Ground effect due to periodic and resonant roughness structures

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ABSTRACT

The recent expansion of cities throughout the world means that traffic noise is an increasing problem. The area of land between the traffic source and the receivers can provide an appropriate space where a series of low-rise roughness structures can be placed as an alternative to conventional noise barriers and earth berms. Through laboratory measurements, we have investigated the effect of periodic roughness elements on the sound propagation above a smooth hard surface. First, the periodicity-induced diffraction created by an array of solid roughness structures was studied both numerically and experimentally in the laboratory. The effects of hollow resonant elements with slit openings have been investigated also to add an additional destructive interference below the first roughness-induced destructive interference and thereby mitigate the adverse effect of the low-frequency surface waves generated by the presence of roughness elements. Finally, we have constructed and tested a nested configuration of slotted hollow roughness elements and measured the effects of the associated multiple resonance phenomenon.
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1. INTRODUCTION

Traffic noise has been a constant source of a nuisance since the invention of the wheels even in the ancient times. This has been further aggravated in the modern days due to the introduction of the motorised means of travel and the urbanisation of the population. This has already reached a point where the traffic noise, in conjunction with other types of acoustic noise, can affect the daily lives and well-being of the people.

Several mitigation methods have been invented and implemented. The latest motor vehicles are fitted with quieter engines and more streamlined shapes than their predecessors. Much research has been carried out on the interaction of the tyres and the road surface. Regulations have been put in place, for example, to impose speed limits, although the noise reduction may not be the primary reason for doing so.

The most common 'passive' means of mitigation is the erection of a high-rise noise barrier alongside a busy road. This has been proven to be beneficial, when not much free land is available, for noise reduction and hence to enhance the quality of the daily lives for the nearby residents. However, the barrier has been often considered as an eye sore due to its negative aesthetic impact on the road users and residents so, sometimes, local people oppose the introduction of a barrier. As a potential remedy, modification such as transparent barriers have been constructed. A barrier with partial opening such as sonic crystals has been researched recently. Combination of both conventional noise barrier and sonic crystal has been recently reported also (1). When sufficient land is present, high-volume and high-rise earth berms have also been built especially alongside high-speed motorways. This is often preferred due to the recycling of soils left over from a nearby construction site. Vegetation belts of 15 m width and various planting schemes were also numerically studied, and it was suggested that the acoustic performance of such vegetation belt could be comparable to a 1.5-m high thin noise barrier (2).

In this paper, as an alternative solution to the high-rise structure of conventional noise mitigation, we explore the feasibility of noise reduction by a low-rise roughness structure on the ground. This approach can be applicable as long as sufficient land is available between the road and the nearby dwellings and can be an interesting alternative to earth berms. Instead of constructing a large structure of earth mounds, displaced soil can be used to build a series of low-rise roughness elements. This can be aesthetically more pleasing and

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reduce the cost of construction and maintenance compared with earth berms.

In the following section, we present laboratory study of the ground effect on the sound propagation due to periodic and resonant roughness structures. Experiments have been carried out at the anechoic chamber at the Open University. These have been compared with the numerical results obtained by the boundary element method (BEM).

2. METHODS

We have built small-scale models of roughness structure placed on an acoustically hard board inside an anechoic chamber. An acoustic source and a microphone were placed close to the surface to investigate the near grazing incidence.

A Brüel & Kjær (B&K) OmniSource type 4295 was used as an acoustic source. A B&K free-field half-inch microphone type 4189 was used as a receiver. A maximum length sequence (MLS) signal was generated and fed into the source through an audio amplifier. The microphone signal was conditioned and filtered through a B&K measuring amplifier type 2636 and was digitised by a National Instruments 6259 data acquisition unit which also digitised the output MLS signal. This chain of the measurement was controlled through Matlab data acquisition toolbox installed in a portable computer.

