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Control of noise by trees arranged like sonic crystals

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Abstract

In this paper, we demonstrate that it is possible to improve the sound attenuation obtained from a mass of trees by arranging them in a periodic lattice. The outdoor experimental results have shown that the largest sound attenuation, within a certain range of frequencies, was obtained for a range of frequencies related to the array periodicity. This behaviour induces us to believe that these arrays of trees work like sonic crystals. The sound attenuation values obtained in outdoor experiments for some periodic tree configurations, especially at low frequencies ($f < 500$ Hz), were far higher than those obtained from a typical green belt or forest. Therefore, these periodic arrays could be used as green acoustic screens.

1. Introduction

Since Eyring [1] studied sound attenuation in the jungle, many authors have been investigating the extent to which vegetation could be used to solve environmental noise problems. As the measurement procedures and set-up designs used in each case were so different, the obtained results were varied and, for that reason, it is not easy to make comparisons. However, from a reading of these authors we can conclude that the mechanism of attenuation is highly frequency

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dependent: at low frequencies the "ground effect" is the most important mechanism for attenuation [2] although at some frequencies lower than 500 Hz the sound level increases [3]. In all cases, at frequencies lower than 1 kHz, vegetation is transparent to sound [4]. In the middle frequency range, the main effect on sound attenuation is due to scattering by leaves and branches. In general, forests attenuate noise mainly at high frequencies ($f > 2000$ Hz) owing to the absorption of sound by the foliage [5]. In all cases, it is necessary to employ a great width of belts (some tens of metres thick) to obtain little attenuation [6].

The idea of sonic crystals appeared in the 90 s, when it was demonstrated that a periodic array of scatterers (cylindrical rods) inhibited sound transmission due to a periodicity in the density of the area they covered [7–9], just as photonic crystals according to their periodicity do with light for certain frequency ranges. Since then, many transmission experiments have been performed under controlled conditions [10,11] to analyse the influence of two factors (a) the type of array structure used and (b) the density of scatterers within each array structure. One of the main advantages of sonic crystals is that by varying the lattice constant it is possible to attain peaks of attenuation over a certain range of frequencies.

In this paper, we present experimental results which show that a belt of trees organised in a periodic array produces peaks of attenuation at low frequencies ($f < 500$ Hz) not as a consequence of the ground effect but as a result of the destructive interference of the scattered waves. Moreover, the results reveal that with this type of arrangement we get more attenuation than with classic tree belts using less width, and that therefore these not extensive periodic arrays of trees can be used as green acoustic screens.

2. Measurement conditions

2.1. Characteristics of the samples

To check if regular arrangements of trees can attenuate certain frequency ranges, we carried out two types of measurements. First, we measured in existing fields where trees (poplar groves, orange fields and cypress fields) had been planted in different arrays. Secondly, we took measurements in a nursery where trees were placed in flowerpots, making possible their displacement in order to build different arrays. In all cases, we considered that their external shapes were roughly circular, the form most frequently used for scatterers in our experiments with sonic crystals. The lengths of the arrays were sufficient to render negligible the effect of diffraction from the lateral edges. The land surfaces on which the measurements were carried out varied, from hard ground in the case of the nursery to grass in the case of the black poplars and tilled soil in all other cases.

2.2. Apparatus and measurements

We used a directional sound source B&K 4204 emitting white noise, a microphone B&K Type 4166, and a dual channel signal analyser, type B&K 2148, to get a narrow band frequency spectra.

