NOISE CONTROL BY ROUGHNESS-INDUCED GROUND EFFECTS AND VEGETATIVE COVER

K Attenborough DDEM, MCT, The Open University, Milton Keynes, MK7 6AA
I Bashir DDEM, MCT, The Open University, Milton Keynes, MK7 6AA
TJ Hill DDEM, MCT, The Open University, Milton Keynes, MK7 6AA
S Taherzadeh DDEM, MCT, The Open University, Milton Keynes, MK7 6AA

1 INTRODUCTION

The phenomenon of ground effect has been studied widely and it is an accepted component of outdoor sound prediction schemes. Destructive interference between direct and ground-reflected sound gives rise to a frequency-dependent attenuation in excess of that due to wavefront spreading and atmospheric absorption. In many outdoor noise prediction schemes, ground surfaces are considered either as 'acoustically-hard', which means that they are perfectly reflecting, or as 'acoustically-soft' or a mixture. According to ISO 9613-2[1], any ground surface of low porosity is to be considered acoustically-hard and any grass-, tree-, or potentially vegetation- covered ground is to be considered acoustically-soft. Although this might be an adequate representation in some circumstances, it oversimplifies a considerable range of properties and resulting effects. Even the category of ground known as 'grassland' involves a wide range of ground effects. Hitherto recognition that ground effects may contribute to traffic noise attenuation, have been restricted to outdoor surfaces that are porous. Moreover exploitation of ground effect has been initiated through the development of porous road surfaces which influence traffic noise generation as well as propagation. Less attention has been paid to exploitation of the effective finite impedance associated with roughness on an otherwise acoustically-hard ground. The effective impedance arises because of multiple scattering by the roughness elements[2].

Results are described of laboratory and field measurements over hard surfaces on which roughness elements in the form of (2D) parallel strips bosses have been added. The acoustical performances of randomly- and periodically-spaced roughness are compared. Numerical simulations are used to explore the potential effectiveness for traffic noise reduction of periodic roughness configurations in the form of parallel low walls.

Typically vegetation has been assumed to have little or no noise-reducing properties. Results of field measurements and simulations are reported that demonstrate the potential usefulness for noise control of vegetative ground cover in the form of crops.

2 LABORATORY MEASUREMENTS AND NUMERICAL PREDICTIONS OVER HARD ROUGH SURFACES

2.1 Measurements

The influences of surface roughness on ground effects have been investigated in a systematic manner by measuring propagation from a point source over various shapes and spacings of roughness elements placed on an acoustically-hard surface in an anechoic chamber. Figure 1(a) shows a representative measurement configuration. The open end of a pipe attached to a Tannoy loudspeaker, is placed so that its centre is at a known height on one side of an array of nineteen 1 m long parallel varnished rectangular strips of Medium Density Fibreboard (MDF) spaced at regular intervals across a glass sheet. On the other side of the array is a Bruel and Kjaer half-inch (13 mm) microphone at the same height as the source. Figure 1(b) shows a series of measured excess attenuation spectra obtained over 1 m long varnished wooden semi-cylinders of (approximately) 1 cm radius. The source is located at 7 cm height above the glass plate surface and the receiving microphone is at a horizontal distance of 70 cm from the source and also at a height of 7 cm above the glass plate. For this geometry, the difference between the lengths of the direct and reflected paths is 0.014 m which means that the expected frequency of the first destructive interference over an acoustically-hard smooth surface is at 340/0.028 = 12.3 kHz. The black solid line in Figure 1(b) shows the excess attenuation spectrum measured without any strips i.e. over the smooth hard glass plate surface. Without any roughness elements, there is a minimum near 12 kHz which corresponds to the frequency of the first destructive interference between the sound travelling directly to the receiver and that reflected from an acoustically-hard glass plate surface. Up to about 3 kHz, the EA values with the glass plate alone are near +6 dB i.e. in this frequency range the sound pressure at the receiver is double that travelling directly from the source. The other curves in Figure 1(b) show the results of increasing the number of regularly-spaced semi-cylinders placed with uniform centre-to-centre spacing (4 cm) around the point halfway between source and receiver.