The measurement was performed in two steps. First, the response of the bare board was measured. Then, the response of the board with roughness elements was measured. The actual sequence was not important as long as the pair of measurements could be completed in a relatively short interval. During the measurements, the position of the acoustic source and the microphone was fixed.

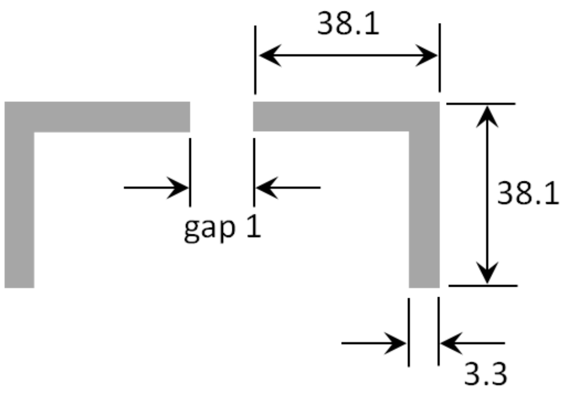
We then calculated the insertion loss (IL) of the roughness elements referenced to a smooth surface by calculating the transfer function between the responses of each measurement pair.

To validate the measurements, we used an in-house program for a two-dimensional boundary element method. The numerical insertion loss corresponding to the configuration of each measurement was also calculated through BEM.

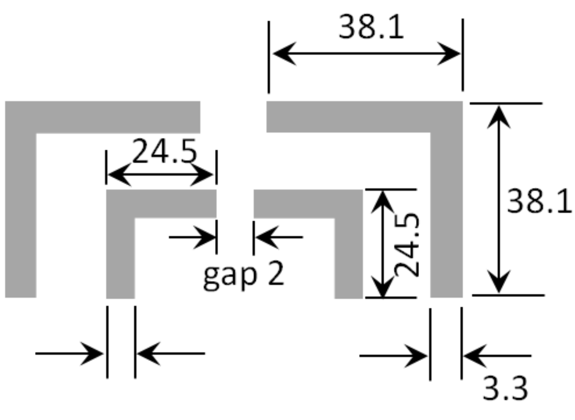
3. MATERIALS

Two metre long and 3.3 mm thick aluminium angles with two different sizes were used to construct roughness elements. The lager angle has the outer dimension of 38.1 mm (1.5 in) as shown in Figure 1. The smaller one has the outer dimension of 25.4 mm (1 in).

For a smooth surface, we used a 10-mm thick plastic board with the dimension of 122 cm $\times$ 138 cm. To accommodate the 2-m long angles, the sides of the plastic board were extended by 5-mm thick glass sheets. Care was taken to ensure the smooth transition between the plastic board and the glass sheets. This extended board structure was elevated by several single bricks which in turn were placed on top of the grid floor of the anechoic chamber. The elevation of the board was necessary to achieve a near grazing incidence due to a rather bulky size of the B&K source.



(a)



(b)

Figure 1 – Cross-sectional dimensions of aluminium angle structure. (a) a single structure. (b) a double structure. The dimensions are in mm.

4. NON-RESONANT PERIODIC ROUGHNESS STRUCTURE

The acoustical effects of a series of small-scale roughness structures periodically placed on a smooth hard surface have already been studied (3). To compare with data for the resonant structure discussed later, measurements have been made on roughness consisting of regularly spaced solid rectangular elements.

To be non-resonant, a roughness element has to be acoustically solid. The composing material itself needs to be acoustically hard and there is required to be no hollow space inside which is partially open to outside. Since we intended to investigate the resonant structure shown in Figure 1, instead of acquiring a pure solid element of the same outer dimension, we utilised the element in Figure 1a. The gap 1 was filled with a plaster. Then, the now closed hollow space was filled with other materials such as wooden bars and sand contained by duct tapes.

