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# A tunable acoustic barrier based on periodic arrays of subwavelength slits

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The most usual method to reduce undesirable enviromental noise levels during its transmission is the use of acoustic barriers. A novel type of acoustic barrier based on sound transmission through subwavelength slits is presented. This system consists of two rows of periodic repetition of vertical rigid pickets separated by a slit of subwavelength width and with a misalignment between them. Here, both the experimental and the numerical analyses are presented. The acoustic barrier proposed can be easily built and is frequency tunable. The results demonstrated that the proposed barrier can be tuned to mitigate a band noise without excesive barrier thickness. The use of this system as an environmental acoustic barrier has certain advantages with regard to the ones currently used both from the constructive and the acoustical point of view.  [http://dx.doi.org/10.1063/1.4921834]

Acoustic barriers are in common use to reduce noise levels and have been extensively studied since the middle of the 20th century. Over the last decades a variety of acoustic barrier designs have been investigated to increase the screening effect. The research carried out focuses on the top edge of the barrier shape[1,2] and the addition of an absorptive material to the noise barrier.[3–5] At the end of the nineties, the use of periodic structures, called sonic crystals, as acoustic barriers were proposed.[6,7] Sonic crystals consist of periodic arrays of scatterers that produce high attenuation in selective ranges of frequencies related with their lattice geometry. These ranges of frequencies are called band gaps and the underlying physical mechanisms including Bragg interferences, local resonances, and the coexistence of Bragg scattering and local resonances, are all the possible mechanisms for acoustic attenuation. Acoustic barriers based on sonic crystals are still a research topic of high interest.[8–11]

In recent years, a topic that has attracted considerable attention has been the "extraordinary acoustic transmission" through subwavelength apertures. A large amount of papers have examined, both theoretically and experimentally, the physical mechanisms that contribute to extraordinary acoustic transmission. Due to the fact these structures are able to control sound, they are good candidates to be used in developing devices for engineering applications. The extraordinary acoustic transmission through a subwavelength slit was reported by Lu et al.[12] and the acoustic transmission through subwavelength hole arrays was reported experimentally by Hou et al.[13] Christensen et al.[14] reported theoretical results for subwavelength slits and holes arrays. Fabry-Perot resonances inside the holes are the phenomena responsible for the acoustic transmission peaks. Sound attenuation at ultrasonic frequencies was reported by Estrada et al.[15] They showed, both theoretically and experimentally, that higher sound attenuation than predicted by the law of mass can be obtained and the cause of this phenomenon was the existence of Wood anomalies.[16] The role of the geometrical parameters in acoustic transmission through perforated plates was also reported.[17,18] The transmission through two perforated plates with subwavelength hole arrays and separated by an air gap at ultrasonic frequencies has also been studied.[19,20]

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In last years, various alternatives have been proposed as soundproof subwavelength structures. Membrane-type acoustic metamaterials built with a periodically distributed membrane structure with attached resonating masses[21,22] were proposed as low frequency soundproof structure. Sound insulation in the low frequency range has been achieved by using composed multilayer membrane coated perforated plates.[23] The use of periodically distributed Helmholtz resonators[24,25] has also been proposed as structures capable of attenuating band noises. All these proposed structures are not open so they were not transparent to air. Recently, Kim and Lee[26] proposed a frequency tunable soundproof window with airflow that consists of a three-dimensional array of resonators with many holes centered on each resonator. In this paper we present a new acoustic barrier based on subwavelength slits as an alternative to classical acoustic barriers and to sonic crystal ones. As the sound attenuation capabilities of the barrier presented in this paper can be tuned as a function of the geometrical parameters without an excesive thickness and it is an open structure, the proposed barrier could be used to attenuate band noise, such as that made by mechanical equipment or industrial noise.