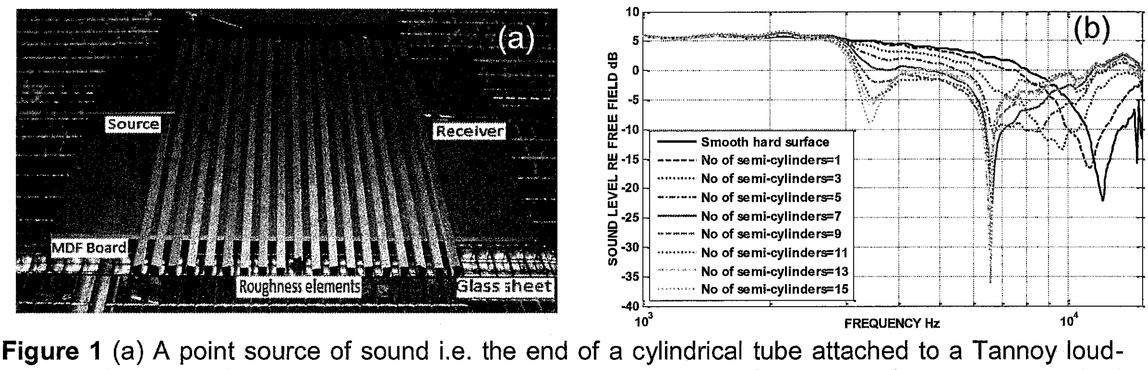

Figure 1 (a) A point source of sound i.e. the end of a cylindrical tube attached to a Tannoy loud-speaker (not visible), is located at a known height on one side of an array of nineteen varnished MDF strips placed at regular intervals (centre-to-centre spacing = 4 cm) on a glass sheet. The glass sheet rests on an MDF board supported by the grid floor of the chamber. On the other side of the array is a receiving microphone at the same height as the source. (b) Excess attenuation spectra measured with (point) source and receiver at 0.07 m height and separated by 0.7 m over a glass plate on which are placed up to fifteen 1cm radius periodically arranged varnished wooden semi-cylinders with centre-to-centre spacing of 4 cm starting with the first semi-cylinder positioned halfway between source and receiver.

As the number of semi-cylinders is increased, the frequency of the main destructive interference is progressively lowered and its depth is increased. With fifteen regularly-spaced semi-cylinders the main destructive interference is near 6500 Hz i.e. at less than half the frequency of destructive interference for the same source-receiver geometry over the smooth glass plate without any roughness elements present. With nine or more regularly-spaced roughness elements, an additional destructive interference near 3500 Hz becomes noticeable. This is a consequence of the regular spacing of the roughness elements.

Experiments have been conducted also with identical parallel strips of various shapes with 'random' spacing. A random number generator was used to produce the edge-to-edge separation distances (other than zero). Figure 2 shows an example of the difference in EA spectra resulting from 'random' and regular arrays of the same number of semi-cylinders for the same source-receiver geometry as for Fig. 1(b). Each of the 'random' distributions results in a different excess attenuation spectrum. That shown in Fig.2 represents the average over five different 'random' distributions. Random roughness distributions result in a single broad excess attenuation maximum rather than the two or three narrow EA maxima measured when the spacing is regular.

The extra dips in the EA spectrum associated with regular spacing are the result of *diffraction grating* effects. Diffraction gratings are used in optics. During reflection from a diffraction grating, each of the periodically spaced elements acts as a secondary source of wavelets which interfere constructively or destructively depending on angle. At an angle corresponding to constructive interference the diffracted rays from the adjacent elements will be in phase and the path length difference will be a wavelength or an integer multiple of a wavelength. At all other angles, there will be some destructive interference (cancellation) between the wavelets. Destructive interference will be at its maximum when the wavelets are exactly out of phase. For plane waves incident near grazing incidence, i.e. at an angle of incidence near 90° measured from the normal to the surface, the lowest frequency of maximum destructive interference is given by the speed of sound divided by twice the spacing. For a centre-to-centre roughness element spacing of 5 cm, the lowest diffraction grating interference is at 340/(2×0.05) = 3400 Hz. The next diffraction grating destructive interference frequency will be at twice this frequency i.e. 6800 Hz. These frequencies are close to those of the two dips in the EA spectrum obtained over semi-cylinders with regular centre-to-centre spacing of 5 cm (see Fig.V.6(a)). However the lower frequency dip near 3400 Hz is close also to the dip observed with random spacing and therefore may be considered to be a combination of diffraction grating and roughness-induced effects. The total excess attenuation spectrum over a periodically-rough surface resulting from regular spacing, which includes additional diffraction-grating-related dips, can be called *diffraction-assisted ground effect.*

