Designing of a simulation software for acoustical layout and shape optimization of new materials for diffusers in room acoustics and architecture

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Project duration: 08.06.2012 - 07.12.2013

1. Abstract

The present report describes the research on acoustic metamaterials carried out throughout this project. It is of great interest, specially, in the private sector to offer new and cost-effective solution to solve difficult problems. This need requires continuous transfer of knowledge and technology from academia to the private sector in order to develop novel products. In this effort to provide the partner company with new resources, metamaterials offer countless options for this purpose. The novel field of acoustic cloaking is studied in depth. Several designs of cloaking devices are presented together with their advantages and disadvantages. Performance among them is assessed through simulations of sound pressure field distribution and total scattering cross section. Lastly, a beam-bending metamaterial is presented and evaluated.

2. Introduction

In the last 10 years physics has experienced the arrival and growth of a new research field. This new area, called metamaterials, has attracted special interest due to its potential applications. The term metamaterial is a broad definition that describes a group of engineered materials which provide certain properties not commonly available in nature, such as negative refractive index, negative effective mass density, etc. Their particular properties are generated by its internal physical structure rather than its chemical composition.

Although these materials were initially proposed and investigated in the field of electromagnetism, their physical characteristics have allowed to expand their development to other areas such as optics, mechanics, acoustics, etc. where also materials interact with propagating waves. The range where a metamaterial behaves as such occurs where the internal structure of the material is much smaller than the wavelength of the interacting wave.

The incidence of any type of wave on a rigid body, in this case acoustic waves, generates a reflected wave as a result. The control of these reflected waves is particularly important since it allows to improve the acoustic quality in many situations. For example, in architectural acoustics such control of the reflection it translates into a better perception of music or speech. In industrial applications, the use of specially crafted materials as the ones investigated here, allows to reduce the scattering generated by rigid bodies.

3. Results

Acoustic Cloaking

Cloaking refers to the ability of a metamaterial to make an object invisible. This idea was introduced by Pendry et al. [Pen 06, Cum 06] in 2006 and since then on it has led to numerous papers. The principle of cloaking is based on the form-invariance of Maxwell's equations and a design technique called transformation optics [Che 09, Yan 09], which together define how to shape a material to achieve certain purpose, in this case a cloaking device.

In 2007 Cummer et al. [Cum 07] presented one of the first acoustic cloaks, this was based on the experience gained through previous work regarding electromagnetic cloak. It exploits the equivalence between acoustic wave propagation in two dimensions and electromagnetic propagation in isotropic media. The duality of both equations is given by the values shown below where
The result of this equivalence implies that it is possible to create a cylindrical shell with a particular spatial distribution of mass density and bulk modulus that will bend the trajectory of any incident wave around the center of a rigid object with minimum scattering. The material spatial distribution required for such result is given by

\[
\rho_r = \frac{r}{r-a}, \quad \rho_\theta = \frac{r-a}{r}, \quad \frac{\lambda}{\lambda_0} = \left(\frac{b-a}{b}\right)^2 \frac{r}{r-a}
\]

where \( r \) is the radius, \( a \) and \( b \) are the inner and outer radii of the cloak, and the quantities with subscript 0 are those of the background medium. The effect of a cloaking device is shown in Figure 1. There, three cases are depicted: (a) A point source radiating in free field, (b) A rigid cylinder generates a perturbation in the sound field and (c) A metamaterial around the cylinder minimizes the perturbations.

A year later two new designs for acoustic cloaking were proposed by Cheng et al. [Cheg 08] and Chen et al. [Che 08], these designs were based on a bi-layered structure that could potentially facilitate the actual realization. The idea behind these designs was to eliminate the need of an anisotropic material distribution by replacing this by a set of inhomogeneous isotropic layers that emulate the same effect. Both designs present a rather good performance as show in Abb 2.
Solid Acoustic Cloaking

Although these proposed cloaking devices proved to greatly minimize the scattering and therefore provide a significant performance, these designs assume that the constitutive materials of the cloak are fluids and any practical cloaking would require some sort of solid components to at least sustain its structural integrity.

Since the beginning of research in this area it was pointed out that equations of motion for elastic media do not share the form-invariance present in equations of electromagnetism and acoustics. This unfortunate characteristic of elastic media increases the difficulty to create a solid cloak since it implies that coordinate transformations cannot be implemented precisely as distribution of elastic properties. Despite this limitation, in 2010 Urzhumov et al. [Urz 10] presented a solid cloaking and studied the influence of the shear modulus. Urzhumov concluded that it was possible to implement a solid cloak under some restrictions. Although this discretized model does not require an anisotropic material it imposes several new constrains regarding thickness and filling fraction of the layers. Specifically, the ratio of the filling fraction between layers required is extremely high, between 100-2000 times. This unfortunate fact makes difficult to test such design using a Finite Element Method (FEM), which is the common tool used to predict the acoustic behavior in these type cases. However, if the idealized, continuous and anisotropic model of the cloak is used, it is possible to simulate its behavior successfully. Figure 4 shows some examples at different frequencies. The simulations there show similar results compared to the images in Figure 1. The main difference is given by the incident wave, which now consists of a plane wave whereas before a cylindrical wave was used.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Without cloak</th>
</tr>
</thead>
<tbody>
<tr>
<td>510</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>1000</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>2570</td>
<td><img src="image3.png" alt="Diagram" /></td>
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</tbody>
</table>
In 2008, Li [Li 08] introduced a new concept of cloaking where the hidden region is mapped into a line or a plane. This characteristic make it to be known as Carpet cloak. The advantage of this design is that none of the required parameters have a singularity and, moreover, all their components are isotropic. In the same way as before, the original carpet cloak was developed in the field of electromagnetics and then extended into acoustics [Zhu 10, Zha 12, Pop 11, Zig 12]. The simplicity of this design offers the advantage that can be easily manufactured without the complexity that an anisotropic material imposes, where material parameters not only depend on the spatial position but also on the direction of wave propagation.

