Int. J. Environ. Res., 3(3):327-334, Summer 2009
ISSN: 1735-6865

Optimization of Profiled Diffuser Barrier Using the New Multi-impedance Discontinuities Model

Monazzam, M.R.

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

Received 29 Nov. 2008; Revised 11 May 2009; Accepted 20 May 2009

ABSTRACT: The paper describes an investigation about the application of the new multiple-impedance discontinuities model for optimizing profile diffuser barriers. The new multiple-impedance discontinuities model is much faster than the numerical method, thus it is used in an optimization process. The A-weighted insertion loss was used for the traffic noise spectrum.The result of optimization, which is done by simplex downhill method, showed that the chosen method combined with the appropriate cost function is both a fast and effective way to optimize a diffusive profiled barrier, improving the performance of the barrier in the whole frequency bandwidth of the reactive profiled barriers. The optimized barrier improves the A-weighted insertion loss of all different tested barriers including absorbent, quadratic residue sequence and random sequence barriers.The introduced optimization process in this investigation is fast, clear and flexible so that any different ribbed surfaces and dimensions utilized on any different T-profile barriers can be optimized. The parameter used to optimize is just simply the well depth sequence, which is easy to realize and practical to design.

Key words: Profiled noise barrier, Diffusion, Optimization, Multiple-impedance discontinuities, Quadratic residue diffuser

INTRODUCTION

Different methods of optimization processes have been being used to optimize the performance of diverse noise control devices. In 1984 Medwin used an extension of the Biot-Tolstoy rigorous closed form impulse solution to optimize a finite noise barrier (Medwin, 1984).The acoustic pressure impulse was calculated at each source/ receiver path for each segment of the barrier and then the integrals are compared.The process repeated by adjusting new segments so as to maximize attenuation at a few different frequencies. The number of iterations is questioned in this work and it seems that high number of iterations is going to be very difficult to achieve.

An optimization process was used by Cox and D'Antonio to provide better broadband notch diffusers (D'Antonio and Cox, 2000). The summation of energies over all the sources and receivers was taken as an error parameter and then using an iteration process it was minimized. Although finally they concluded that even the optimized diffuser performance could be improved, their optimized diffuser showed improved performance relative to the presented diffusers. An optimization processes have also been being used for traffic noise barriers. Thorsson has made many efforts to optimize low height nose barriers using different methods in a few separate investigations. The equivalent sources method (ESM) was used by him in 2000 to optimize a 1m height rectangular barrier (Thorsson, 2000). The surface admittance was the parameter to be altered and the goal for optimization was to minimize the magnitude of sound pressure on a vertical line of receivers 20m from the barrier. The outcome, which was a set of surface impedances for different parts of barrier, was difficult to realize in practice. Moreover the

*Corresponding author E-mail:mmonazzam@hotmail.com

introduced method only works for a certain simple geometries. It was also found that a disturbance of the source strengths directly affected the surface impedance.

In a separate attempt Thorsson used a constrained sequential quadratic programming method (SQP) to do an admittance optimization on both barrier and ground (more detail on this method could be found at (Gill, *et al.,* 1981; Thorsson, 2003). The frequencies above 500 Hz were not optimized, although the performances of a few optimized as well as absorbent barriers in different situations were calculated at higher frequencies up to 2 kHz. The computing time consumption, which seems to be very high, was not mentioned. A significant improvement was reported (particularly at low frequencies) when the top surface of a 1m T-shape barrier, as well as the ground close to the source at the specular reflection point, was covered with the optimized admittance surface. Apart from Thorsson two more examples on barrier optimization of traffic noise barriers are (Burge, 2000). In this paper, it is aimed to use the new multiple – impedance discontinuities model for optimization process on reactive T-profile barriers.

MATERIALS & METHODS

An iterative scheme can be used to design the shape of diffuser barriers. Three factors are needed to enable this optimization: (a) parameters to define the diffuser barrier geometry; (b) an accurate prediction method for the performance of the diffuser type at the desirable condition, (c) and a cost function that characterizes the quality of the performance.