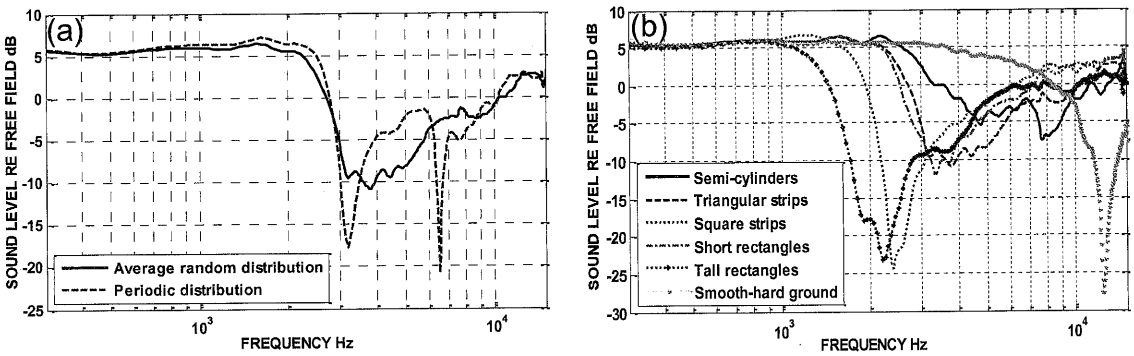

Figure 2 Excess attenuation spectra measured with (point) source and receiver at 0.07 m height and separated by 0.7 m over a glass plate on which are placed: (a) fifteen 1cm radius varnished wooden semi-cylinders either randomly with mean centre-to-centre spacing of 5 cm or regularly distributed at 5 cm spacing about the specular reflection point (b) randomly distributed semi-cylinders (solid line), triangular strips (dashed line), square strips (dotted line), short rectangular strips (dash-dot line) or tall rectangular strips (dash-diamond line) with average centre-to-centre spacing of 5cm. The measured EA spectrum for the smooth hard glass base (no roughness) is shown by the dotted (asterisks) curve. The 'random' distribution spectra represent the average of measurements over five different random distributions for each shape.

Despite the extra peaks introduced by regular spacing, for a given geometry, mean roughness element spacing and roughness element height, the overall broadband excess attenuation for random and periodic spacing are similar. On the other hand, regularly spaced roughness might be more practical and aesthetically-interesting.

2.2 Numerical predictions

The EA spectrum caused by a rough hard surface can be predicted using numerical methods. In particular, use has been made of a two-dimensional Boundary Element Method (BEM)[3] which involves dividing the surfaces of interest into a number of small hypothetical elements and adding their contributions to the overall sound field resulting from a line source. Although it is a 2D method, it is able to predict the sound field from a point source over surfaces containing roughness strips along a line normal to the roughness element axes and has been found to give good agreement with laboratory data[4].

The BEM has been used to predict the *insertion loss* caused by roughness strips parallel to a road assuming dimensions and geometry intended to be indicative of those that might be used along surface transport corridors. The insertion loss is calculated with respect to a smooth acoustically-hard surface, i.e. it is the difference in predicted levels before and after the roughness is introduced.

Table 1 shows predictions for the insertion loss due to surfaces composed of 26 identical roughness elements of various shapes but with the same cross sectional areas (0.035 m^2) starting 1 m from the source and occupying a total width of 15 m. This means that the edge-to-edge spacing of the roughness elements is not fixed at 0.3 m but varies between 0.1 m for the isosceles triangular strips and 0.4 m for the square strips. Two receiver locations are considered at 1.5 m and 4 m heights and at a horizontal distance of 45 m from a vertical line through tyre/road and car engine sources on the nearest carriageway. Predictions are for a **single** (nearest) lane of cars and for a source composed of **four** traffic lanes containing 15% Heavy Goods Vehicles (engine height at 0.75 m) and 85% cars. The predicted insertion losses for a single lane of (combined source) cars are between 9.7 dB and 12.2 dB at the lower receiver and between 4.9 dB and 8.6 dB at the upper receiver. Those for a four lane mixed traffic source are significantly smaller than those predicted for single-lane traffic; a maximum insertion loss of 8.3 dB is predicted for the lower receiver and a maximum of 3.2 dB for the higher receiver. This is the consequence of many sources being further away from the nearest roughness strip.

Table 1 BEM-predicted Insertion Losses with respect to a smooth acoustically-hard surface for component and combined HARMONOISE[5] Type 1 car sources on a single lane and a combination of car and HGV sources (85 % cars; 15 % HGV) distributed over four lanes at a speed of 70 km/h and receiver heights of 1.50m and 4.00 m at a horizontal distance of 45 m from the nearest road side edge, with the intervening (otherwise acoustically-hard) surface composed from 26 roughness elements with various shapes in a 15 m wide configuration (i.e. variable edge-to-edge separation) starting 1 m from the nearest source line.