We placed 6 of these fabricated non-resonant structure on the extended board. The near side of the first element was placed 5 cm horizontally from the exit of the acoustic source. Then, they were arranged axially parallel to one another. The centre-to-centre spacing was chosen to be 15 cm. The tip of the microphone was secured horizontally 90 cm away from the source. The measured heights of the source and the receiver were 81 and 60 mm respectively. Both source and microphone were positioned horizontally that is parallel to the surface of the board. An imaginary line connecting the loudspeaker and the microphone was perpendicular to the axes of 6 roughness components, which makes it possible to interpret the measured data as if they were obtained two-dimensionally despite the fact that the actual measurement was carried out using a point source.

Figure 2 shows the insertion loss measured with 6 periodically placed rectangular roughness components on the hard surface. For the BEM calculation, we assumed that the roughness elements were entirely solid so that in the boundary-only discretisation of BEM, two vertical sides and the top side of each element were made continuous with the ground surface. The overall agreement between the measured and predicted IL is good. Although the line-of-sight between the source and the receiver was secured for this configuration of near grazing incidence, the insertion loss we can achieve is demonstrated to be significant depending on the frequency range of interest. However, it is noted that the benefit will be reduced for higher source and receiver positions, i.e., when the grazing angle is increased.

Since the agreement between data and predictions for the 6 element surface is encouraging, the BEM has been used also to predict for an extended configuration of 20 identical elements with the same centre-to-centre spacing (thereby increasing the source-receiver distance to 3 m) for which measurements were not possible in the OU anechoic chamber. The simulated IL spectra predicted for 6 and 20 roughness elements are compared in Figure 3. It is clear that for the most of the calculated frequencies the predicted insertion loss is higher if there are more roughness elements. However, there is one exception. For frequencies below 1 kHz, one can see that the performance of 20 elements was worse than that of the lesser 6 elements.

This negative insertion loss below 1 kHz is evidence that a surface wave is generated by the periodic roughness structure. It is known that it takes some distance for a surface wave to develop. That is why we did not witness the surface wave for the 6 roughness elements. Although this surface wave differs in nature from a Rayleigh wave it is interesting to note that it has been shown theoretically that a Rayleigh wave also requires some distance from a source to appear (4). In fact, in Figure 2, due to the lack of strong surface wave, one can see a positive insertion loss , albeit small, in this frequency range which is well matched between the measured data and simulation.

In the context of traffic noise mitigation, Figure 3 demonstrates that a higher insertion loss can be achieved when more land is available between the road and the nearby residential or industrial area. However, when a very low frequency is of particular interest, this can be equally disadvantageous as the surface wave develops. Therefore, it would be ideal if we can filter out some of the surface wave while maintaining the positive insertion loss at higher frequencies.

5. RESONANT PERIODIC ROUGHNESS STRUCTURE

Resonators have been implemented in many applications to reduce the sound at particular frequencies. As an extension to a conventional sonic crystal, Krynkin et al. (5) demonstrated that the insertion loss was markedly changed around the resonant frequencies inherent to an array of hollow cylinders with slit openings positioned in air. They adjusted the resonant frequencies by changing the dimension and number of slits. We apply this mechanism of resonance to roughness elements placed on the base surface. Krynkin et al. (5) restricted their investigation to ‘circular’ cylinders due to the ease in handling them theoretically in the cylindrical polar coordinate system. However, when a ground surface is involved to support the roughness elements, we consider that the components with circular cross-sections are not necessarily practical to implement because additional supporting structure has to be improvised. This may not be an issue during a small-scale laboratory testing, but will have to be dealt with should its large-scale equivalent be installed

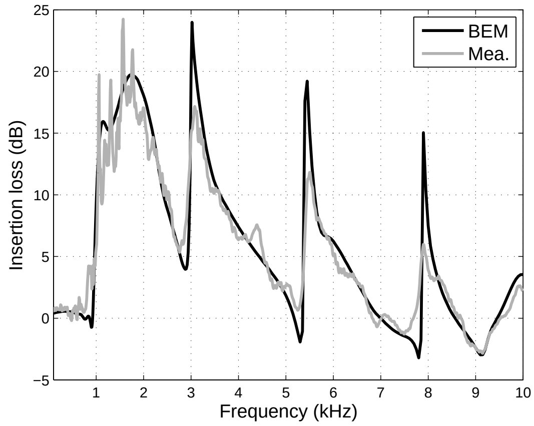


Figure 2 – The comparison of the insertion loss measured (in grey) and predicted by BEM (in black) for 6 non-resonant roughness elements periodically placed on an acoustically hard board.