To measure the effectiveness of the belt we obtained the sound attenuation spectrum. In the nursery experiment, where we could remove the structure, we measured the sound emitted by the

Table 1
Characteristics of the samples in the study

Tree	Radius (m)	Height of trees (m)	Width of the belt (m)	Microphone height (m)	Microphone-belt distance (m)	Source-belt distance (m)
Orange tree	2	≈ 3	19	1.2	2	2
Cypress 1	0.047	1.2	12	0.6	0.1	1.9
Black poplar	0.2	>3	9.2	1.6	4.5	0.1
Laurel (Nursery)	0.25	1.45	2.9 (T, R) 3.5 (M)	0.85	1.3	2.3
Cypress 2 (Nursery)	0.047	2.5	1.2	1.2	1.15	2.15

The width of the belt in the case of the laurel trees used in the nursery was the same for the triangular and rectangular lattices (T, R) but different for the multiple periodic rows (M).

source in the same position both without the structure (direct sound) and with it (interfered sound). In all other cases (existing fields), because the trees were not cut, we measured the direct sound near the sample so that the characteristics of the ground and the atmospheric conditions were the same. In both cases, the sound attenuation was calculated as the difference between the two signals. This parameter, when used to measure the effectiveness of a road traffic noise barrier, is usually called insertion loss. In Table 1, we define the characteristics of the samples in the study. By radius we refer to the radius of the circle formed by the intersection of the trees and the plane, which including the sound source and the microphone, is parallel to the ground. In the case of the black poplar trees only the radius of the trunk is referred to, while in the other samples, the radius includes the trunk, the branches and the leaves. The experiments were performed in an open place as far away from obstacles as possible to prevent unwanted reflections. The measurements were made at the end of winter and at times when background noise and wind levels were weak enough to have no effect on them. All trees used in the experiments were evergreen, except the poplar groves.

3. Data collection

Fig. 1 shows the geometrical characteristics of the arrays used in this work. In existing fields we studied square arrays for orange trees and poplar groves and multiple periodic rows for cypress trees. In the nursery we experimented with triangular and rectangular lattices for cypress and laurel trees, and multiple periodic rows for laurel trees.

The sound attenuation depends on the direction from which the sound impinges on the sample, thus we measured two different directions of the k wave vector, 0 and α degrees for the two-dimensional arrays, changing the position of the source and the microphones. The values 0 and α degrees correspond to two of the high symmetry directions of each array analysed.

The sound attenuation is obtained over a range of frequencies that depends on the lattice constant of the array (p and a), and is given by Bragg's law for diffraction [12].

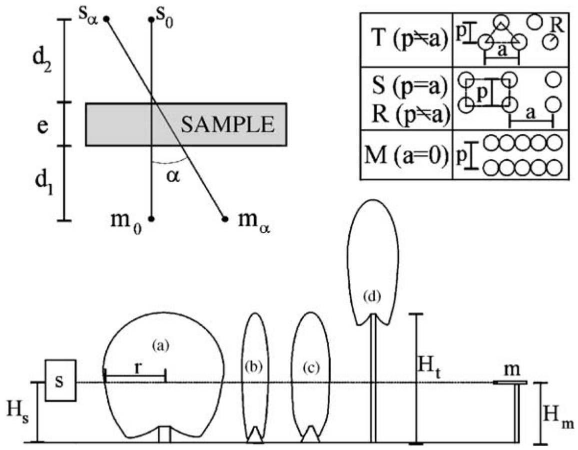

Fig. 1. Measure arrangement and geometrical characteristics of the different sonic crystals made with the trees used in this work. The width of the belt is e, m_0 and m_α are the positions of the microphone, s_0 and s_α are the corresponding positions of the source, H_s is the height of the source, H_m is the height of the microphone, H_t is the height of the tree and r is the radius of tree: (a) orange tree, (b) cypress, (c) laurel, (d) black poplar. In the inset, the lattices used with their typical parameters are represented: (T) triangular lattice; (S) square lattice; (R) rectangular lattice; (M) multiple periodic rows.

