New materials, new sounds: how metamaterials can change the timbre of musical instruments

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Introduction

The main goal of this research is to seek the expansion of the sound properties of existing traditional musical instruments, which through the time have evolved their forms and materialities from the technological advances of the cultures where they have been developed. The final purpose of this work is to contribute to this enrichment, applying the new possibilities that come from the development of metamaterials, trying to permeate into the culture and given to interpreters new ways of musical expression, in the same way that digital technologies, such as augmented reality, machine learning and others, are trying to do in the field of digital musical instruments (Tan & Lim, 2016; Bovermann et al., 2017).

Traditional musical instruments are complex acoustic systems. In most of them, the production of sound depends on the collective behavior of several vibrators, which can be made of different materials, weak or strongly coupled to each other (Fletcher & Rossing, 1998). If we couple an absorbent material to the sound box of a musical instrument, its sound changes: some harmonics are dampen or all the components of the sound are attenuated. In this research, the relevant question is: what happens if we couple to the sound box of a musical instrument a material with the capability of to absorb specifics and tunable ranges of frequencies? If the spectral content of a sound is modified perceptibly while the amplitude and fundamental frequency remain constant, we say that the timbre changes. The main goal of this work is to characterize acoustically synthetic materials, called tunable mechanical metamaterials, and to explore the opportunities of sound manipulation that they bring for the modification of the tonal qualities of musical instruments.

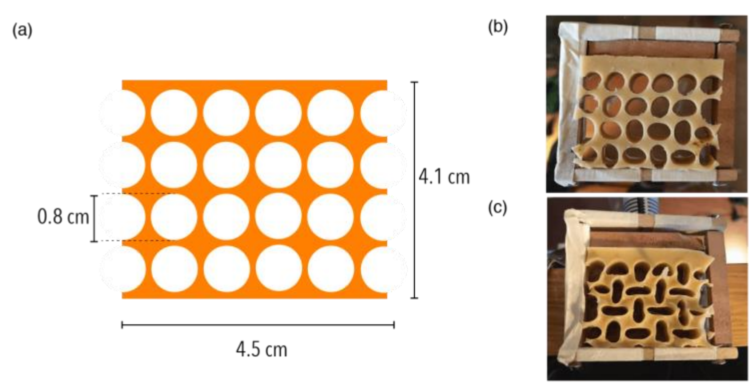

Figure 1: (a) Metamaterials: squared arrays of circular holes in a silicone elastomer matrix. (b) Metamaterial with a deformation of 1%. (c) Metamaterial with a deformation of 11%.

Metamaterials are rationally designed composites aiming at effective material parameters that go beyond those of their ingredients. Some mechanical metamaterials are artificially structured composite materials that enable manipulation of the dispersive properties of vibrational waves. We use mechanical metamaterials with the structure presented in figure 1 (a), i.e. arrays of circular holes in a elastomer matrix. These metamaterials exhibit auxetic behavior with a negative Poisson's ratio. It means that when the structure is stretched in the axial direction, it expands in the transversal direction, in contrast with typical materials (Bertoldi & Boyce, 2008; He & Huang, 2017). Furthermore, they have frequency band gaps (ranges of frequencies with no vibrational transmission), which can be tuned by adjusting their geometry and/or stiffness by different levels of mechanical deformation (see figure 1 (b) and (c)), giving us a simple way of making tunable mechanical passband filters.

Experimental method

We make a metamaterial, labeled as M1, with the geometry shown in figure 1: an array of 6x4 circular holes of 8 mm of diameter in a elastomer matrix made of silicone Elite Double 22 Fast, with a thickness of 5 mm. In order to obtain its frequency response, it is compressed at different levels while a mechanical excitation is performed, using the experimental setup described in figure 2. A spectrum analyzer (Stanford System SR780) sends a sweep sine signal from 300 Hz to 1000 Hz with constant amplitude. The signal is amplified by a power audio amplifier (Gemini XGA5000) and a mechanical vibrator (SF 9324) is activated, which excites the metamaterial. An accelerometer (PCB 356A14), connected to a signal conditioner (PCB 408E09), receives the response of the metamaterial, and the power spectrum is obtained by the spectrum analyzer. The specimen is compressed by a mechanical press and the measurement is repeated. The frequency spectra are stored in a computer for further analysis.