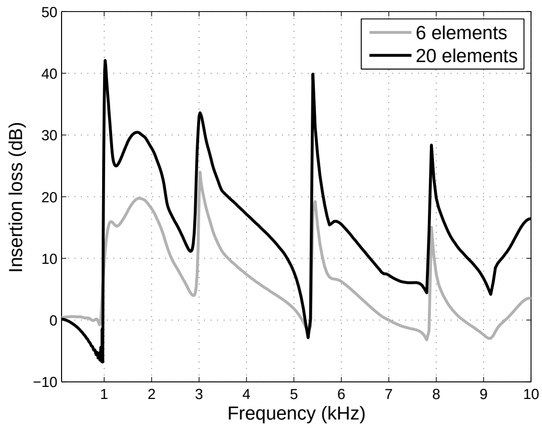


Figure 3 – The comparison of the predicted insertion loss for 6 roughness elements (in grey) and 20 elements (in black) periodically placed on an acoustically hard board.

outdoors. In addition, to keep the circular shape and required dimension, they could not carve the slit all along the length of the cylinder: the slit was discontinuous in every 20 cm or so. Therefore, we have chosen the angles shown in Figure 1 due to their availability and the ease in keeping the slit uniform along the length and also for adjusting the slit gap. We have also selected the ones made of aluminium in place of other types of materials such as PVC and wood because of its rigidness and well-defined edge along the length.

For the resonant roughness components shown in Figure 1a, we have kept exactly the same geometry and configuration as those of the non-resonant roughness elements in the preceding section. Figure 4 shows the BEM comparison between the resonant elements made of single pair of angles shown in Figure 1a and the solid rectangles whose insertion loss was already shown in Figures 2 and 3. One can see the significant change in IL at the frequencies where the surface wave is likely to occur should the number of elements be sufficient to generate a surface wave. Just short of 1 kHz, the predicted IL value is dramatically increased. However, it is also noted that below those beneficial frequencies the situation gets worse. This so-called “double-edge sword” phenomenon of resonant elements made of hollow structure with slit opening was also demonstrated by Krynkin et al. (5). In both Krynkin et al. (5) and here in Figure 4, we observe that the level of the advantage is more than that of the negative implication.

At frequencies higher than 1 kHz in Figure 4, one can notice that the overall level of beneficial insertion loss is at least retained for the resonant structure with often increase in the frequencies likely corresponding to the higher modes of the resonance. Therefore, it is clear that the introduction of the resonant mechanism to the roughness elements is largely beneficial.

We have also conducted the measurement corresponding to this resonant configuration. The positions of the source and receiver were the same as those used for the testing of the non-resonant elements in the preceding section. Care was taken to place the resonant elements at the same position as the non-resonant components for a faithful comparison. Figure 5 shows both the measured and predicted insertion loss for this resonant arrangement. We are satisfied by the good agreement over the whole frequency range of measurement. It is encouraging to see even the minor discrepancies from the non-resonant spectrum shown in Figure 4 are well portrayed in the measured data.

