The Role of Top Surface to Performance of Reactive T-Shape Noise Barriers

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ABSTRACT

T-shape profile barriers are one of the most successful barriers among many different profiles. It has been shown that, using welled diffusers on the top of T-shaped barriers makes a reactive barrier that shows better performance than that of any other used profile barriers compared with their equivalent absorbent barrier. The contribution of the top surface of reactive T-profile barriers to their efficiency in the shadow zone is discussed in this paper. The new multiple impedance discontinuity (NMID) method was used on a few multi-welled surfaces and the application of the findings on the diffuser T-profile barrier along with a descriptive theory of the welled surface effect was presented. An acceptable agreement between the result of the NMID model and BEM method for a few welled surfaces were found. The area-averaged impedance model was also used in the NMID model and it was found that this model can be a good performance indicator for a multi-welled surface. In order to explain the contribution of the top surface of a T-profile barrier, it is adequate to use the NMID model on a mixed ground equivalent to the top surface of the barrier where the source and receiver are located at near the ground where the separation of source and receiver is identical with the overall span of the cap. The effect of average admittance of top surface is dominant and the effect of the impedance discontinuity is overshadowed by this effect.

Keywords: Noise, Barriers, Impedance, Acoustics

INTRODUCTION

Many investigations have been done to find ways of improving the efficiency of traffic noise barriers without increasing its height. T-shape profile barriers are one of the most successful barriers among many different profiles. It is shown by several investigators that in the same dimension, the T-shape profile has the highest performance compared to other profiled barriers [1-4].

It is also shown in numerous previous investigations that covering the top surface with absorbent material improve the performance of the T-profile barrier significantly [3, 5]. Furthermore, it is also shown that, using quadratic residue diffusers on the top surface of the T-shape barrier significantly increases the performance of absorbent T-shape barriers in their frequency bandwidth [3]. It is also illustrated that, using Schroeder diffusers on the top of T-shaped barriers shows better performance than that of any other used profile barrier compared with their equivalent absorbent barrier [3, 4].

The reason behind improving the performance of the rigid profile compared to a simple rigid barrier is explained by the higher effective height of the T-shape profile compared to that of a single rigid barrier. Little has been done so far to explain the reason behind the top surface effect of barriers with this profile. The wave emitted from a point source located on a rigid ground, hitting the first edge of a T-shape profile barrier, is diffracted along the top surface, travels to the far end of the T part and finally is again diffracted to the shadow zone by the second edge of the barrier. If the top surface is completely even and perfectly rigid, no excess attenuation is expected. Ignoring the atmospheric effects like wind, temperature, etc, there are only two diffraction points in this particular case and the barrier acts like a wide single rigid barrier, the performance of which, within the shadow zone, could be explained by its effective height. However, if the top surface is uneven or it is not rigid, wave propagation over the
surface will be diffracted. Therefore, in this case, the amount of expected diffraction is more than that of a single rigid barrier. Hence, the efficiency of a T-profile barrier could no longer be explained only by its effective height. In other words, in such a case the top surface contributes to the performance of the barrier.

The contribution of the top surface of reactive T-profile barriers to their efficiency in the shadow zone is discussed in this paper. In order to explain the contribution of an uneven, absorbent or mixed top surface, it could be treated as a mixed ground. Therefore, it is firstly necessary to investigate the performance of wave propagation over a mixed impedance ground. The problem to be considered here is the propagation of sound waves from a source above an infinite plane surface including regions of different impedances defined by straight line discontinuities perpendicular to the direction from source to receiver. Sound propagation over an impedance discontinuity is also of importance in connection with environmental noise control such as road traffic noise. The effects of combining different types of surface cover are considered here while the effects of atmospheric condition and ground topography are ignored.

Many different methods of solution for the two-impedance boundary (a single discontinuity) have been presented. In 1987, Enflo B. and Enflo P. derived an exact solution in the form of a triple integral [6]. However, the asymptotic approximations in this method are only valid when the source and receiver are far from the discontinuity, both in the ground and the distance from source to discontinuity much less than that from source to receiver. The De Jong model was modified and a new multiple impedance discontinuity method (NMID) was developed [7-10]. The NMID model can be used for the prediction of sound-wave propagation above a mixed, stripped soft ground that is created by porous strips, embedded grooves, or wells with different depths.

This paper is going to use the introduced mixed ground theory (NMID model) and the effect of the imaginary part of admittance to explain the contribution of top surface on the performance of reactive T-shape barriers.