In this attempt, it is aimed to keep the overall dimension of barrier unchanged. Therefore, a T-shape barrier with overall height of 3 m and the cap span and thickness of respectively 1 and 0.3 m is introduced. The top surface of the T-shape barrier is covered with a QRD, which is the most common welled diffuser. Detailed information on the design, diffusive and absorptive properties of this kind of surfaces can be found either in the Cox and D’Antonio’s book or Monazzam’s recent paper (Cox and D’Antonio, 2004; Monazzam, and Lam, 2008). According to the Monazzam’s findings, the average amount of imaginary part of admittance of welled surface used at the top surface of barrier most significantly affects the performance of the barrier. Therefore, the well depth as well as its arrangement play very important role to the efficiency of the whole structure (Monazzam, 2005).

The only variant here is the well depth, which is responsible for the top surface admittance of the barrier. The maximum well depth is also constraint to 0.29 m, which is slightly less than the thickness of the barriers’ cap. Thanks to the findings presented in Monzzam’s paper, the problem is reduced to a welled surface equivalent to the top surface of the presented models (Monazzam, 2005). In this case, all calculations are done on a simplified model and then will be extended to an equivalent barrier.

It is more practical to use the well depth as an optimization parameter instead of the surface admittance (as used by Thorsson (Thorsson, 2003)). If one uses the surface admittance for the optimization, unrealistic and unachievable result may be obtained as Thorsson in his two separate investigations ended up with (Thorsson, 2000; Thorson, 2003).

The nMID model, which is a new multi-impedance discontinuities model, is introduced by Lam and Monazzam, full details of the method, can be found in (Lam and Monazzam, 2006). The model was found to give a good approximation for the propagation of wave above a welled surface. This method is much faster than the BEM method; hence numerous iterations can be done at a very short time. An accurate numerical method can also be used to verify the result of this approximate method. Therefore, the area averaged admittance nMID model is used to assess the wave propagation above the welled surface at 1/3 octave centre frequencies. In this paper the normalized surface admittance for absorptive fibrous material is calculated by the empirical equations of Delany and Bazely (Delany & Bazely, 1970). For narrow wells, the model described by equation 8 of Wu et al. is used to compute the normalized surface admittance (Wu, *et al.,* 2000). The source is located at 0.001 m height and the receiver is placed at 0.35 m above rigid ground, which is separated 1 m from the source horizontally. This geometry is shown to give an adequate estimation on this kind of problems (Monazzam, 2005).

Downhill simplex method is a numerical method to obtain the minimum of a function of more than one independent variable, which consists of a series of steps, i.e., reflections and contractions. A few different steps are designed in this method including; a) reflection away from the high point, b) a reflection and expansion away from the high point, c) a contraction along one dimension from the high point, or d) a contraction along all directions toward the low point. More detail can be found in (Press, 1989).

Because the performance of the welled surface is determined mainly by the well depth sequence of the boundary, the optimization is a multidimensional minimization with N variables, where N is the total well number of the surface. Computing the excess attenuation using the nMID model is not very expensive, so the downhill simplex method is appropriate to create an optimum welled surface. The optimum welled surface will directly be used at the profiled barrier and it will form the optimized diffuser barrier. In fact, by optimizing the well depth arrangement, various well-tuned and well-distributed admittances can be generated, and higher surface as well as barrier performance can be achieved. The process to produce an optimum profiles single T-shape barrier covered with welled surface is based on an iteration process;
(1) A welled surface with N wells in one period is constructed. The overall length of the diffuser is 0.84 meter (if number of wells in each period is 7, the well width will be equal 0.12 m). (2) The performance of the welled surface is calculated using area averaged admittance nMID model (Lam and Monazzam, 2006). (3) The result of step (2) is converted to the A-weighted traffic noise spectrum (A detailed description of the A-weighted traffic noise spectrum is presented in appendix A), which is $IL(A)_w$ in Equation 3. (4) Similar to step (2) the performance of an equivalent absorbent surface is predicted by the nMID model. (5) Similar to step (3) the result of step (4) is converted to the A-weighted traffic noise spectrum, which is $IL(A)_R$ in Equation 3. (6) A cost function is defined. (7) The well depths are altered according to the downhill simplex method. (8) Steps (2)-(7) are repeated until a minimum in the cost function is achieved indicating an optimum diffuser surface, the structure will then be employed on a T-profiled barrier to present an optimum reactive T-profile barrier. In order to define the cost function, it is sensible to remind the following relation, which it has been found by Monazzam, between reactive surface and reactive T-profile barrier (Monazzam, 2005).