4. Results of the measurements

In Fig. 2, we show a typical sound attenuation spectra for triangular and rectangular lattices made with laurel (filling fraction = 0.47) and cypresses (filling fraction = 0.07) in two of the directions of high symmetry. In the case of laurel it appears that the whole tree acts as the centre of scattering since there are experimental peaks of attenuation located at the positions predicted by Bragg's law for diffraction in these directions (see Table 2). It is important to point out that the attenuation peaks appear at low frequencies. We repeated the experiment varying the constant lattice and the type of trees (cypresses). We built the same sonic crystals again although this time their filling fraction was smaller than the previous one (filling fraction = 0.07). As the existence of attenuation peaks strongly depends on the filling fraction within the sound crystals [10], in the case of cypresses, no attenuation peaks were obtained. It is interesting to point out that, according to the results shown in Fig. 2, the existence of attenuation peaks and their position within certain frequencies seems to be an exclusive function of parameters that govern the behaviour of sonic crystals (their filling fraction and their angle of incidence) and not other factors such as the type of land, foliage, etc. A possible explanation of this behaviour might be that the thinness of the tree belts used meant that the effect of the ground on sound attenuation was negligible in comparison with the effect of the sound crystal.

Attenuation peaks did not appear in the measurements carried out in the pre-existing fields (poplar groves and cypress), as the filling fraction values were also too small. The case of the orange fields is special since the external shape of the tree may be considered spherical and, therefore, we were dealing with a square two-dimensional array formed by three-dimensional scatterers. This could be the reason why the attenuation peaks did not appear well defined in the data in spite of the high filling fraction.