**MATERIAL AND METHODS**

To extend the performance of a mixed surface to the contribution of the top surface of an equivalent T-shape barrier, the properties and dimension of the mixed surface must be identical with the top surface of the barriers. The only difference is due to the location of the mixed surface, which lies on an infinitely large rigid ground while the top surface of the T-shape barrier is considerably above rigid ground. In this investigation from now onward, every mixed ground corresponding to any T-shape barrier will be named the same as barrier’s model name following the word ‘surface’. For example the surface model ‘G’ is a mixed ground having all properties and dimensions of the top surface of the barrier model ‘G’ located in the rigid ground. The

### Table 1. Design QRD based model names and corresponding configurations

<table>
<thead>
<tr>
<th>Models</th>
<th>No of QRD</th>
<th>N</th>
<th>( f_r ) (kHz)</th>
<th>Well width (cm)</th>
<th>Well sequence</th>
<th>QRD sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>1</td>
<td>7</td>
<td>400</td>
<td>12</td>
<td>0 1 4 2 2 4 1</td>
<td>1</td>
</tr>
<tr>
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<td>7</td>
<td>315</td>
<td>12</td>
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<td>1</td>
</tr>
<tr>
<td>GH</td>
<td>1</td>
<td>7</td>
<td>500</td>
<td>12</td>
<td>0 1 4 2 2 4 1</td>
<td>1</td>
</tr>
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<td>7</td>
<td>400</td>
<td>12</td>
<td>0 4 1 2 1 4 2</td>
<td>1</td>
</tr>
<tr>
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<td>7</td>
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<td>12</td>
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<td>1</td>
</tr>
<tr>
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<td>3</td>
<td>7</td>
<td>400</td>
<td>4</td>
<td>0 1 4 2 2 4 1</td>
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<td>1</td>
</tr>
<tr>
<td>TH</td>
<td>1</td>
<td>13</td>
<td>630</td>
<td>6</td>
<td>0 1 4 9 3 1 2 10 10 12 3 9 4 1</td>
<td>1</td>
</tr>
</tbody>
</table>
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Fig 3. Comparison of the contribution of three different QRD surfaces (corresponds to the top surface of three different barriers where ‘GL’, ‘G’ and ‘GH’ represent a surface having respectively QRDs tuned to 315, 400 and 500 Hz) with an equivalent absorbent (flow resistivity is 20000 Ns/m$^2$) surface at the mid point between source and receiver (NMID model).

Definition of two different mixed grounds including “QRD\textsuperscript{1} surface” and “absorbent surface” is shown in Fig. 1 schematically. Similarly, the definition of two different equivalent barriers including “QRD barrier” and “absorbent barrier” is shown in Fig. 2.

The NMID model as well as the boundary element method is used at the following situations and conditions to investigate the wave propagation over the top of the barrier’s profile.

Two different boundaries are examined in this investigation:

a) The tested surfaces are equivalent to the top surface of the T-profile barriers but located in rigid ground (Fig. 1).

In this situation the following conditions are considered:

- Wave propagation over the boundaries using NMID model and BEM method (Full details of the method based on a boundary integral equation for calculation of the pressure at a receiver point have been presented) [3].
- Wave propagation over the boundaries using an area-averaged admittance method applied in the NMID model
- Contribution of a layer of fibrous material on the QRD surface using area-averaged NMID model

b) The tested boundaries are a few T-shape barriers coated with different absorbent and welled surfaces. The dimensions of all testes barriers are the same in which the overall height is 3 m, cap thickness 0.3 m and overall length of the cap is 1 m. To avoid ground interference, the source and all receiver positions are kept on the ground. The distance from source to the centre line of the barriers is 5m and the results of 50 receiver points from 2 m till 250 m behind the barriers are averaged. The difference between the tested barriers is only related to their top surfaces. The top surfaces of tested QRD based barriers are defined in Table 1.