$$IL(A)_{RS} - IL(A)_{AS} \approx (IL(A)_{RTB})_{C2,} \quad \text{Equation 1}$$

where $C1$ the defined geometrical condition for the calculation of wave propagation is over the surface, which is source and receiver's heights are respectively 0.001 and 0.35 m and they are separated by 1 m. The relation in Equation 1 exists when the A-weighted insertion loss of barriers are averaged over wide range of receiver points on the ground, which is in fact the condition $C2$ at the introduced relation. $IL(A)_{RS}$ and $IL(A)_{AS}$ are the A-weighted performance of reactive and absorbent surface respectively. Similarly $IL(A)_{RTB}$ and $IL(A)_{ATB}$ are respectively the A-weighted insertion losses of reactive and absorbent T-profile barriers. Therefore a cost function "C", which is a criteria used to describe the quality of the barrier, is defined as below;

$$C = 10 - \Delta IL(A) \quad \text{Equation 2}$$

where $\Delta IL(A)$ is the amount of the A-weighted improvement made by the welled surface compared to an absorbent surface, which is called "Ref" surface. The geometrical condition for the "Ref" surface is the same as welled surface the difference is about the surface condition, which is absorbent rather than welled. The flow resistivity for the absorbent material is 20000 Ralys (MKS) and the thickness is equal to the maximum well depth of the welled surface. This is also constraint to 0.29 m. The number 10 in Equation 2 is the amount of A-weighted improvement we wish to achieve. The lower the cost function the better the improvement and consequently the better the diffuser barrier. If the amount of improvement is negative, the cost function will be more than 10 and if positive the cost function gets less than 10. The aim in this optimization is that to minimize the cost function, which it therefore maximizes the barrier performance in terms of A-weighted insertion loss. The is calculated by;

$$\Delta IL(A) = IL(A)_w - IL(A)_R \qquad \text{Equation 3}$$

Where $IL(A)_w$ and $IL(A)_R$ are the broadband insertion losses of respectively welled and "Ref" surfaces at the defined receiver position for the A-weighted traffic noise spectrum (BS EN 1793-3:1998). A-weighted insertion loss is a popular index in traffic noise mitigation. In this index the performance of the barrier is weighted according to human sensation. Therefore any improvement in this index could be perceived by human ears.

The other advantages of this cost function is that because it is believed that the reactive barriers are very frequency selective, therefore they may perform very high in a certain frequencies but in some other perhaps the amount of improvement is not as much. Therefore by using this cost function that anxiety vanishes. Because this cost function is a realistic function, it will also give a very good clue to the designers to meet their goals. Weighting the insertion loss of the barrier according to the traffic noise spectrum won't show the strength and weakness of the barrier in different frequencies, since it is only an overall index. Therefore, once an optimized barrier is found, its performance at different frequencies will be predicted.

RESULTS & DISCUSSION

As it was mentioned earlier a limitation of the implemented optimization method is that one need to run the optimization process many times with different starting conditions because the minimization is being carried out within bounded space. The space holds several restricted minima which the minimization routines could become fascinated, partially at the edges. The result shown below is the result of a few attempts of the iteration process. There are many untried starting points that might have a better minimum available.

As an example, the diffuser used at the top surface of the presented QRD T shaped barrier which is called model "G" here has been optimized. The parameters of the sample are: prime number N=7, well width 0.12 m, fin width is ignored. For a moderately good comparison, the maximum depths of the wells are limited to 0.29 m in the optimization process.The achieved depth sequence of optimized profile structure is listed in Table 1. along with depth sequence of the QRD and a random sample.