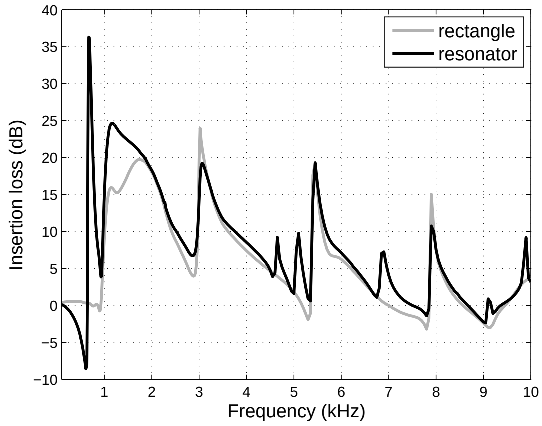


Figure 4 – The comparison of the predicted insertion loss for 6 rectangular roughness elements (in grey) and 6 resonant elements (in black) periodically placed on an acoustically hard board.

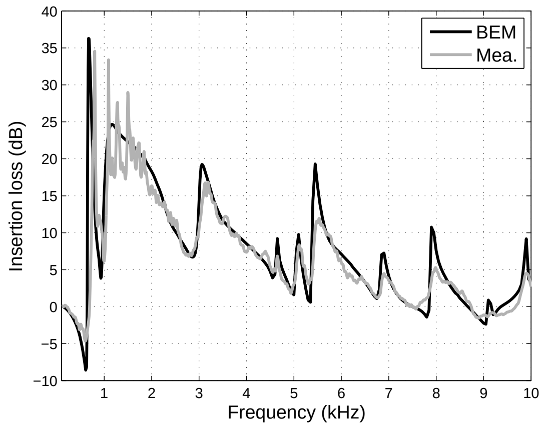


Figure 5 – The comparison of the insertion loss measured (in grey) and predicted by BEM (in black) for 6 resonant roughness elements periodically placed on an acoustically hard board.

6. DOUBLE RESONANT PERIODIC ROUGHNESS STRUCTURE

Although it was demonstrated that the impact of the resonance could be mostly positive, it was also shown that the performance can get worse for a very low frequency. Therefore, it would be ideal if there is a way to improve or change the IL at frequencies where it is made worse. The spectrum of the insertion loss due to roughness elements can be designed by a different choice of parameters such as the number and dimension of the individual element, the centre-to-centre spacing, and the slit gap and number for resonant elements. These variations will, however, alter the IL spectrum throughout the broadband of the frequencies. Should it be desirable to keep the response of the overall frequencies and a necessity arise to alter the spectrum at particular frequencies, the introduction of additional resonances at different frequencies may be considered.

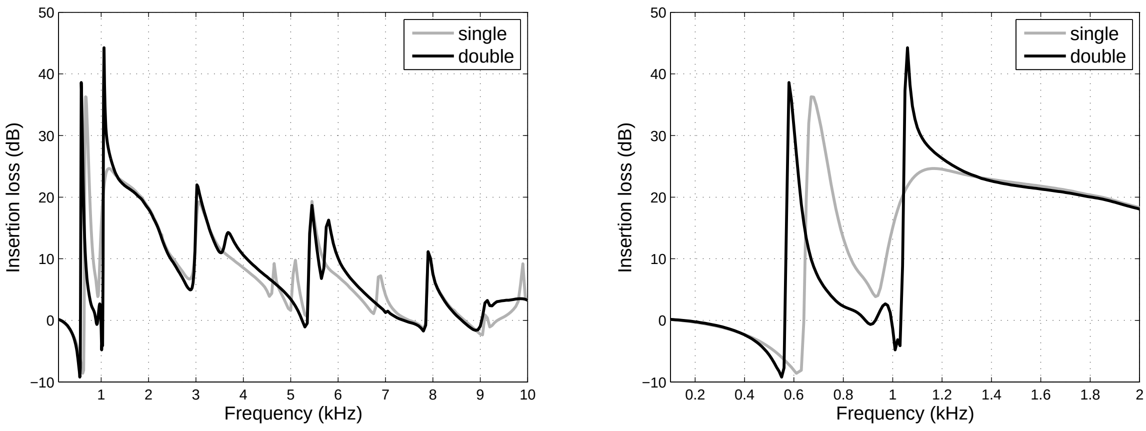
Elford et al. (6) proposed a modification to a conventional sonic crystal by adopting a concentrically repeated arrangement of circular hollow cylinders with slit openings, a resemblance to the nested arrangement within a Russian doll. They numerically studied, by using the finite element method (FEM), an array of a sonic crystal each of which was composed with up to 6 or 7 nested circular shells. No measurement was attempted, however. It was concluded that their design could produce multiple resonance band gaps which could be potentially beneficial in an application to the road traffic noise.