In order to measure the effect of applying metamaterials to a vibrant system, we attached the characterized metamaterial M1 to the sound box of an acoustic guitar using a coupling gel, to obtain and analyze its acoustic behavior using the setup described in figure 3. A string tuned to a convenient frequency is plucked, with and without the M1 sample coupled to the sound box at different positions, and the sound is recorded for frequency analysis. A pencil condenser microphone Samson C02 and a Steinberg UR44 interface were used to perform the experiment. The metamaterial was coupled in positions A and B (see figure 3 (a)). Each measurement was performed five times in equal conditions.

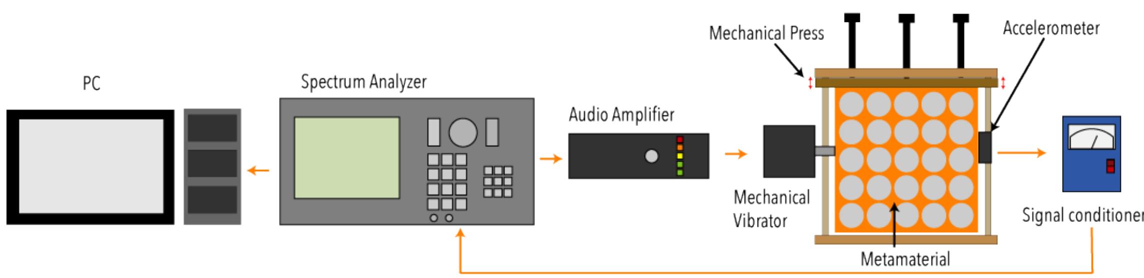

Figure 2: Experimental setup used for acoustic characterization of metamaterials: a spectrum analyzer, audio amplifier and a mechanical vibrator were used for excitation. An accelerometer, signal conditioner, and a computer were used for receiving and storing the material response. The deformation was performed using a mechanical press.

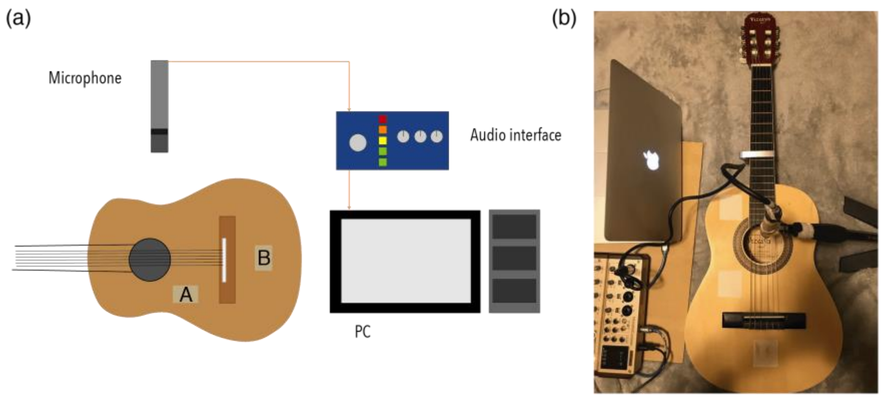

Figure 3: (a) Schematic of the experimental setup used for acoustic characterization of the influence of the metamaterial coupled to the sound box of an acoustic guitar. A pencil condenser microphone Samson C02 and a Steinberg UR44 interface were used to perform the experiment. The metamaterial was coupled in positions A and B. (b) Setup photography.

Results

Figure 4 (a) shows the power spectrum of the M1 sample in two states: the metamaterial without deformation (S1 spectrum, black dashed line), which presents one band gap at 400 Hz, and the metamaterial with a deformation of 11% (S2 spectrum, pink line), with a band gap around 530 Hz. It means that the components around 400 Hz of a mechanical vibration could be absorbed by the metamaterial without deformation, while if it is tuned with a compression of 11%, components around 530 Hz will be attenuated. The insert figure present the ratio S1/S2.