Table 1. Depth sequence of the utilised diffuser for different reactive barriers (in m)

QRD (in model "G")	Random sequence	Optimisation
0	0	0.288
0.0613	0.028	0.125
0.2445	0.084	0.265
0.1225	0.14	0.203
0.1225	0.196	0.237
0.2445	0.252	0.272
0.0613	0.28	0.101

The optimized sequence is used to construct a barrier called barrier model "OPT". The random sequence structure is also used to construct a barrier called "Rand" barrier. All the dimensions are remain the same as barrier model "G". The performance of the barriers are predicted using 2D BEM and the result of optimized barrier at 1/3 octave centre frequencies is compared with that of "Ref" , "Rand" and the barrier model "G" at three different receiver conditions. Full detail of the boundary element method used in this investigation can be found in Monazzam and Lam's paper (Monazzam and Lam, 2005).At the first attempt the average of results of 20 receivers on the ground starting from 2 m and extended to 250m is concerned. Finally a receiver position with 50 m distance from centre line of the barriers is located on the rigid ground. The source is placed on the ground separated 5 m from the centre line of the barriers.

The result of the comparison with the optimized barrier, QRD, random sequence and absorbent barrier, which are averaged over 20 receiver locations on the ground, are illustrated in Fig. 1. The figure clearly shows that inside the frequency bandwidth of the diffusers, which we are interested (from almost 200 Hz till around 1200

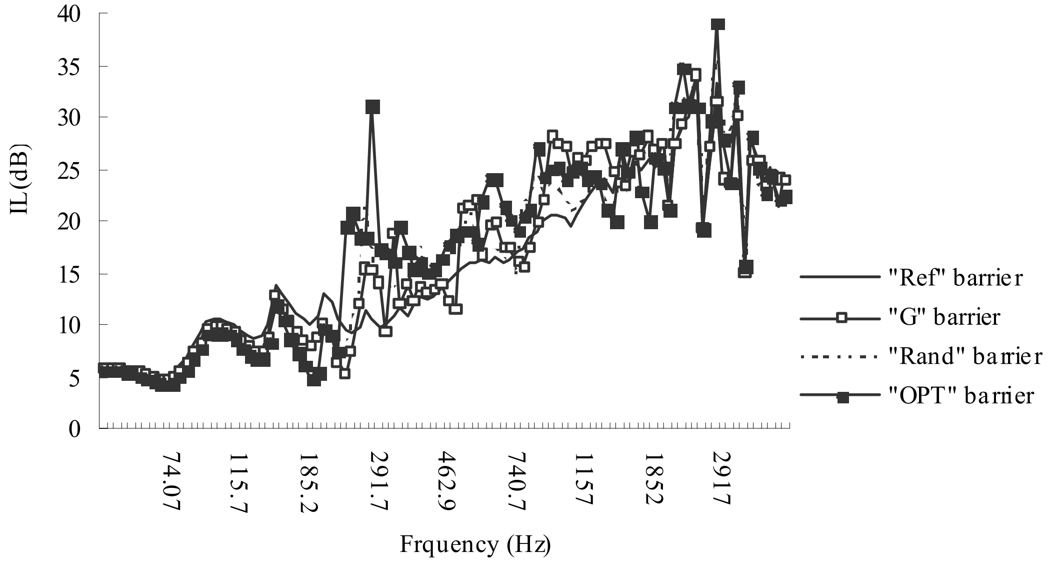

Fig. 1. Predicted frequency spectra for four different barriers averaged at 20 receiver points on the rigid ground from 2 m to 250 m