	Predicted Insertion Loss (dB)							
Source Vehicles	Type 1 (car)		Type 1 (car)		Type 1 (car)		4 lanes cars + lorries	
Source Type	Rolling Noise		Engine Noise		Combined Sources on single nearest lane		Combined Sources on four lanes	
Receiver Height (m)	1.50	4.00	1.50	4.00	1.50	4.00	1.50	4.00
Semi-Cylinders (radius 0.15 m)	12.5	8.1	7.8	3.1	10.5	6.4	6.4	2.6
Equilateral Triangles (0.247 m high)	14.7	10.7	9.2	4.9	12.2	8.6	8.3	3.2
Squares (side 0.19 m)	13.4	9.4	8.3	3.3	11.2	7.2	7.7	2.7
Isosceles Triangles (base 0.47 m, height 0.15 m)	11.1	7.9	7.7	3.8	9.7	6.6	5.3	2.6
Short Rectangles (base 0.3m, height 0.236m)	13.0	8.5	7.8	2.7	10.7	6.4	7.0	2.5
Isosceles Triangles (base 0.3m, height 0.236m)	14 .5	10.6	9 .1	4.7	12.1	8.5	8.4	3.2

3 LOW PARALLEL WALLS

3.1 Background

Regularly-spaced parallel walls with height ≤ 0.3 m are a particular type of 2D surface roughness. Examples of their acoustical effects were provided by the rectangular wooden strips in the laboratory data reported in section 2. Bougdah *et al*[6] have reported laboratory measurements over arrays of between fourteen and twenty one 0.001 m thick identical aluminium walls with heights of up to 0.025 m and regular spacing of between 0.008 m and 0.025 m. For a source at 0.04 m height and receiver at 0 m height and 1 m from the source, the insertion of a 0.325 m wide 14-wall array with 0.025 m height and inter-wall spacing of 0.024 m, located with its nearest edge 0.5 m from the source, was found to give a maximum overall insertion loss of 10 dB. Bougdah *et al* suggest that physical effects other than surface wave creation and the roughness-induced effective ground impedance may be involved. One of these is the resonance which occurs when the wall height is a

quarter of the wavelength of the incoming sound. Some of the incident sound energy is used to create resonance of the 'plugs' of air between the walls. For a wall height of 0.3 m this resonance occurs at about 280 Hz. Bougdah *et al* refer also to diffraction-grating effects. Essentially these are related to spacing between the walls and the diffraction-assisted ground effect discussed in section 2. The third additional mechanism suggested by Bougdah *et al* is that of interference between direct and multiply-reflected (i.e. between adjacent walls) paths. But this describes a subset of multiple scattering, diffraction and coherent reflection.
On the basis of their measurements and conjectures, Bougdah *et al* have suggested that the following factors may be important in designing a low wall system for noise reduction:

- Wavelength of incident sound,
- Wall depth,
- Total number of diffracting elements,
- Wall width,
- Source and receiver locations,
- Nature of the individual diffracting elements
- Overall distance covered by the diffracting elements.

The 'nature' of the diffracting elements is not defined but the work reported in section 2 suggests that *shape* and *cross-sectional area* are important. Bougdah *et al* suggest that 'rib-like' arrays could be used for traffic noise reduction in central reservations of motorways and on top of other structures such as earth bunds or rows of garages. The use of low parallel walls for road traffic noise reduction was suggested by van der Heijden and Martens in 1982[7]. They reported outdoor experiments using between 16 and 21 parallel brick walls (40 m long) with heights varying between 0.05 m and 0.6 m and located in a meadow. They found an overall insertion loss of 4 dB(A) over the frequency range between 100 Hz and 12.5 kHz and an insertion loss of up to 20 dB(A) in the 400 to 1000 Hz 1/3 octave bands. Van der Heijden and Martens considered that the main mechanism for noise reduction by parallel low walls is the creation and reduction of surface waves. Although surface waves are an important consequence of the use of low parallel walls on an acoustically-hard ground, the acoustical influence of a low parallel wall system extends over a wider range of frequencies than that affected by the surface wave. Essentially, low parallel wall structures result in frequency dependent finite impedance for acoustically-hard ground which changes the ground effect.