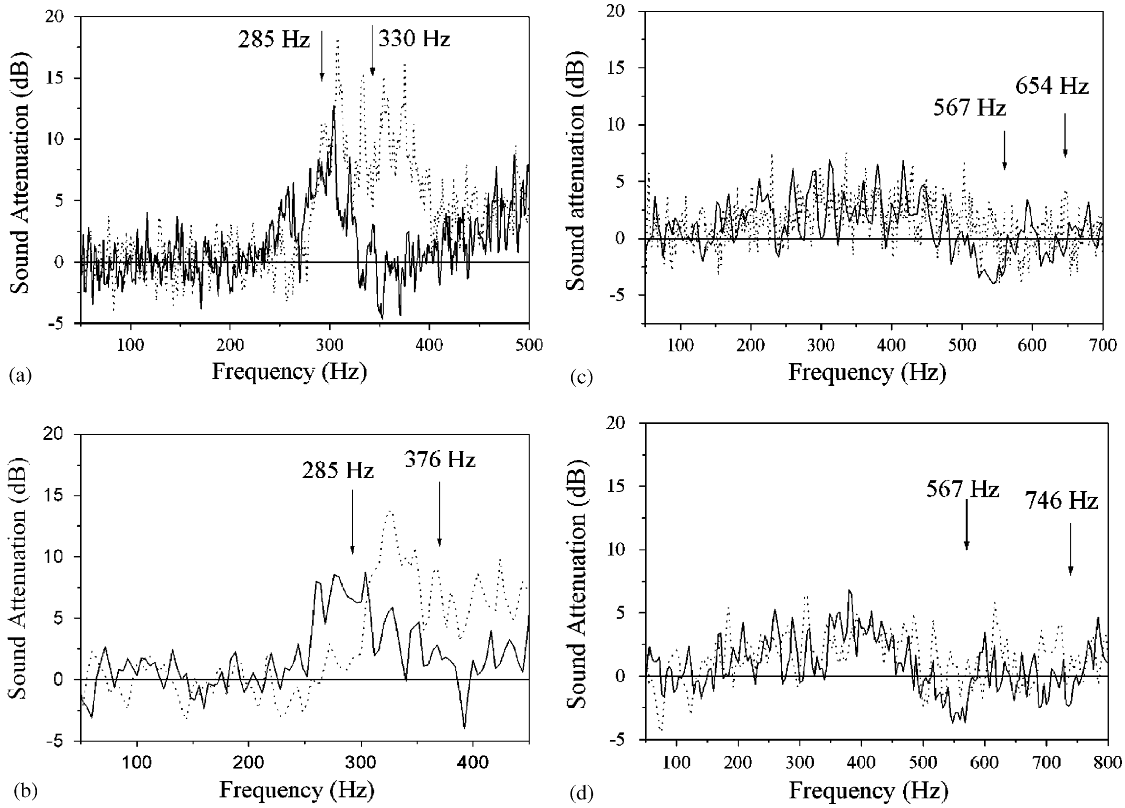

Fig. 2. The position of the first attenuation peak for laurel and cypress trees in the nursery for triangular lattices (—— 0°; ········ 30°) and rectangular lattices (—— 0°; ········ 40.6°): (a) laurel—triangular lattice; (b) laurel—rectangular lattice; (c) cypress—triangular lattice; (d) cypress—rectangular lattice.

Table 2
Characteristics of the arrays formed

Tree	Array	Number of rows	a (m)	p (m)	Bragg freq (Hz)	Filling fraction	α measured (deg)
Orange tree	Square	4	5	5	34	0.5	0
Cypress 1	Multiple periodic rows	12	—	1	170	0.007	0
Black poplar	Square	8	1.1	1.1	154–218	0.1	0–45
Laurel (Nursery)	Rectangular	5	0.7	0.6	283–373	0.47	0–40.6
	Triangular	5	0.7	0.6	283–327	0.47	0–30
	Multiple periodic rows	5	—	0.75	227	0.35	0
Cypress 2 (Nursery)	Rectangular	5	0.35	0.3	567–746	0.07	0–40.6
	Triangular	5	0.35	0.3	567–654	0.07	0–30

The angle α indicates the directions of high symmetry used to take the measurements.

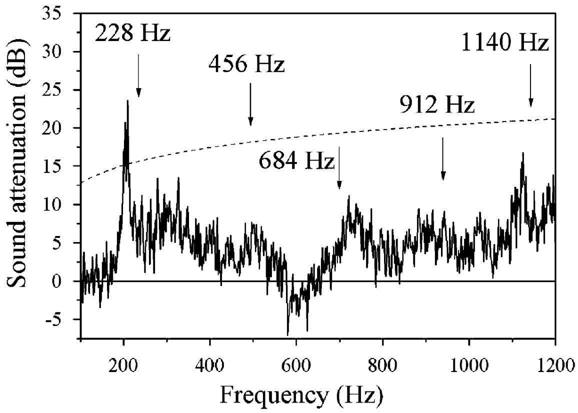

Fig. 3. Comparison between the experimental attenuation spectrum obtained with a multiple periodic rows lattice made with laurel and the values obtained by Maekawa (see Ref. [13]). The multiple periodic rows lattice had 5 rows, it was 3.5 m wide and the lattice constant was 0.75 m.

Owing to the area around each tree needed for the natural growth of trees, the normal natural filling fraction is lower than that suitable to obtain attenuation peaks, as we found was the case for the existing fields. Therefore it is necessary to produce arrays that allow trees to function as scatterers. The solution would be a one-dimensional array or multiple periodic rows. In this type of sonic crystal, the repetition of scatterers occurs only in one dimension (see Fig. 1). Thus, we can build a belt by placing several rows of trees separated from one another by a constant distance (p). For this purpose, we built a sonic crystal formed by five rows of laurel (filling fraction = 0.35) in the nursery. Fig. 3 shows the comparison between our results and those predicted by Maekawa [13] for thick noise screens. The use of Maekawa abacus, based on experimental data, is a classical way to calculate the sound attenuation produced by a semi-infinite plane screen. Using this abacus the sound attenuation is obtained as a function of the frequency and it only takes into account the diffraction along the edges of the screen. This model neglects the reflection and the absorption of the barrier and the ground effect. When we calculated the sound attenuation by using this abacus we considered a screen of the same dimensions as the ones used in our study. Obviously, the attenuation obtained with the multiple periodic rows is smaller than Maekawa′s values, except in the first attenuation peak. However, the multiple periodic rows presented good peaks of attenuation over a large range of frequencies (0–1200 Hz). Sound attenuation values obtained by Beranek's prediction [14] for belts with the same width as the ones we studied are close to zero throughout the range of frequencies shown.

