Acoustic metamaterials based on cavities drilled in two dimensional waveguides

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Abstract

In this work we study the realization of quasi-two-dimensional acoustic metamaterials by complex fluid-like cavities drilled in a two dimensional waveguide. The cavities are filled with a metafluid and a rigid cylinder is placed at the center, then the system behaves like a soft fluid-like shell with a high density cylinder in the center. This system is known to present complex resonances and we have shown that by means of an array of these structures we can obtain either single or double negative acoustic metamaterials. Because the large number of parameters (height of the waveguide, depth of the cavity, radius of the internal cylinder, etc.) we have developed a new type of "phase diagrams" that can be used to fully understand this complex system.

1. Introduction

Acoustic metamaterials are sub-wavelength engineered structures whose effective parameters present an extraordinary behavior. For example, it has been found that with these structures it is possible to fabricate fluid-like materials with anisotropic mass density, required for cloaking shells and other transformation acoustic devices, inhomogenous acoustic parameters for the realization of gradient index devices or single and doubly negative acoustic metamaterials, that is, fluid-like structures with one or two acoustic parameters being negative.

Single negative acoustic metamaterials does not allow the propagation of sound since the wavenumber becomes complex and, therefore, the waves inside it become evanescent. Double negative acoustic metamaterials present negative refraction, an important phenomenon that allows the realization of, among other interesting devices, a lens with sub wavelength resolution.

The realization of devices with negative parameters for propagation in air is not easy since them require "soft materials", that is, acoustic materials with mass density and bulk modulus smaller than that of air. In this paper we solve this problem by working in a waveguide, where we can create structures that behave like acoustically soft scatterers.

2. Cavities in a wave guide as fluid-like shells

Figure 1 shows the schematics of the scatterer used in this work. A cavity of depth L is drilled in a waveguide of height h with a rigid cylinder of radius R_e on its center. The cavity can be filled with a metafluid (a fluid made of an array of rigid cylinders) with mass density $\rho_s > \rho_b$ and speed of sound $c_s < c_b$, being ρ_s and c_s the acoustic parameters of the metafluid and ρ_b and c_b those of the air.

The mass density of the metafluid will always be larger than that of air, however if the depth L of the cavity is large enough it can behave as a fluid-like material with mass density given by $\rho_a \approx h/(L+h)\rho_s$,

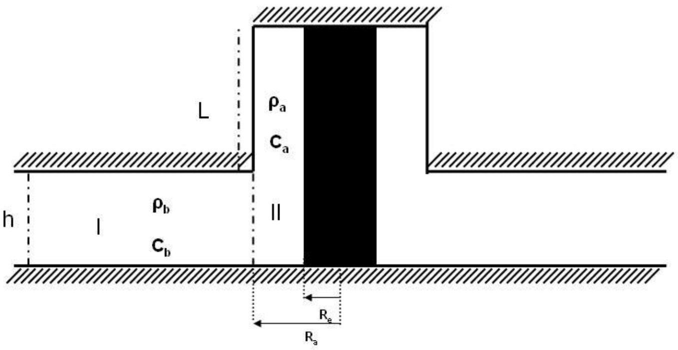

Fig. 1: Schematic view of the acoustic scatterer studied in this work. A cavity of depth L and radius R_a is drilled in a waveguide of height h. This cavity is filled with a metafluid of mass density ρ_a and speed of sound c_a. Finally an acoustically rigid cylinder of radius R_e is placed at the center of the cavity.

therefore the effect of the wave guide is to create an effective "soft" scatterer. This combination of soft scatterer plus rigid cylinder can be properly designed for having complex resonances and, therefore, an array of these structures will present locally negative acoustic parameters.

3. Phase Diagrams

Phase diagrams have been developed to study this complex system. They are necessary due to the large number of parameters and the complexity of the equations involved, since the scattering of sound by these cavities is complex to analyze.

Left panel of Fig. 2 shows one of these phase diagrams. In this example the height of the wave guide is $h = 0.3a$, where a is the lattice constant of the periodic array of cavities. These have a radius of $R_a = 0.3a$, and they are filled with a metafluid of mass density $\rho_s = 2\rho_b$ and speed of sound $c_s = 0.3c_b$. The radius of the rigid cylinder is $R_e = 0.5R_a$. The blue region shows the region where the effective bulk modulus becomes negative as a function of the depth of the cavity L/h.

Right panel of Fig. 2 shows the effective bulk as a function of the frequency for the ratio $L/h = 3$, corresponding to the red line of the pahse diagram. We see how the two regions of negativity of the bulk modulus corresponds to two resonances of the cavity.

4. Conclusion

In summary, acoustic metamterials with negative parameters for the propagation of sound in air require fluid-like materials with acoustic parameters smaller than that of air. This is not a property easy to obtain, but we have shown that with the help of cavities drilled in waveguides these metafluids can be obtained. Due to the large number of degrees of freedom we have developed a type of plots called "phase diagrams" in order to help to understand the regions at which we can obtain metamaterials with negative parameters.

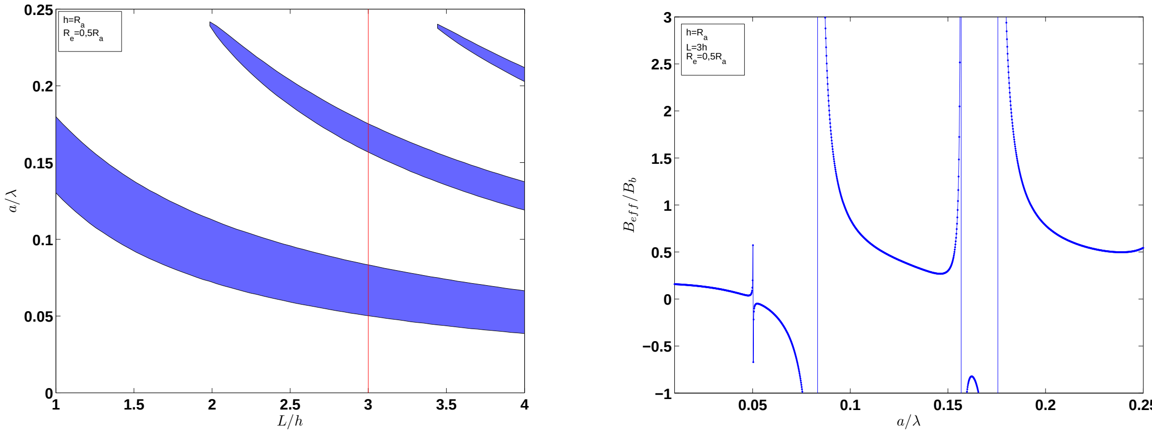

Fig. 2: (Left panel) Phase diagram showing the regions of negative bulk modulus for a cluster of cavities arranged in an hexagonal lattice. The radius of the cavity is $R_a = 0.3a$ and the radius of the rigid cylinder is $R_e = 0.5R_a$. The cavity is filled with a metafluid of mass density $\rho_a = 2\rho_b$ and speed of sound $c_s = 0.3c_b$. The height of the waveguide is set to $h = 0.3a$, and a sweep in the L/h ratio has been performed running from $L/h = 1$ to $L/h = 4$.The vertical red line is drawn at $L = 3h$, which has been plotted in right panel.

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