Physical Realization of Anisotropic Fluid-Like Metamaterials

Daniel Torrent and José Sánchez-Dehesa

Universidad Politécnica de Valencia
C/Camino de Vera s/n, 46022 Valencia (Spain)
email: datorma1@upvnet.upv.es

Abstract

In this work we present some applications of anisotropic fluid-like metamaterials, mainly those regarding Acoustic Cloaking Devices and the so called "Radial Wave Crystals". It is shown how the requirements for building these metamaterials are quite restrictive, and some ideas about their fabrication from isotropic and homogeneous materials are analyzed. A physical realization of these type of structures is shown and their physical characterization is explained by means of some spectral-based experiments. Finally, it is explained how to export these results to into Electromagnetic Waves.

1. Introduction

Acoustic cloaking devices [1] require for their realization inhomogeneous fluid-like materials with anisotropic mass density. This property is not usual in common fluids, so that it has to be engineered in the framework of metamaterials. One way to obtain this property is, as reported in [2], by means of a multilayered fluid-fluid structure, as shown in Figure 1. In [2] it is shown that, in the low frequency limit, such structure would behave like a fluid-like material with anisotropic density, so that these structures are suitable for the design of acoustic cloaking shells.

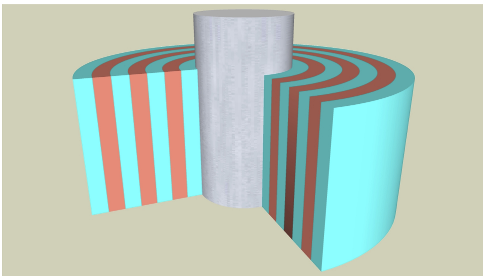

Fig. 1: Multilayered structure for the design of anisotropic fluid-like materials.

However, the problem of keeping layers of different fluid materials together and stable is still a difficult task, but it can be shown that this problem can be solved by working with sonic crystals (periodic arrangements of elastic cylinders) or, in two dimensions, by waveguide- based structures, as shown in Figure 2. This last structure will be better explained in section 3.

Also, when considering the propagation of acoustic waves in cylindrically anisotropic fluid-like materials, it was found in [3] that the corresponding wave equation can be made invariant under radial translations, therefore all the formalism previously developed for sonic or photonic crystals can be now applied to a new type of crystals named "Radial Wave Crystals". These new type of structures are also difficult to made, but they have similar properties to those required for building cloaking shells, what makes these problems closely related.

ISBN 978-952-92-7734-6

This work shows the realization and characterization of an acoustic metamaterial that could be the starting point for these new type of structures.

2. Wave propagation in cylindrically anisotropic fluid-like materials

Wave propagation in anisotropic fluid like materials is described, assuming a pressure field of the form $P(\boldsymbol{r},\omega) = \sum_q P_q(r,\omega)exp(iq\theta)$, by the following differential equation

$$\frac{1}{r}\partial_r(r\rho_r^{-1}\partial_r P_q(r,\omega)) + (\omega^2/B - q^2/(r^2\rho_\theta))P_q(r,\omega) = 0 \tag{1}$$

where rho_r and rho_θ are the components of the density tensor and B is the compressibility of the medium.

This equation is the basis for designing cloaking devices, but it was shown too that it can be made invariant under translations, provided that the cuantities r/ρ_r, $\rho_\theta r$ and B/r be periodic. If these conditions are satisfied a new type of crystals are found, called “Radial Wave Crystals”. A similar phenomenon is found in three dimensions and for Electromagnetic Waves. As shown in [3, 4] the application of these structures as high quality resonators is straightforward, so that it is worthwhile to make the effort of physically realize them.

We see therefore that both cloaking devices and Radial Wave Crystals require metamaterials with similar properties, specially because they need fluid-like materials with anisotropic properties. In the next section we will explain briefly the physical realization and experimental characterization of a fluid-like cylinder that, although homogeneous, presents anisotropy in their acoustic parameters.

3. Experimental characterization of an anisotropic fluid-like cylinder

The left panel of Figure 2 depicts the sample that we have built and characterized. It is a corrugated structure that, when the wavelength of the sound wave is three of four times the distance between grooves, behaves like an anisotropic fluid like material, due to the fact that the change in height acts as an impedance mismatch, and therefore it behaves like a fluid-fluid system.

All the grooves of type 1 or 2 have the same depth, what makes of this system a homogeneous fluid like cylinder, but anisotropic. With this assumption we can model the propagation of sound like

$$\frac{1}{r}\partial_r(r\partial_r P_q(r,\omega)) + (\omega^2/c_r - q^2\gamma^2/r^2)P_q(r,\omega) = 0 \tag{2}$$

being $c_r = \sqrt{B/\rho_r}$ the radial speed of sound and $\gamma = \sqrt{\rho_r/\rho_\theta}$ the anisotropy factor.