5. Conclusions

Measurements have shown that tree belts are able to attenuate certain bands of frequencies with more effectiveness if they are arranged in a lattice configuration (at low frequencies). The structures built up in this shape present behaviour typical of sonic crystals, the level of attenuation obtained depends on the filling fraction, and the position of the attenuation peaks obtained along a certain range of frequencies depends on the type of lattice used as well as the angle of incidence at which the sound strikes the barrier.

Sonic crystals can be created using trees as scattering centres and the location of the attenuation peaks appear as Bragg's law predicts.

These two conclusions would suggest that the pattern in which trees are planted could be a factor to take into account when considering the sound attenuation produced by a group of trees, as well as the type of tree, ground surface and the width of the tree barrier.

Finally, it would seem that the most effective way of creating sonic crystals from trees as noise reducing devices, while at the same time respecting the area needed for the natural growth of trees, would be multiple periodic rows. This use of one-dimensional arrays produces attenuation peaks at low frequencies with a small width of belt.

However, this is the first time trees have been used as scatterers in sonic crystals and further investigation is required to optimise the attenuation of these belts, varying some factors such as the type of array or the species of trees chosen. In conclusion, we think that it would be possible to build a new type of ecological noise screen, using trees.

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References

[1] C.F. Eyring, Jungle acoustics, *Journal of the Acoustical Society of America* 18 (1946) 257–270.
[2] W.H.T. Huismann, K. Attenborough, Reverberation and attenuation in a pine forest, *Journal of the Acoustical Society of America* 90 (1991) 2664–2677.
[3] M.A. Price, K. Attenborough, N.M. Heap, Sound attenuation through trees: measurements and models, *Journal of the Acoustical Society of America* 84 (5) (1988) 1836–1843.
[4] R. Bullen, F. Fricke, Sound propagation through vegetation, *Journal of Sound and Vibration* 80 (1982) 11–23.
[5] F. Fricke, Sound attenuation in forest, *Journal of Sound and Vibration* 92 (1984) 149–158.
[6] J. Kragh, Road traffic noise attenuation by belts of trees, *Journal of Sound and Vibration* 80 (74) (1981) 235–241.
[7] R. Martínez-Sala, J. Sancho, J.V. Sánchez, V. Gómez, J. Llinares, F. Meseguer, Sound attenuation by sculpture, *Nature* 378 (1995) 241.
[8] M.M. Sigalas, E.N. Economou, Attenuation of multiple-scattered sound, *Europhysics Letters* 36 (1996) 241–245.
[9] M.S. Kushwaha, Stop-bands for periodic metallic rods: sculptures that can filter the noise, *Applied Physics Letters* 70 (1997) 3218–3220.
[10] J.V. Sánchez-Pérez, D. Caballero, R. Martínez-sala, C. Rubio, J. Sánchez-Dehesa, F. Meseguer, J. Llinares, F. Gálvez, Sound attenuation by a two-dimensional array of rigid cylinders, *Physical Review Letters* 80 (1998) 5325–5328.
[11] D. Caballero, J. Sánchez-Dehesa, R. Martínez-Sala, C. Rubio, J.V. Sánchez-Pérez, L. Sanchis, F. Meseguer, Suzuki phase in two-dimensional sonic crystals, *Physical Review B* 64 (2001) 0643031–0643035.
[12] C. Kittel, *Introduction to Solid State Physics*, seventh ed., Wiley, New York, 1996.
[13] Z. Maekawa, Noise reduction by screens, *Applied Acoustics* 1 (1968) 157–173.
[14] J.L. Beranek, *Noise and Vibration Control*, McGraw-Hill, New York, 1971.