In order to predict the performance of an acoustic barrier before fabrication, the commercial software COMSOL 3.5.a had been used to obtain the numerical predictions. The simulation of the devices in the audible range was developed considering a 2D system of rigid pickets with infinite length (along Z direction) in air and the acoustic barrier is considered to be endlessly long in order to evaluate only the transmission through the barrier and disregard the diffraction at the top edges and at the end of the structure. This 2D system has been designed with two rigid picket rows because, as will be seen later, it is sufficient to obtain a high level of attenuation. The domain were the Helmholtz equation has to be solved consists of two rows of rigid pickets with the dimensions shown in Figure 1. These are confined between two completely reflected lines which are parallel to the wave propagation direction (Y direction) and are separated by 0.35 m (picket width plus subwavelenght slit). With these conditions, the samples can be considered as an infinitely long device formed by two rows of rigid pickets. This artifice has been successfully used in several analysis related with periodic structures,[27,28] allowing the reduction of the computational cost. At the end of the domain, a Perfectly Matched Layer (PML) is considered to avoid unwanted reflections and therefore behave as free-field, see Figure 1.

In a first step towards building the device, we have defined the preferred frequency band to attenuate noise and the maximum thickness, which were chosen at 1000 Hz and 0.3 m respectively. By using these conditions, two basic structures were considered and built with two rows of wood pickets of width 0.3 m and depth 0.1 m, distributed periodically with a period of 0.35 m and with a slit width of 0.05 m, separated by an air gap of 0.1 m. Each row had six pickets. In the first one, there is no lateral misalignment between the rows (Sample A) and in the second one the lateral misalignment between the rows is 0.175 m (Sample B). Figure 2 shows a schematic plan of the structures considered.

The measurements of the subwavelength acoustic barrier were carried out in an 8 x 6 x 3 $m^3$ anechoic chamber. The measurement system consisted of a bi-dimensional robotized measurement system. National Instruments cards were used to synchronise both the microphone and the data acquisition of the temporal signal. Continuous white noise generated by a directional sound source

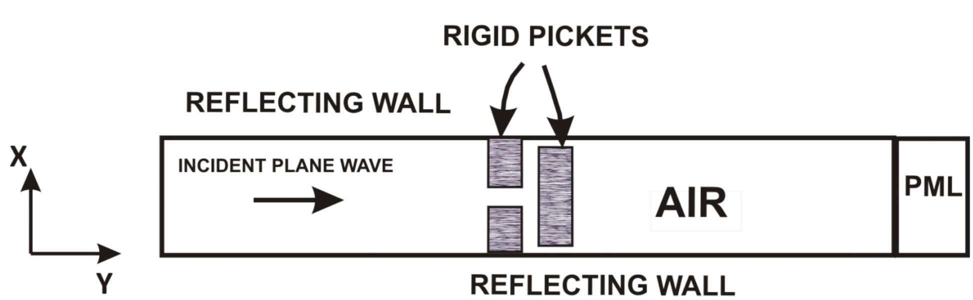


FIG. 1. Plan view of the simulated device. The reflecting lines and the PML define the boundaries of the domain. The pickets have been considered as rigid, and the incident wave has been considered as a plane wave.

