Seeking for spectral manipulation of the sound of musical instruments using metamaterials

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ABSTRACT

The sound of practically all traditional musical instruments is unique and depends on the collective behavior of various vibrators, each one with their own acoustic and mechanical properties. If we pluck a string of an acoustic guitar, a part of the wave is reflected by the sound box, and the other fraction of the elastic energy sets in motion the sound box surfaces. Thereby, the vibration of the surfaces (soundboard, ribs, back and sound hole), are the basis of the guitar sound production.

In this work, we explore the effect of locally coupling tunable mechanical metamaterials to the soundboard of an acoustic guitar, in order to absorb specific ranges of frequencies and change its vibrational properties. We show the preliminary results of our research, which involves a mechano-acoustic characterization of tunable mechanical metamaterials and the analysis of the effect of applying them to an acoustic guitar when a string tuned to a convenient frequency is plucked. We observe that this simple mechanism is an alternative to manipulate the spectral properties of the sound signal produced by the instrument. Although the results are inaudible, they seem promising for future explorations of sound manipulation of musical instruments.

CCS CONCEPTS

• **General and reference → General conference proceedings**.

KEYWORDS

acoustic, musical instruments, new materials, sonic interaction design

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1 INTRODUCTION

Musical instruments are complex acoustic systems, and their sound production depends on the collective behavior of several vibrators [4, 9]. When we play an acoustic guitar, the entire guitar body vibrates: strings, top plate, air cavity, ribs, sound hole, back plate. Each one contributes to the qualities of the resulting sound, and the importance of this contribution relies heavily on their mechanical properties, defining their resonant frequencies and normal modes.

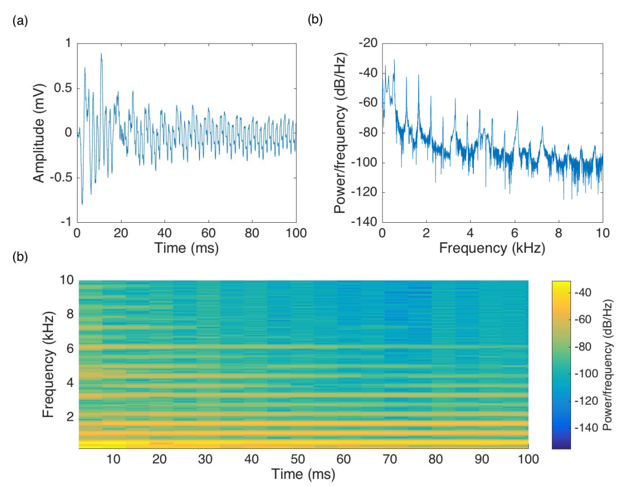

Figure 1: (a) Audio signal $x(t)$ produced by a plucked string tuned to 554 Hz. (b) Power spectral density of $x(t)$. (c) Spectrogram of $x(t)$.

In figure 1 we observe different properties of the sound produced by a plucked string tuned to 554 Hz (note $C_5^{\#}$). Panel (a) shows the audio signal $x(t)$. The amplitude gives us information about the sound pressure and how it changes over time. In terms of sound quality, the signal provides information about the loudness, attack, decay, sustain and release of the sound. Information on the frequency domain is not provided. Figure 1 (b) shows the power spectral density of $x(t)$ between 20 Hz and 10 kHz. It is related with the distribution of power into the frequency components of the signal. The strongest peak corresponds to the fundamental frequency, associated with the pitch of the perceived sound. Finally, panel (c) shows the spectrogram of $x(t)$, and gives us information about the evolution of the frequency components over time. These components, like the fundamental and subsequent harmonics that are present in the first instant in the sound, disappear at different times. The amplitude of each component defines its degree of *presence*, and the decay over time defines its *persistence*. The presence and persistence of frequency components determine the timbre of the musical instruments [2].

Our main goal is to alter specific spectral properties of the sound of musical instruments. In this work we focus on changing the presence of certain spectral content of the plucked string sound, through a simple and reversible mechanical manipulation of the sound box. This manipulation involves coupling a tunable mechanical metamaterial to the soundboard of the guitar in order to absorb a specific range of frequencies of the mechanical waves traveling through it.