Rib-like corrugations have been of interest also in room acoustics. Surface profiles in the form of regularly spaced walls separating wells or grooves or troughs are used as *diffusers*. Diffusers in rooms are intended to redistribute the reflected sound energy spatially so that specularly-reflected sound is less prominent. This ensures that the sound field in an enclosed space is uniform (or diffuse) and that the delayed arrival of reflections from the room surfaces does not create an environment in which speech or music is difficult either to hear or perform. Considerable research has explored height profiles for walls and wells that are most efficient for diffusion. The most commonly used designs are the Quadratic Residue Diffuser (QRD) and the Prime Root Diffuser (PRD)[8]. A diffuser can be designed to be an absorber as well. In a structure intended primarily as a diffuser, the well width is too large for absorption through viscous and thermal effects. Reducing the well width increases the absorption. Indeed it is possible to create an efficient sound absorber with sufficiently narrow slit-like pores. A method of improving the low-frequency influence of diffuser/absorber structures involves the insertion of a perforated plate into some of the wells. The spatial ordering of the wells can be arranged to achieve maximum well coupling and hence maximum absorption[9]. Various designs of road traffic noise barrier involve the introduction multiple diffracting edges[10]. It has been reported that a sequence of wells of uniform depth mounted on the upper surface of a T-profile noise barrier could produce a similar insertion loss to a soft, reactive surface[11]. Work has been carried out also on applying QRD profiles to 'T', 'Y' and other barrier profiles and a QRD system tuned to 400 Hz has been proposed as the most efficient design for reducing road traffic noise[12]. Nested self-similar configurations, i.e. *fractal* arrangements, have been found to give improved transmission loss through periodic structures such as sonic crystals[13].

The reduction of road traffic noise over low parallel wall systems is explored using numerical predictions in the next two sub-sections.

3.2 Identical regularly-spaced parallel walls

A single conventional noise barrier causes sound to *diffract* around its top. The performance of such a barrier depends on the path length difference between the direct path between source and receiver and the path to source and receiver via the top of the barrier. The greater the path length difference, the greater is the attenuation. This means that to be most effective the barrier should be placed as close as possible to source or receiver. If the barrier is positioned close to the source, its effectiveness decreases as the receiver moves further way. However the performance of a parallel low wall system depends on the interaction of sound with all of the walls. This means that the first wall need not be close to the source. Indeed if it is placed sufficiently close to the source, diffraction by the first wall dominates the interaction with the wall array. Unlike for a single wall noise barrier, with a source near the ground, the performance of a low parallel wall structure improves as the receiver moves further away but the gain in performance becomes marginal beyond a certain distance. However, for both conventional barriers and low wall systems, meteorological effects will have increasing importance at longer ranges.

Figure 3(a) shows BEM predictions of the insertion loss due a 30 wall array, given a single lane of simultaneous car road/tyre and engine sources and a receiver at 1.5 m height, for ranges of 10 m, 20 m and 50 m, wall thickness (0.05 m, 0.1 m and 0.15 m) and centre-to-centre spacing between 0.1 m and 0.5 m. The default wall thickness assumed is 0.05 m. Where more than one point appears for a given range, then calculations have been made for additional wall thickness values of 0.1 m and 0.15 m. The predicted insertion loss varies between 4 dB at 10 m range and 13 dB at 50 m range. The 50 m range insertion loss predictions are similar to those predicted for a 1.5 m high receiver at 45 m range due to a 'roughness barrier' with widths of between 11 m and 20 m containing 26 elements of various shapes and heights (see Table 1). Figure 3(a) indicates that the predicted insertion loss is not sensitive to the wall spacing. Figure 3(b) shows BEM predictions of insertion loss due a parallel wall array, given a receiver at height 1.5 m and simultaneous car sources, for ranges of 10 m, 20 m or 50 m, number of walls 12, 15 or 20, wall widths of 0.05 m, 0.1 m or 0.15 m and centre-to-centre spacing of 0.3 m, 0.4 m or 0.5 m. The predicted insertion loss is not sensitive to wall width.