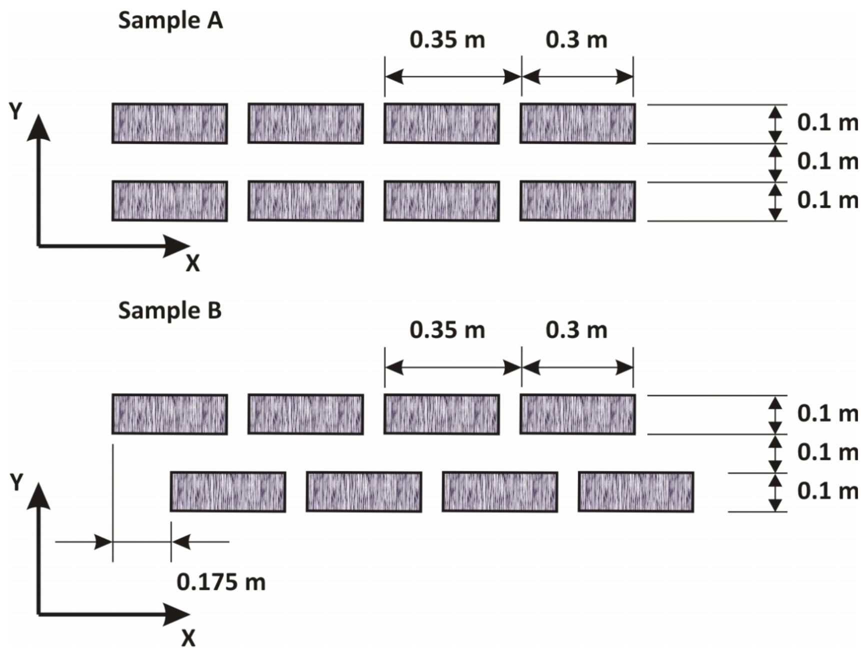


FIG. 2. Schematic plan of the acoustic barriers considered. The Sample A with no lateral misalignement between its rows and the Sample B with a lateral misalignement between its rows of 0.175 m.

(GENELEC 8040A), emiting from right to left, located 2 m from the device was used throughout the measurements in order to consider the wave impinging, at normal incidence, on the sample as a plane-wave. Figure 3 shows a scheme of the experimental device and the measurement system. The sound level as a function of frequency was obtained from the Fast Fourier Transform (FFT) of the temporal signal. The frequency range 100-2500 Hz was covered in 6 Hz steps. The acoustic attenuation properties of this barrier are represented by its attenuation spectrum by means of the insertion loss (IL), defined as the difference between the sound pressure levels recorded at the same point with (interfered pressure field) and without (direct pressure field) the barrier $IL = 20 \cdot \log_{10}\left|\frac{p_{Direct}}{p_{Interfered}}\right|$

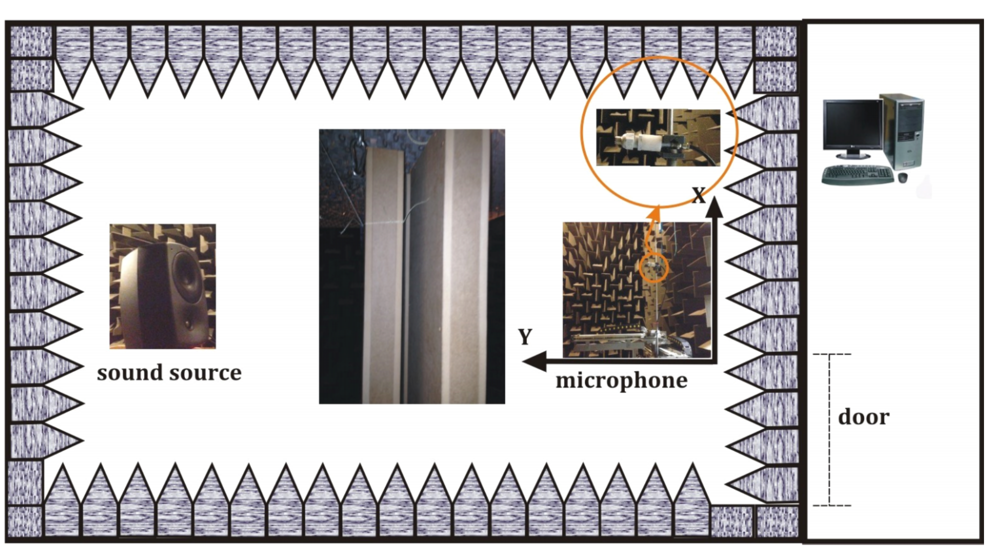


FIG. 3. Scheme of the anechoic chamber with the experimental device and the measurement system.