In figure 4 (b) we observed the average FFT of the sound signals produced by the acoustic guitar. The plucked string was tuned in 500 Hz. Black lines correspond to the results without coupling the M1 sample. Red lines are the FFT of the signals produced with M1 coupled in A position, with a deformation of 11%. Finally, blue lines are the same case than red ones, but with M1 positioned in B. Each measurement was performed five times. No changes in sounds were perceived in any case, but we observe a mean attenuation of 2.3 dB between the amplitude of the fundamental frequency, measured at 504 Hz, without and with M1. Although the sounds produced by the guitar are indistinguishable, we can see these changes in the frequency spectra. These preliminary results seem promising for future explorations that will allow us to change the timbre of musical instruments using metamaterials.

Conclusion

Our main result is that we can measure band gaps, between 300 Hz and 1000 Hz (audible regime), in soft, 2D periodic structures called mechanical metamaterials, which depend on their deformation level. In addition, we present preliminary measurements of the effect of attaching a metamaterial to the sound box of an acoustic guitar. Through a frequency analysis we show that although we cannot hear the effects of band attenuation, we can see them. Tunable mechanical metamaterials can be used as a tool to create mechanical filters that allow us to expand the acoustical properties of musical instruments, modifying their tonal qualities, in a dynamical and reversible way.

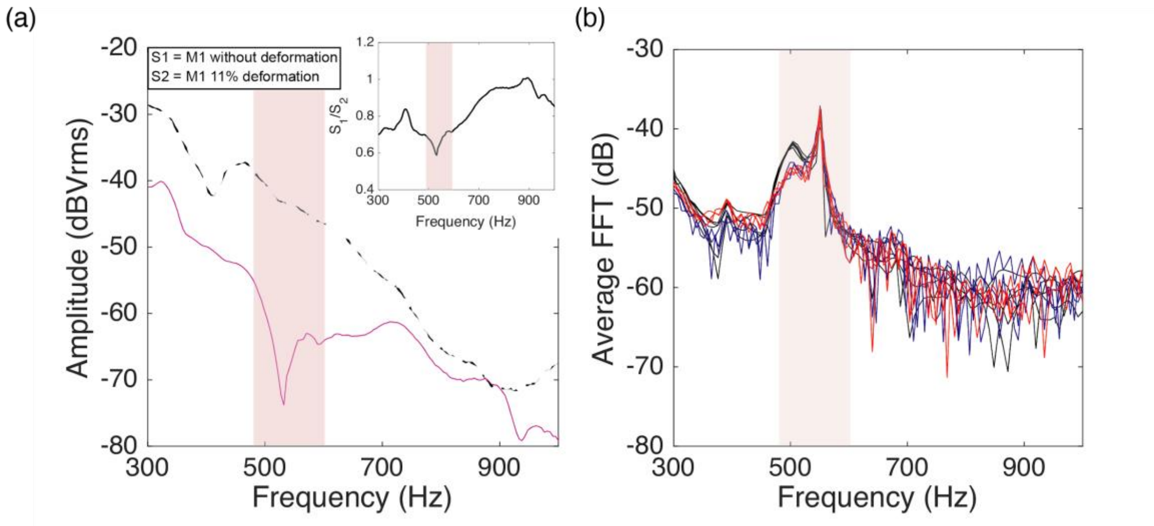

Figure 4: (a) Power spectrum for M1 without deformation (S1, black dashed line) and with deformation of 11% (S2, pink line). Frequency response presents a band gap around 530 Hz. (b) Fast Fourier transform average of of the sound signal produced by the acoustic guitar. A string tuned in 500 Hz was plucked: (black lines) without M1 coupled to its resonance box, (red lines) with 11% deformed M1 coupled in A position, (blue lines) with 11% deformed M1 coupled in B position. Each measurement was performed five times.

Acknowledgments

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