Hz); the optimized structure improves the performance of "OPT" barrier compared with all other barriers. Nevertheless outside the frequency bandwidth the amount of improvement reduced particularly at very low frequencies.In Fig. 2. the amount of improvement of "OPT", "Rand" and barrier model "G" compared with the "Ref" barrier are shown. The improvement of optimized barrier is extended at a wide frequency range and purely positive varying from 2 dB to more than 15 dB. In contrast, both "Rand" and "G" barriers have less performance than "Ref" barrier some where in the frequency spectrum. Although both "Rand" and "G" barrier contain a well with zero depth, the performance of "Rand" barrier with more distributed well depth sequence is higher than barrier model "G".In Table 2 the overall A-weighted insertion loss of the aforementioned barriers at three different receiver locations is shown. The optimized barrier with insertion loss 17.9 dB (A) at wide receiver locations on the ground improves the performance of both "Ref" and "G" barrier by 1.3 dB (A). In this situation it also increases the performance of "Rand" barrier by 0.7 dB (A).

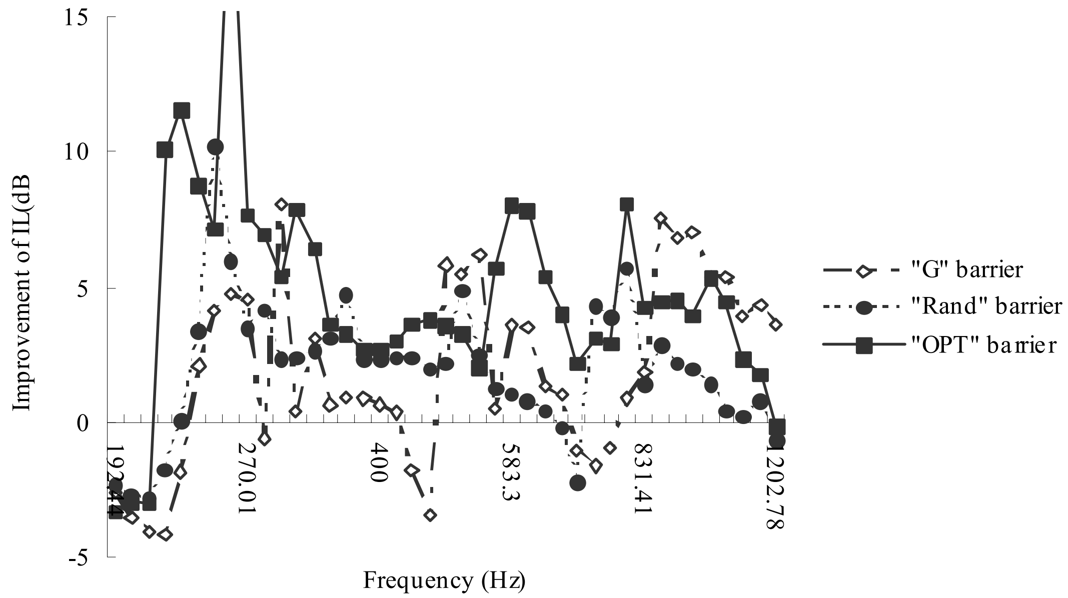

Fig. 2. Difference in insertion loss of three different diffuser barriers relative to that of the "Ref" barrier averaged at 20 receiver points on the rigid ground from 2 m to 250 m

Table 2. Broadband A-weighted man insertion loss calculated at three different conditions for four different barriers

"Ref" barrier		Barrier model "G"		"Rand" barrier		"OPT" barrier	
Mean (dB(A))	Δ IL(dB(A))	Mean (dB(A))	Δ IL(dB(A))	Mean (dB(A))	Δ IL(dB(A))	Mean (dB(A))	Δ IL (dB(A))
16.6	0	16.6	0	17.2	0.6	17.9	1.3
18.1	0	19	0.9	19.2	1.1	19.7	1.6
16.5	0	17.5	1	17.6	1.1	18.5	2

* The result of 20 receivers located on the rigid ground from 2 m to 250 m is averaged
** The result of 9 receivers located at 1 (-20.0); 2 at (-50,0); 3 at (-100,0); 4 at (-20,1.5); 5 at (-50,1.5); 6 at (-100,1.5); 7 at (-20,3); 8 at (-50,3); 9 at (-100,3) are averaged
*** The receiver located at 50 m distance from barriers on the rigid ground and ΔIL is the difference between the mean insertion loss for a mentioned barrier and the mean insertion loss for its equivalent absorbent T-Shape screen