RESULTS

Sound propagation over diffuser surfaces

The performance of three different QRD surfaces with different well depths (frequency designs) is compared with an equivalent absorbent surface (Ref), in Fig. 3. In the tested frequency range, which is a good representation of the frequency bandwidth of the tested QRDs, there are four distinct dips for the QRD tuned to 315 Hz, 3 dips for QRD tuned to 400 Hz and finally two dips for the QRD tuned to 500 Hz. The dips get shorter as frequency increases for all three different models. As one can see the first minima are lowest for all three models and it decreases as the design frequency increases. Therefore, in the defined frequency range (roughly from 250 Hz to 1 kHz) the overall performance is the best for the QRD surface with highest maximum well depth and it is the worst for the QRD surface with lowest maximum well depth. At the absorbent surface; however no maxima or minima are visible (due to the absence of ground interference in this frequency range) and the performance of the surface in the tested frequency range and selected geometric condition improves as the admittance of the surface increases, something which is not true for QRD surface. Although at QRD surface the absolute value of admittance is mostly higher than that of an absorbent surface, the excess attenuation has no such trend as one can see at the ‘Ref’ surface.

Average admittance effect

According to Nyberg theory [11] wave propagation over a two-valued infinitely periodic striped impedance can be approximated by using area-averaged impedance method, which is;

\[
\text{area-averaged impedance} = \frac{\beta_b b + \beta_a a}{a + b}, \quad \text{Eq: 1}
\]

Where $a$ and $b$ are the widths of the two strips.

In our case there is no such periodic mixed ground, however in the case of small width, a reasonably high number of strips and also having the condition of $a + b \ll \lambda$ ($a \ll \lambda/2$ in our case where the widths of strips are the same), it is assumed that the situation is very similar to Nyberg condition. Therefore, area-averaged admittance is defined which is,

\footnote{Quadratic Residue Diffuser is a Schroeder (welled) diffuser with quadratic residue sequence.}
Wave propagation over a few QRD surfaces is calculated using an area-averaged admittance in the NMID model. The results for three different QRD surfaces with different frequency designs are shown in Fig. 4 in which the related average imaginary admittance of the surfaces are also included in the graphs. Although the agreement with the BEM prediction is not as good as the proper NMID model, this simple area-averaged admittance method does predicted the accuracy of the performance peaks and gives a reasonable indication to the general trend of the performance.

Reducing the design frequency increases the value of maximum and minimum excess attenuation, which relates to the fluctuation of the average imaginary part of admittance for each surface. In fact, increasing the maximum well depth of the QRD shifts the first resonant frequency toward lower frequencies and therefore, at the tested frequency range more maxima and minima are seen for a surface having lower frequency design or larger well depth.

The maximum effect of the QRD surface is always at the frequencies which have a negative imaginary part of admittance and lowest performance of the surface is mostly at the frequencies with positive imaginary part of admittance. This trend is visible in all different QRD surfaces presented in the Fig. 4 where the best agreement occurs at the first resonant frequency, although this effect is seen at the second and third harmonic resonant frequency. This phenomenon could be explained by the theory that was given in [10]. The spring-like reaction of the surface at the frequencies with a negative imaginary admittance improves the efficiency of the surface. However, this surface at the frequencies with positive imaginary admittance with a very small boundary loss factor reacts like rigid surface and even the mass-like reaction could vary the effectiveness of the surface.

QRD surfaces covered with a layer of absorbent material

In order to investigate the contribution of absorbent materials to the welled surfaces, the top surfaces of different QRDs are coated with a layer of fibrous material. The performance of the QRDs treated with absorbent layer is compared with the surface with no absorbing layer using area-average NMID model. The effects of an absorbent layer on the top surface of the surfaces.
familiar QRD surfaces including models ‘GL’, ‘G’, and ‘GH’ are shown in Fig. 5.

In all three experiences one can clearly see that utilizing absorbent material on the top surface of the diffusers does not improve their efficiency. The main negative effect is on the maximum points, while, at the minima no significant changes are made. In fact, the minima correspond to a surface with rigid behavior therefore, the absorbent material reasonably improves the performance at that particular area, which is visible at a few minima in the graphs. The best example to show a little improvement of the minima is the QRD tuned to 500 Hz, although it does not seem to be significant.

**Contribution of diffractions at discontinuities**

Fig. 6 shows the effect of the arrangement of the wells at the top surface of the QRD barriers. Three different QRD designs with the same average admittance are compared in this graph. Every single QRD has different well sequence while, the overall dimension remains the same.

