increasing the treated surfaces by quadratic residue diffuser the effective frequency shifted to even lower frequencies and as a result more overall improvement in this barrier is achieved. In this case barrier model PGGS, which is a fully diffusive 5 degrees tilted parallel barrier, improves the performance of its equivalent rigid barrier (barrier model PRS) by 1.8 dB(A).

The effect of tilting angle is also studied and it is found that by tilting the barriers from 0 to 10 degrees in parallel set up, it is possible to reduce the degradation effects in parallel barriers. However increase in tilting angles the absorption effect of fibrous materials and also diffusivity of the quadratic residue diffuser is reduced significantly. This because by tilting the barrier stem, both angles of incident and reflection increased and therefore the absorption ability and diffusive behavior of both mentioned surfaces is reduced. In this case all the designed barrier from rigid, partially absorbent, fully absorbent, partially rigid and even to some extent the diffusive barriers have better performance with 10 degrees tilting in parallel set up. In this case the highest performance is produced by barrier model PGGST, but the most economic traffic noise parallel barrier, which produces high performance, can be designed by covering the tope surface of barrier number 1 by just a QRD with frequency design of 400 Hz (barrier model PGST) and tilting angle of 10 degrees. The average A-weighted insertion loss in this barrier is predicted to be 16.3 dB (A).

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