In this paper, we apply the same strategy of placing a smaller resonant structure within a larger one. We do this in the context of a roughness element in contact with a ground surface. To demonstrate the feasibility of this idea we have investigated a double structure only. It is also noted that our proposal of using L-shaped angles is easier to be implemented and hence validated by the corresponding measurement than the circular counterpart.

We tested the configuration shown in Figure 1b for a double resonant roughness elements. All the dimension of the outer element including the slit gap are the same as those of a single resonant structure in Figure 1a. The slit gap of the inner element was chosen to be 1 mm. Figure 6 shows the numerical comparison of the insertion loss between single and double-resonant elements on the smooth surface. It is observed that in higher frequencies the overall spectra are similar each other with only occasional changes. In terms of the amount of the difference, the variation at the lower frequency near the fundamental resonance may not necessarily differ from the rest of frequencies. However, the shifting of the first resonance and the introduction of the second resonance are certainly of interest in case even a lower frequency needs to be addressed. It is also noted that, just below the frequency of the second positive insertion loss, there appears negative insertion loss as discussed for the single resonant elements.

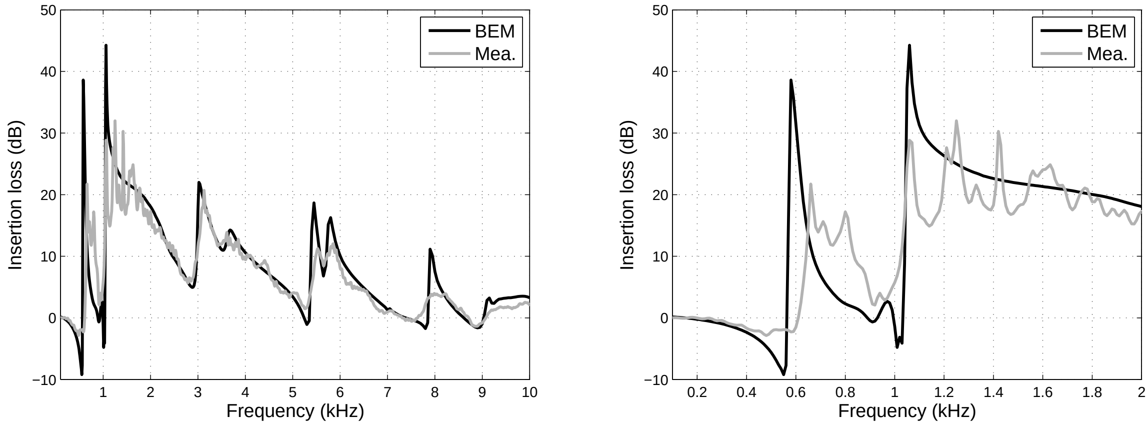
Figure 7 compares the measured and predicted insertion loss. Yet again it is found that the overall agreement is good. However, the measured separation of the first and the second resonance does not seem to be as pronounced as predicted.

In Figure 8, the measured insertion spectra for both single and double resonant configuration are compared. Throughout the displayed frequency range, the frequency responses are similar except for some minor changes due to modes of resonances. As shown so far in Figures 5 and 7, even these smaller change are well described by the corresponding BEM calculations. Perhaps, the lower-frequency variation is more of interest as shown in Figure 8b. In comparison with Figure 6b, it gets clearer that the IL maximum at around 1060 Hz of the double element may represent the second resonance maximum predicted by BEM. As predicted numerically, the measured results also confirms that the IL maximum of the fundamental resonance for the double structure shifts towards a lower frequency compared to that of the single roughness element. There are discrepancies between measurements and predictions, nevertheless the measured insertion loss illustrates that the double resonant structure can provide a higher level of positive insertion loss around the fundamental resonant frequency. That is, for example, there is more advantage than disadvantage in the frequency range from 600 to 1000 Hz due to the introduction of the second smaller resonant component.