Thus the q-polar component of the pressure field P_q is given by

$$P_q(r,\omega) = J_{\gamma q}(\omega r/c_r), \tag{3}$$

which is a Bessel function of real order γq. Note that propagation through this medium is characterized by the radial speed of sound c_r and the anisotropy factor $\gamma = \sqrt{\rho_r/\rho_\theta}$. The experiment set up shown in Figure 2 allows the determination of both quantities.

The experiment consists in exciting sound resonances within the cavity formed by the cylinder and the aluminum tap, as shown in figure 2. The peaks observed in the spectra where identified as the zeros of the derivatives of the Bessel functions, so that from a set of equations

$$J'_{\gamma q}(\omega R_0/c_r) = 0 \tag{4}$$

we can determine the constants γ and q.

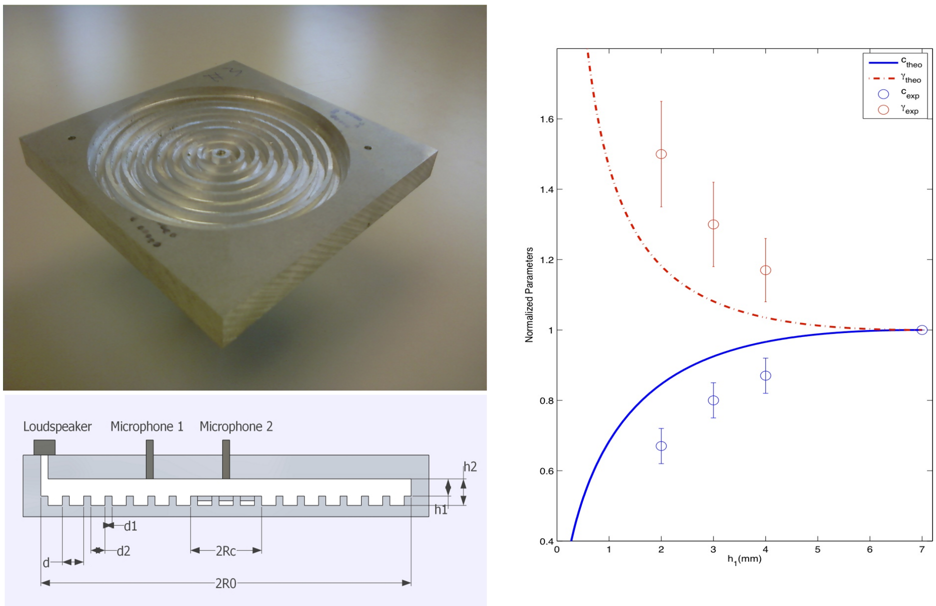

Fig. 2: Left panel:Picture and schematic view of the experimental characterization of the anisotropic fluid-like cylinder.Rigth panel: Experimental data obtained from the spectra of the cylindrical cavity.

In the right panel of figure 2 the experimental data obtained for the radial speed of sound c_r (blue circles) and for the anisotropy factor γ (red cirles) are shown for three different samples. We can see that the values obtained fairly agrees with the expected ones by the theory, though a very simple model was obtained. However, a better theoretical model is expected within the near future.

4. Conclusions

Cloaking devices and Radial Wave Crystals require complex fluid-like metamaterials for their realization, mainly because for both type of structures we require anisotropic and inhomogeneous metamaterials.

This work has shown that these structures can be designed with isotropic and homogeneous materials, and some ideas for doing this are given here.Also, an anisotropic fluid-like cylinder was built and characterized by means of a spectroscopic measurements, which suggest that we are in a good way to build more complex structures.

Finally it has to be mentioned that, specially in two dimensions, almost all results found here can be exported to electromagnetic waves, specially in the microwave regime.

References

[1] Steven A. Cummer and David Schurig, One path to acoustic cloaking, *New Journal of Physics* vol. 9, p. 45, 2007.

[2] Daniel Torrent and José Sánchez-Dehesa, Acoustic cloaking in two dimensions: a feasible approach, *New Journal of Physics* vol. 10, p. 063015, 2008.

[3] Daniel Torrent and José Sánchez-Dehesa, Radial Wave Crystals: Radially Periodic Structures from Anisotropic Metamaterials for Engineering Acoustic or Electromagnetic Waves, *Physical Review Letters* vol. 103, p. 064301, 2009.

[4] Daniel Torrent and José Sánchez-Dehesa, Acoustic resonances in two dimensional radial sonic crystals shells, *Arxiv* arXiv:1003.0214v1 ,2010.