As many metamaterials, the carpet cloak, consists of an array of unit-cells with a given distribution. First, the parameters of the unit cell must be defined according with the cloaking requirements. Once the parameters estimation is done [Fok 07], the array is created on top of the region that wants to be cloaked. A diagram of the carpet cloak geometry is shown in Figure 5. Given the small size of the numerous perforations used, it is tempting to assume that viscous losses will play an important role in the effect created by the cloak. However, it was proved that such losses do not influence the resulting sound field in any special way, i.e. the cloaking performance remains constant whether the losses are considered or not. The only noticeable effect is a slight reduction of the local sound pressure.
The broadband performance of the carpet cloak was assessed through simulations for several frequencies, as shown in Figure 6. In a similar way, the response of the cloak at different angles of incidence was simulated. The results, shown in Figure 7, present a consistent performance irrespective of the angle of incidence.

<table>
<thead>
<tr>
<th>1715 [Hz]</th>
<th>3430 [Hz]</th>
<th>6860 [Hz]</th>
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Abb. 6 – Scattered pressure with and without carpet cloak for different frequencies.

<table>
<thead>
<tr>
<th>0 [deg]</th>
<th>30 [deg]</th>
<th>45 [deg]</th>
<th>60 [deg]</th>
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Abb. 7 – Scattered sound pressure with and without carpet cloak for different angles of incidence relative to the ground.

**Beam-bending metamaterial**

The idea behind this type of materials is to be able bend a normally incident wave front to a given angle. This metamaterial is so-called Beam-Bending [Pop 09] or Beam-shifter. Although there are several beam-bending designs found in the literature [Akl 12, Lia 12], the characteristic of the one presented here is that the exit angle is modified whereas in all other cases the exit angle is identical to the incident angle and the beam-bending takes place only inside the material itself. The change in the trajectory angle increases the travel distance of a wave and thereby increases the energy losses when the metamaterial is combined with a classic acoustic absorbent material. Commonly this task at low frequencies is highly inefficient, when only classic absorbing materials are used, since the large wavelengths in this spectral range requires the implementation of large size absorbers.

Simulations showed that, as expected, an increase in the thickness of the metamaterial results in an increase in the exit angle. With a reasonable thickness of 0.6λ, an angle of 30 [deg] is obtained, Figure 8 depicts this case. Beside this, a particularly interest behavior occurs when the material is exposed to different angles of incidence. Irrespective of the angle of incidence, the difference between incident and exit angle is always constant. This is clearly visible if the incident angle is kept constant and the metamaterial is rotated, the exit angle does not change. Figure 9 shows the result of the radiation pattern when only the metamaterial is rotated. As shown there, the main lobe of the pressure points to approximately 30 [deg] in every case.
(a) Traveling wave passing through the metamaterial of 0.6 \( \lambda \) thickness. \( \lambda \) is the wavelength.

(b) Pressure field generated by a gaussian beam impinging on the metamaterial with a rotation of 22 [deg]. Main lobe of the exit angle situated at 30 [deg].

Abb. 8 – Sound pressure simulations of a beam-bending metamaterial

Abb. 9 – Polar diagram of the exit angle for different rotation angles of the metamaterial. A thickness of 0.6\( \lambda \) generates an approx. angle of 30 [deg].
4. Summary

As stated at the beginning, one of the main objectives of this project was not only to study deeply the novel field of acoustic metamaterials but also serve as a bridge between this new area of science and the partner company wax GmbH. Specifically, this consisted on the introduction of acoustic metamaterials, proposition metamaterials designs and evaluation of their performance; Focusing always in bringing together the scientific research close to a real implementation scenario. Throughout the project, special emphasis was placed on the development of feasible solution to create an acoustic cloaking metamaterial. Such metamaterial is able to create a unique behavior that is not possible to reproduce with classic materials. This behavior can be considered as a special case of uniformed diffusion. The simulations conducted proved that it is possible to hide an acoustically rigid object inside the cloak and minimize almost completely any perturbation in the sound field. Moreover, the acoustic cloaking provides a broadband effectiveness. It was important to notice that there are fundamental differences between fluid and solid cloaks. As part of the solid cloak designs, the described carpet cloak presents itself as a viable option from the manufacturing point of view. Alike as before, this design generates a reasonable performance under broadband excitation.

5. References

6. Contact details

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