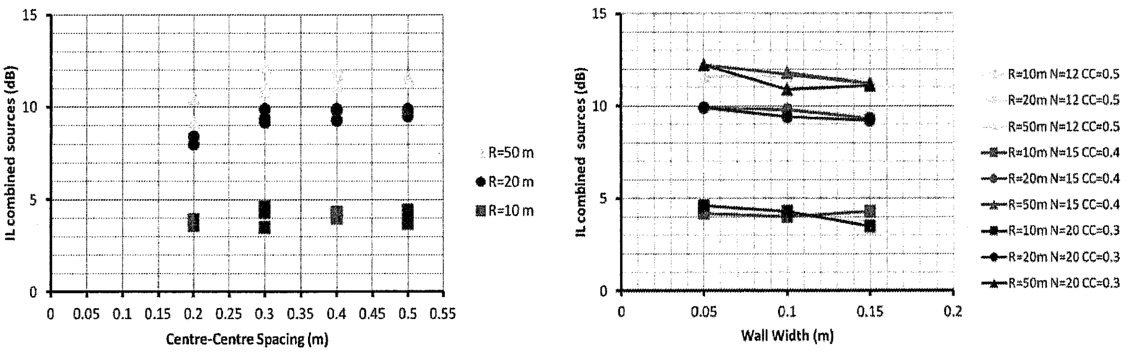

Figure 3 BEM-predicted insertion loss due parallel wall systems for simultaneous car sources and a 1.5 m high receiver at ranges of 10 m, 20 m or 50 m (a) 12 walls with centre-to-centre spacing 0.5 m, 15 walls with centre-to-centre spacing 0.4 m, 20 walls with centre-to-centre spacing 0.3 m, 30 walls with centre-to-centre spacing 0.2m and wall widths of 0.05 m, 0.1 m or 0.15 m (b) 12, 15 or 20 walls with widths of 0.05 m, 0.1 m or 0.15 m and centre-to-centre spacing of 0.3 m, 0.4 m or 0.5 m (as for (a)).

3.3 Height profiles and clusters

The main predicted influence of a cosine height variation along a 30 wall array is to introduce an additional EA maximum below 200 Hz. An N=17 QRD profile is predicted also to introduce an additional low frequency excess attenuation maximum but the main predicted influence of the QRD profile is to smooth the excess attenuation spectrum by reducing both the dips and peaks at higher frequencies. Although there might be some advantage for noise spectra containing lower frequencies, these profiles are predicted to offer less than 1 dB increase in the overall insertion loss for car noise compared with 30 uniform walls with the same centre-to-centre spacing (0.2 m).

More significant increases in insertion loss for car noise are predicted to result from combinations of fractal profiles and clustering. Fig. 4 shows parts of two example fractal wall clusters and the corresponding predictions of excess attenuation spectra. Periodic clustering introduces additional low frequency attenuation but realisation of these profiles requires larger array widths than considered previously i.e. 16.5 m and 26.5 m rather than 6 m. Table 2 shows the predicted insertion losses for these wall arrays. Fractal arrangement #1 is predicted to yield 2.5 dB higher insertion loss than a uniform wall array with the same width and centre-to-centre spacing (1 m).

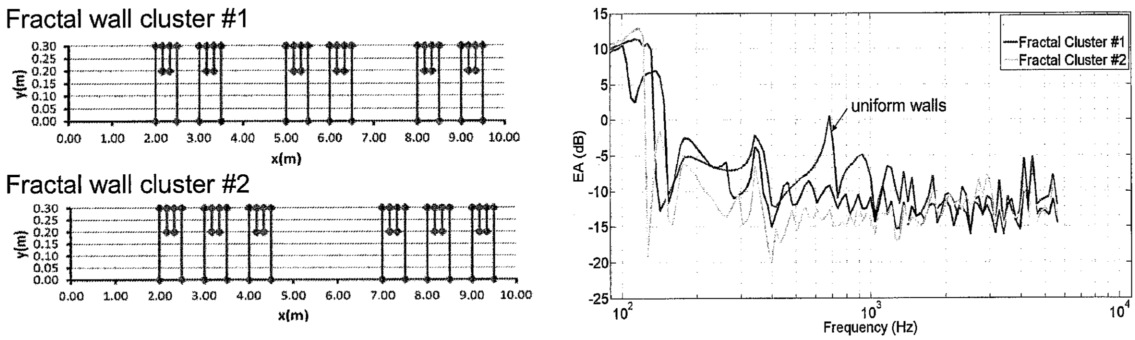

Figure 4 (left) 'Six wall' portions of two 30 wall fractal profile arrays containing (i) two wall clusters (ii) three wall clusters: (right) predicted excess attenuation spectra for fractal profile wall clusters 1 and 2 compared with that predicted for a 30 m wide array of identical walls.

Table 2 Predicted insertion losses as a function of frequency for two fractal 30-wall clusters and a uniform 30-wall array for a single lane of combined tyre/road and car engine noise sources

Centre Frequency (Hz)	Insertion Loss (dB)		
	Uniform walls	Fractal Cluster #1	Fractal Cluster #2
100	-4.6	-2.4	-5.4
125	-3.1	0.3	-2.7
160	14.6	6.1	12.6
200	11.9	10.3	14.4
250	13.2	13.8	18.7
315	11.3	14.0	17.2
400	14.0	16.4	21.4
500	15.2	16.5	20.5
630	10.2	16.6	20.2
800	13.0	18.0	20.6
1000	14.0	18.1	20.1
1250	15.3	19.1	20.4
1600	17.4	19.4	19.4
2000	17.2	18.2	17.3
2500	15.9	16.7	14.7
3150	14.0	15.5	13.5
4000	11.3	12.9	13.3
5000	11.2	12.6	12.3
Broadband	**13.4**	**15.9**	**15.2**