In this figure, also the average imaginary part of admittance is included. A slight effect of well sequence is visible particularly at the mid frequency range. However, the overall trend, which follows the average imaginary part of admittance, is the same for all three different models. It is worth adding that the real part of admittance taking thermal and viscous effect is positive and very small compared to the imaginary part. In another attempt to investigate the effect of edges at the top surface of the T-shape barrier, a new welled surface in barrier model ‘G3’ is introduced in Fig. 7, having more edges and the same average imaginary part of admittance compared with barrier model ‘G2’. In barrier model ‘G3’ the number of edges is almost three fold of that of the model ‘G2’. This new introduced model has slightly higher real part of the admittance due to its smaller well width, which is ignored in this investigation.

The amount of improvement of insertion loss made by the two mentioned barriers is compared with ‘Ref’ barrier in Fig. 7. Slight differences between the performances of the two barriers are visible around the design frequency. Other than that the overall trend for both of them follows the theory of imaginary admittance. It again shows that the effect of average imaginary admittance is rather more important than that of excessive top surface edge effect. The volume of area averaged admittance is changed by introducing QRDs with higher prime number (n=13) at the top of the T-shape barrier. Two different frequency designs are tested in barrier models ‘TL’ and ‘TH’ corresponding to design frequencies of 500 and 630 Hz respectively. The design configuration of these barriers is shown in Table 1. In these surfaces, more variations of the well depths give more fluctuations in the average of imaginary part of admittance compared to the previous models according to Fig. 8 and 9. The theory of average imaginary admittance works for these surfaces too. In both Fig. 8 and 9, the overall trend follows the average admittance theory and again the performance of both
bars. The performance of both models ‘TL’ and ‘TH’ are high at the frequencies at which the imaginary admittance is negative, and they start to reduce at the frequencies where the imaginary admittance is positive. This effect of course is less visible when the average resonant frequencies are very close to each other, since the effect of either the negative or positive part will be affected by another one in these frequency ranges.

**Discussion**

The findings of previous paper are used in this paper to investigate the wave propagation over mixed surfaces corresponding to the interested profile barriers [10]. The surface and barriers along with the desirable source and receiver location were defined. An acceptable agreement between the result of the NMID model and BEM method for a few QRD surfaces are shown. It is shown that, the improvement made by QRD surfaces compared to the equivalent absorbent surfaces are frequency dependant, this was already shown for the QRD barriers in previous papers [3, 4].

Using the theory of negative $\text{Im}(\beta)$ and using area-averaged admittance in the NMID model, it was shown that no absorbent material on the top surface of a QRD surface improves the efficiency of QRD surface; this was already predicted on QRD barriers in previous paper [4]. The reason behind this phenomenon could also be explained by the theory of negative $\text{Im}(\beta)$. The area-averaged impedance model was also used in the NMID model and it was found that this model can be a good performance indicator for a multi-welled surface. In this case, in several different QRD based profile barriers, the theory on imaginary part of impedance was tested. It is also shown that the well sequence, well width and number of the wells in each period of the wells are not as important as the average admittance. It is seen that the performance of the barrier is high when the average of $\text{Im}(\beta)$ is negative and the efficiency begins to decrease as $\text{Im}(\beta)$ shifts to positive. This could also explain all the previous findings regarding the weakness of the QRD barrier, which were mostly when close to the design frequency where the boundary loss factor is zero [3, 4]. The most important implication of the effectiveness of the negative $\text{Im}(\beta)$ is that it provides a simple indicator that can be used in an optimization process. In fact, this theory says that the performance of the diffuser barrier improves if the amount of negative $\text{Im}(\beta)$ increases. On the other hand, the efficiency of the diffuser barrier decreases if the amount of positive $\text{Im}(\beta)$ increases. It was also found that, the effect of average admittance was dominant and the effect of the impedance discontinuity is overshadowed by this effect.
CONCLUSION

It is shown in this paper that in order to explain the contribution of the top surface of a T-profile barrier, it is adequate to use the NMID model on a mixed ground equivalent to the top surface of the barrier where the source and receiver are located near the ground where the separation of source and receiver is identical with the overall span of the cap. Covering the top surface of the wells in QRD surface reduces the amount of imaginary admittance and therefore the efficiency of the surface, in terms of the reduction of excess attenuation.

The assessment based on the average admittance and the effect of negative $\text{Im}(\beta)$ was also found to be true on the profile barriers QRD based barriers using the boundary element method. By changing the number of edges in the top surface, while the average admittance is the same, no significant change in the performance of the profile barriers is seen. Interestingly, the attenuation cannot be improved by adding absorbent materials to the surface, because the effectiveness of the attenuation is less with a purely absorptive surface than the reactive type diffuser surfaces that were investigated here.

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