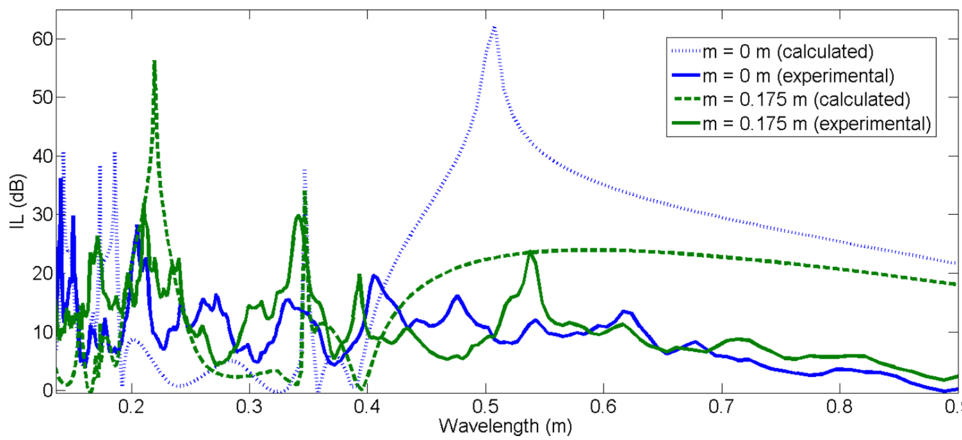


FIG. 4. Calculated and mesured insertion loss at normal incidence for an acoustic barrier considered. Sample A has no lateral misalignment between the rows and Sample B has a lateral misalignment between the rows of 0.175 m.

Figure 4 shows calculated and measured insertion loss at normal incidence for the acoustic barrier considered. At the calculated one, it has been observed that the insertion loss spectra follow a typical acoustic filter pattern. Pronounced insertion loss peaks that are the exact manifestation of the Wood anomaly similar to those observed in optical gratings[16] have been clearly seen. The Wood anomaly for normal incidence in a periodic array of subwavelength slits is given by $l_p = m\,\lambda$, where $\lambda$ is the wavelength, m the diffraction order, $l_p$ is the lattice period. The positions of the Wood anomalies are 0.35 m and 0.17 m for the periodic array of 0.35 m, that corresponds to $\lambda = l_p$ and $\lambda = 0.5l_p$, respectively. The Wood anomaly at the wavelength of 0.17 m is not clearly observed due to the interference with the Fabry-Perot resonance. In the case of the acoustic barrier with no lateral misalignment between the rows, a sharp insertion loss peak at a wavelength around 0.52 m is observed and is explained as a destructive interference between the propagating and evanescent waves[29] of the first diffraction order.

In the case of the acoustic barrier with a lateral misalignment between the rows of 0.175 m, a sharp insertion loss peak at a wavelength of around 0.23 m is observed. This wavelength corresponds to destructive interference between the odd and even Fabry-Perot modes,[30] resulting in an insertion loss increase. The insertion loss peaks corresponding to the Wood anomaly and to the destructive interference between the odd and even Fabry-Perot modes are clearly observed. The measured results are in close agreement with the calculated ones except for some discrepancies in the insertion loss values that are due to the length of the pickets, which were considered infinite, so the diffraction around the edges was not considered and only the transmission through the barrier was evaluated. On the other hand, viscous losses are not included in the calculations.

In order to confirm the different nature of the insertion loss peaks showed in Figure 4, acoustic pressure computation for different wavelengths has been conducted. The time average acoustic pressure mapped within a unit cell for both samples are shown in Figure 5. The distributions of the acoustic pressure fields are quite different for the Wood anomaly wavelengths and the wavelengths corresponding to the destructive interference between odd and even Fabry-Perot modes. For the destructive interference the acoustic pressure field distributions show a spatial decay between the rows of pickets [Fig 5(a) ($\lambda = 0.51$ m) and Fig 5(c) ($\lambda = 0.19$ m) in Sample A and Fig 5(e) ($\lambda = 0.22$ m) in Sample B]. For the Wood anomalies, the propagating wave between the rows completely disappears [Fig 5(b) ($\lambda = 0.35$ m) in Sample A and Fig 5(d) ($\lambda = 0.35$ m) in Sample B].