4 ACOUSTICAL EFFECTS OF CROPS

Aylor[14,15] has measured sound transmission loss (horizontal level difference spectra) through various crops, bushes and trees including (corn) maize, hemlock, red pine, hardwood brush and dense reeds in water. Typically the measurements used loudspeaker source and receiving microphone heights lower than the height of the vegetation. His work has shown that, in addition to ground effect, there is extra attenuation of sound at higher frequencies (> 1 kHz) associated with the presence of foliage. Aylor[14] has suggested that the extra attenuation is the result of a combination of reverberant multiple scattering, viscous and thermal dissipation at leaf surfaces and resonances i.e. sound-induced vibrations of leaves. He suggested that the viscous and thermal losses are proportional to $FL\sqrt{f}$, where F/m is the foliage area per unit volume, L m is the length of the propagation path and f Hz is frequency. He suggested also that the losses due to (reverberant) multiple scattering depend on the scattering parameter $ka = 2\pi fa$, where a is the mean leaf width.

Aylor[15] has suggested that there is a relationship between *normalised* excess attenuation, i.e. the attenuation in excess of that due to ground effect divided by the square root of the product of foliage area per unit volume, and the scattering parameter (which is the product of wave-number and a characteristic leaf dimension). Aylor's data for normalised excess attenuation as a function of scattering parameter, obtained through reeds and corn (with two leaf sizes), can be fitted by

$$\frac{EA(dB)}{\sqrt{FL}} = A\left[1-\exp\left(c-b(ka)\right)\right], \qquad ka \geq c/b \tag{1}$$

where *EA(dB)* represents the excess attenuation in dB, F/m is the foliage area per unit volume, L m is the length of the propagation path, k is the wavenumber = $2\pi f/c$, c is the adiabatic sound speed in air and a m is the mean leaf width. A, b and c are a constants with values of 3, 0.5 and 0.3 respectively for Aylor's data. The lower limit on ka avoids negative values of *EA*. For example, this implies a low frequency limit of around 1 kHz for a mean leaf width of 0.03 m and a low frequency limit of about 100 Hz for a mean leaf width of 0.3 m.

Measurements of horizontal level difference spectra have been made in a field of winter wheat at Butt's Close experimental farm in Woburn Sands, Bedfordshire, UK. The plants were about 1 m tall. The number of stems in a square metre was 414. The mean stem diameter was 2.6 mm and the standard deviation was 0.8 mm. A continuous, broadband sound was generated by a Tannoy driver attached to a 0.6 m long brass tube such that the end of the tube acts as a point source. The height of the source was 0.3 m. Microphones were placed at horizontal distances of 1.0, 3.0, 5.0, 7.5 and 10.0 m from the source and also 0.3 m above the ground. The first of the microphones has been used as a reference. Thereby a set of horizontal level difference spectra (the transfer function between microphone at a given distance and that positioned 1 m from the source) were obtained and have been corrected for the geometrical spreading (i.e. by adding $-20\log(R_2/R_1)$.

Short-range level difference measurements were made also over a carefully cleared area of crops (1.5 m^2) to determine the acoustic impedance of the underlying ground surface. A parallel slit pore model of ground impedance[2,16] was found to enable a good fit of the short-range spectra measured in the cleared area using best fit values of porosity equal to 0.37 and flow resistivity of between 200 and 250 kPa s m^{-2}. As well as showing additional high frequency attenuation, some measurements of excess attenuation spectra over crops at ranges up to 20 m suggest that the presence of plants disturbs the ground effect at frequencies less than 1 kHz, in a similar way to turbulence, by reducing the coherence between direct and ground-reflected ground[2].

Figure 5 shows comparisons between level difference spectra and predictions obtained by simply adding the attenuation calculated from Eq.(1) to ground effect. Above 3 kHz, the presence of the crops leads to extra high frequency attenuation that increases with range. Calculations (not shown here) indicate that the presence of stems alone is not sufficient to account for this extra attenuation.