The optimized barrier at the 9 receiver points (containing higher altitude receiver locations) has an A-weighted insertion loss of 19.7 dB (A) and shows even slightly higher improvement compared to the "Ref" barrier. By comparing the result of different barrier at 20 receiver locations with one receiver point (50 m distance from barrier on the ground), the prominent difference in performance of the optimized barrier compared to the QRD barrier is clearly seen. In model "G" by getting close to the barrier the amount of improvement is also reduced, hence the QRD barrier does not show any improvement at 20 receiver location while it improves by 1 dB(A) at 50 m distance receiver location. It means the low performance of the QRD barrier in the near field damages the overall performance of the barrier on the ground. This weakness of the QRD barrier is also improved by optimization process so that the performance of the optimized barrier is significantly higher than that of the "Ref" barrier either in one receiver point at the far field or at the entire area from 2 m till 250 m behind the barrier. Finally the amount of A-weighted improvement made by barriers "G", "Rand" and "OPT" compared to the "Ref" barrier at the very wide area of the shadow zone (2500 receiver points behind the barriers from 2 m till 250 m on the ground extended to heights of 10 m) are calculated and the result are plotted in Fig. 3 to Fig. 5. The barrier with random sequence wells improves the performance of the "Ref" barrier at almost entire shadow zone excluding the zone very close to the barrier according to Fig. 3. On the ground at the distance beyond 50 m the amount of improvement is almost constant, which is identical to 1.1 dB (A).

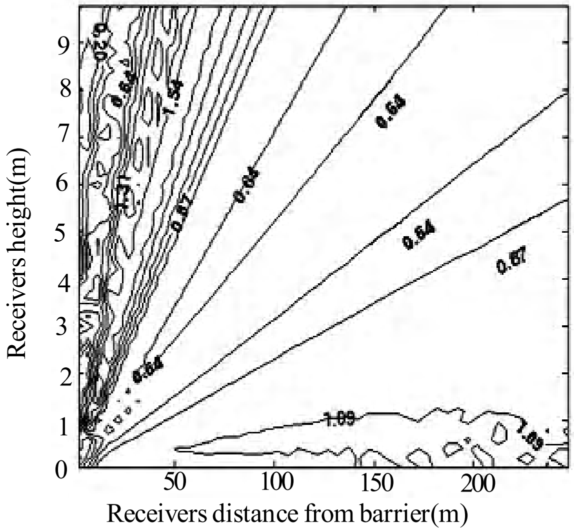

Fig. 3. Improvement of A-weighted insertion loss by barrier model "Rand" compared to the "Ref" barrier

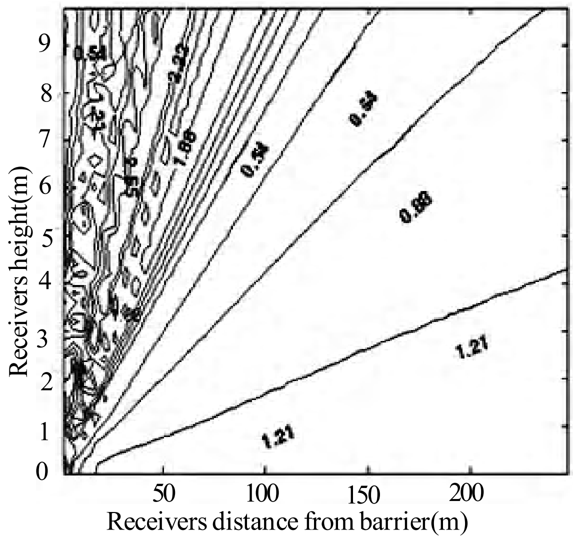

Fig. 4. Improvement of A-weighted insertion loss by barrier model "G" compared to the "Ref" barrier