In conclusion, this paper presents an acoustic barrier based on acoustic transmission through subwavelength slits. The barrier was built with two rows of vertical pickets which were periodically distributed. The idea behind this design is to obtain an open acoustic barrier that could be tuned to suppress a band noise without an excesive thickness. Due to the separation between the pickets, the air can flow through the barrier, so that it could also be used in industrial installations where the airflow is necessary. The mechanisms that explain the noise attenuation in certain

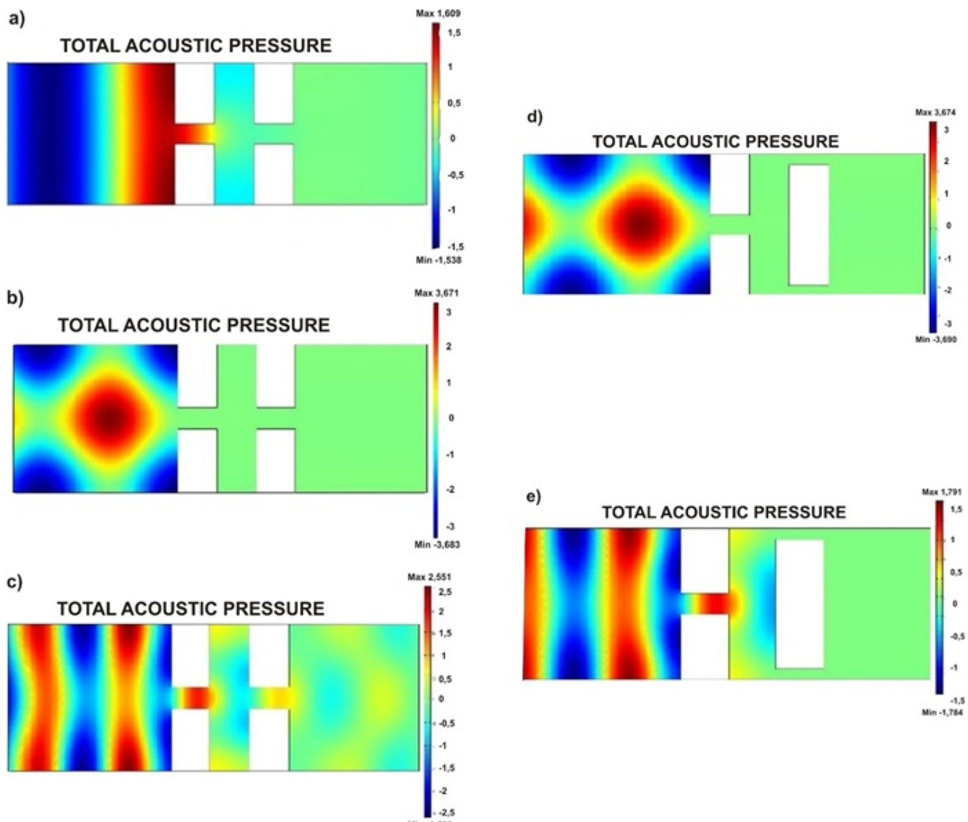


FIG. 5. Acoustic pressure map within a unit cell for sample A (a,b and c) and for sample B (d and e). Fig 5(a) ($\lambda = 0.51$ m) and Fig 5(c) ($\lambda = 0.19$ m) in Sample A and Fig 5(e) ($\lambda = 0.22$ m) in Sample B. Fig 5(b) ($\lambda = 0.35$ m) in Sample A and Fig 5(d) ($\lambda = 0.35$ m) in Sample B.

wavelength ranges are the Wood anomalies and the destructive interference between the even and odd Fabry-Perot modes. Both phenomena depend on the geometrical parameters of the barrier such as periodicity, picket depth and air gaps between picket rows. Laboratory measurements in the anechoic chamber have been carried out in order to compare the results with FEM calculations. The results measured have shown close agreement with the calculated ones.

## ACKNOWLEDGEMENTS

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