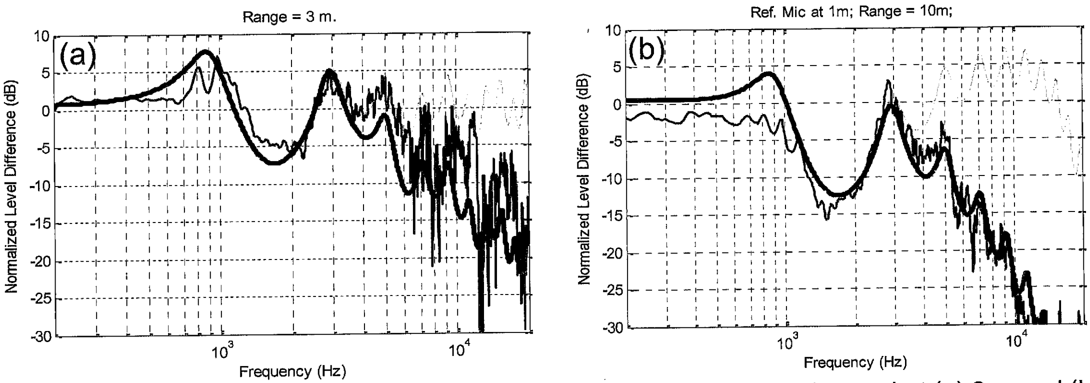

Figure 5 Measured spectrum of the level difference between receivers at 1 m and at (a) 3 m and (b) 10 m from the source (thin solid line); predicted ground effect alone (broken line); ground effect plus viscous and thermal attenuation (Eq.(1) with A = 6, b = 0.5, c = 0.3, F = 3/m and a = 0.012 m (thick solid line).

Consider the situation shown in Figure 6. A single line of cars is 5 m from a 40 m wide strip of densely planted (F = 6.3/m and a = 0.0784 m) corn plants which are 1 m high. A receiver is 1.5 m high 5 m beyond the corn. This configuration implies a direct path length of 25.8 m through the corn.

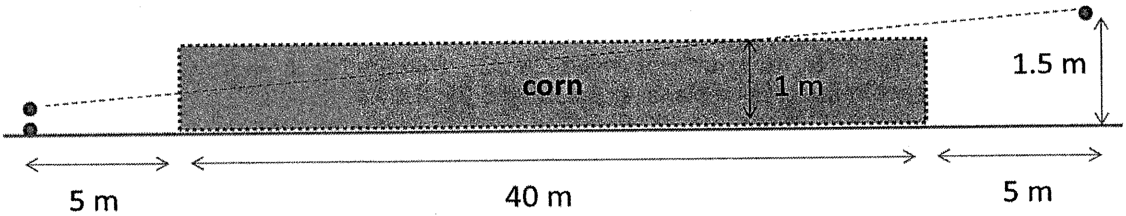

Figure 6 Schematic of a strip of densely planted corn between combined car sources and a receiver 50 m away and 1.5 m high.

Aylor's data for ground effect over a crusted fine sandy loam with measured total porosity 0.45 can be fitted using a hard-backed slit pore layer model[16] with porosity 0.45, flow resistivity 330 kPa s m^{-2} and layer thickness 0.018 m. Using these parameters to calculate the soft ground effect and equation (1) to predict the excess attenuation due to the sound paths through the strip of 1 m high corn, a total reduction in A-weighted combined car source level of approximately 13 dB is predicted at a 1.5 m high receiver compared to the level predicted over an acoustically hard surface. Approximately 7.5 dB of this reduction is predicted due to the ground effect alone i.e. a further 5.5 dB reduction is predicted due to the presence of crops. At a 4 m high receiver the total predicted reduction is 9 dB.

5 CONCLUDING REMARKS

As a result of diffraction assisted rough ground effect, arrays of closely-spaced low (≤ 0.3 m) parallel walls on acoustically-hard ground can be used to give higher insertion loss for traffic noise than would be achieved either with a single low wall nearest the source or with a single (thick) wall of the same height and width as the array. For example a 3.05 m wide array consisting of sixteen identical 0.05 m thick 0.3 m high walls with a regular centre-to-centre spacing of 0.2 m and with the nearest wall 2 m from the line of combined HARMONOISE car sources, is predicted to reduce noise from a single lane of cars at a 1.5 m high receiver, 50 m away from the source by 10 dB i.e. 5 dB more than the 5 dB insertion loss predicted for a 0.3 m high 3.05 m thick wall in the same location.

Higher insertion losses are achievable using fractal height profiles in clusters but these require a wider array occupying a larger land area. For a given wall height a small (up to 2 dB) improvement in performance can be achieved using walls with a triangular rather than rectangular cross section.

There is little broadband advantage in the use of periodic rather than random spacing but periodic arrangements may be preferred for aesthetic or practical reasons.

Roughness-based low noise barriers can be considered as an alternative to conventional road traffic noise barriers in cases where the required insertion loss is 10 dB or less and there is sufficient hard ground is available between the road and the nearest noise-affected locations.

For car noise sources, densely planted seasonal crops can add on the order of 4 dB to the attenuation due to ground effect over cultivated soil. The additional attenuation occurs particularly at higher frequencies and can be predicted in dB/m as a function of foliage density and leaf width.

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