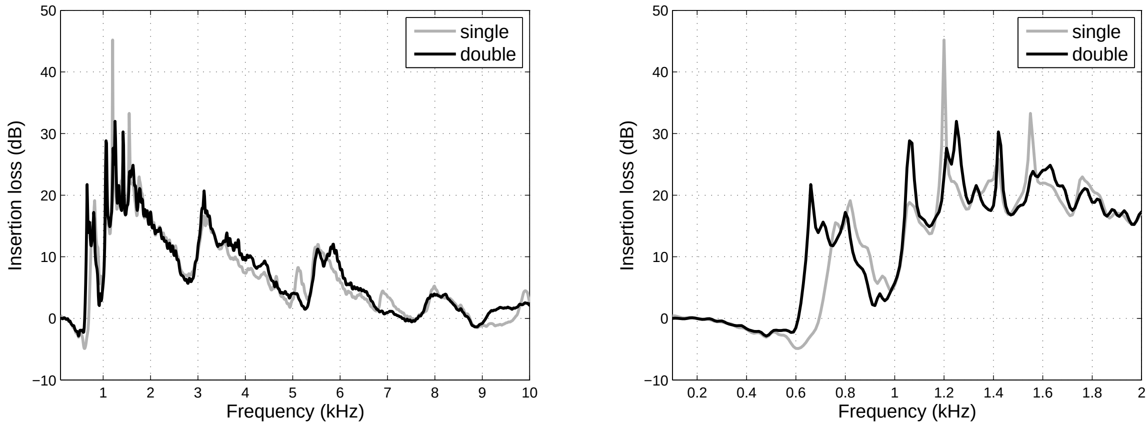
(a) (b)

Figure 6 – The comparison of the predicted insertion loss for 6 single resonant roughness elements (in grey) and double resonant elements (in black) periodically placed on an acoustically hard board. (a) frequency range up to 10 kHz. (b) frequency range up to 2 kHz.



(a) (b)

Figure 7 – The comparison of the insertion loss measured (in grey) and predicted (in black) for 6 double resonant roughness elements periodically placed on an acoustically hard board. (a) frequency range up to 10 kHz. (b) frequency range up to 2 kHz.



(a) (b)

Figure 8 – The comparison of the measured insertion loss for 6 single resonant roughness elements (in grey) and double resonant elements (in black) periodically placed on an acoustically hard board. (a) frequency range up to 10 kHz. (b) frequency range up to 2 kHz.

7. CONCLUSIONS

We have investigated the interaction between the roughness elements and the ground during sound propagation. Rectangular elements were placed periodically on an acoustically-hard smooth surface and were studied by both measurements and BEM predictions. First, regular or complete rectangles – without hollow space – were studied. We reiterated what has already been known: such configuration can produce a significant amount of positive insertion loss near grazing incidence. However, it was also re-confirmed that the acoustic performance can be affected adversely by the generation of an unwanted surface wave at low frequency. As a potential means of mitigating the surface wave effects, we have investigated propagation over resonant rectangular elements with slit openings connected to the interior hollow space. We demonstrated that the additional structural modification worked as a resonator to reduce some of the surface wave energy. To investigate tuning the resonator mechanism further, we explored a nested configuration of resonant roughness elements and confirmed that a double structure could provide more benefits than a single structure. Our results suggest that such single and multiple resonant structures could be designed to alter the response of the frequency range prone to the surface wave while maintaining the performance for the rest of the frequencies. The results reported here obtained with laboratory scale configurations can be used as the basis for designing larger scale systems for reducing outdoor noise.

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