QRD barrier model "G" in Figure 4 also shows higher performance than that of the "Ref" barrier for almost the entire area behind the barrier; the only exception is the zone very close to the barrier at which its performance is less than that of the "Ref" barrier.Unlike "Rand" barrier the performance of barrier model "G" on the ground slightly improves with increase the receiver's distance so that the amount of improvement reaches 1.21 dB (A) at the distance of 250 m. And in the far field (beyond 50 m) the performance of this barrier reduces as the receiver's altitude increases. The highest improvement is above 2.5 dB (A), which is located at a very narrow zone with horizontal angle of 0.165 (Radian) (or 9.1 degrees) and standard deviation of 0.0017. This zone for the barrier model "G" in comparison with the highest performance zone at the "Rand" barrier has less standard deviation and slightly higher altitude.According to Fig.5. the highest performance zone for "OPT" barrier is at the same position of the highest performance zone for the barrier model "G", although the amount of improvement is slightly above 3.5 dB(A) in this zone, which is higher than that of the barrier model "G". The overall trend in the "OPT" barrier is also very similar to the trend of barrier model "G" but the amount of improvement in almost all areas behind the "OPT" barrier is higher than barrier model "G" by around 1 dB(A).

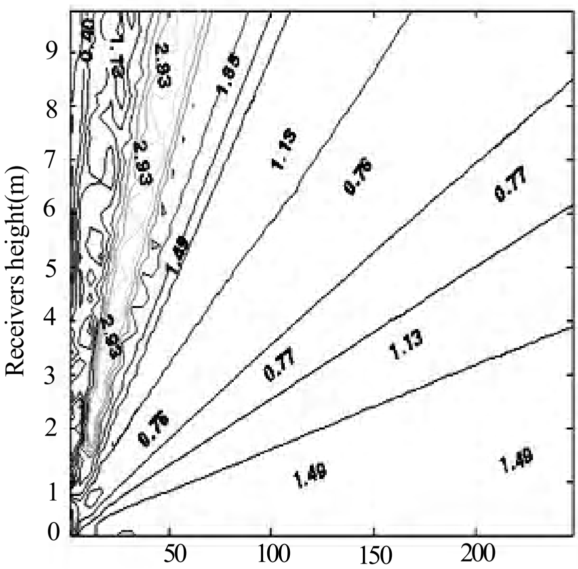

Fig. 5. Improvement of A-weighted insertion loss by barrier model "OPT" compared to the "Ref" barrier

CONCLUSION

In this investigation the application of the nMID model using area average admittance method for optimization of profile diffuser barrier is studied. The nMID model is much faster than the numerical method, thus it is used in an optimization process.The A-weighted insertion loss was used for the traffic noise spectrum, as it is one of the most common barrier indexes at urban noise mitigation. This index eradicates the anxiety of the frequency selectivity of the reactive barriers. It is easy to compare and useful for designers.

The result of optimization, which is done by simplex downhill method, showed that the chosen method combined with the appropriate cost function is both a fast and effective way to optimize a barrier, improving the performance of the barrier in the whole frequency bandwidth of the reactive barriers. The optimized barrier improves the A-weighted insertion loss of all different tested barriers including absorbent, QR sequence and random barriers at all three different receiver conditions. In this case it increases the efficiency of the "Ref", "G" and "Rand" barrier by 2, 1 and 0.9 dB (A) on the rigid ground 50 m away from the barriers.

It is encouraging that using the method not only improves the performance of the barrier on the ground but also it expands the improved efficiency of the barrier in almost the entire shadow zone behind the barrier by roughly the same amount. Furthermore the highest performance of the optimized barrier is at the same position as the barrier model "G", which shows that the optimized barrier improves the efficiency of the barrier evenly at entire zones behind the barrier.The introduced optimization process here is very fast, clear and easy so that any different welled surfaces and dimensions utilized on any different T-profile barrier may be optimized. It is worth adding that the obtained optimized barrier is the result of a few attempts with a certain starting points, which means still plenty of untested starting points and attempts exist. This indicates that even more improvement might be achieved by using the introduced method by different starting points and additional attempts. The parameter used to optimize is just simply the well depth sequence, which is easy to realize and practical to design.

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