2 TUNABLE MECHANICAL METAMATERIALS

Mechanical metamaterials are rationally designed composites aiming at effective material parameters that go beyond those of their ingredients [7]. Some of them allow the manipulation of the dispersive properties of the mechanical waves that travel along them. [1, 3]. The idea to use mechanical metamateriales to manipulate sounds has been recently applied in composing spatial soundscapes [5], but its implementation manipulating the sound source has hardly been studied, and that is the problem that we want to tackle.

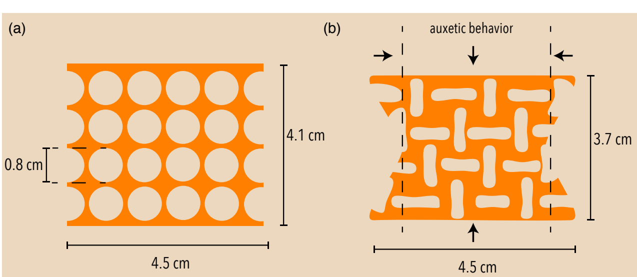

Figure 2: (a) Used mechanical metamaterials: squared arrays of circular holes in an elastomer matrix. (b) Metamaterial with a deformation of 11%: during the compression, the square array of circular holes is transformed upon reaching a critical deformation, into a periodic pattern of alternating, mutually orthogonal, ellipses [1].

We use mechanical metamaterials with the structure presented in figure 2 (a), i.e. arrays of circular holes in an elastomer matrix. These metamaterials exhibit auxetic behavior with a negative Poisson's ratio. It means that when the structure is compressed in the axial direction, it shrinks in the transverse direction, in contrast with typical materials (see figure 2 (b)) [1, 6]. This kind of mechanical metamaterial presents frequency band gaps (ranges of frequencies with no vibrational transmission), which can be tuned by mechanical deformation.

The elastomeric matrix exhibits strong material nonlinearities, and therefore applied deformation induces a significant stiffening effect, providing a tool to tune the position and width of the band gaps [1, 11]. Adjusting the stiffness by different levels of mechanical deformation, gives us a simple way to make tunable mechanical pass-band filters that, by eliminating the stress that causes the deformation, recover their initial periodic structure. It means that we have a reversible and repeatable tuning process.

3 METAMATERIAL MECHANO-ACOUSTIC CHARACTERIZATION

The mechanical metamaterial used is based on existing models [8, 10]. We make a sample, labeled as M1, with the geometry shown in figure 2: an array of 5x4 circular holes of 8 mm of diameter in a elastomer matrix made of silicone Elite Double 22 Fast (Young's modulus $E = 0.8$ MPa and density $\rho = 1160$ kg/m^3), with a thickness of 5 mm.

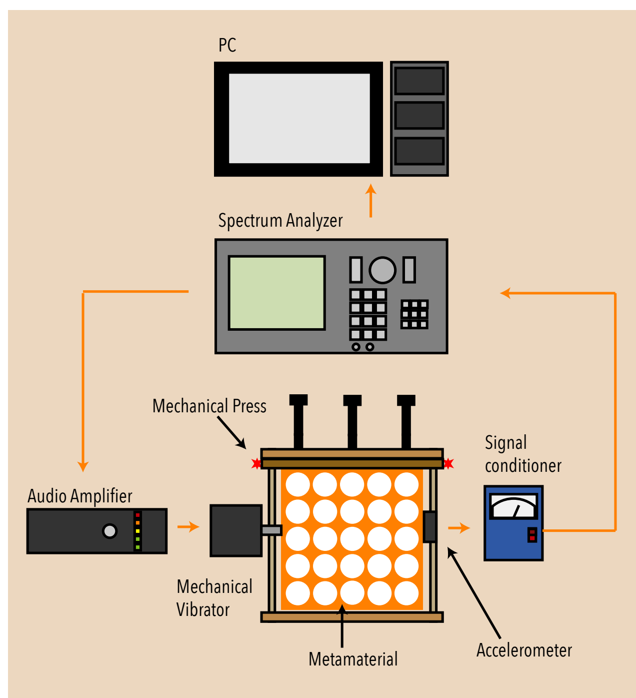

Figure 3: Experimental setup used to obtain power spectrum of mechanical metamaterials under deformation.

In order to obtain its frequency response, the metamaterial is compressed at different levels while a mechanical excitation is performed, using the experimental setup described in figure 3. 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.

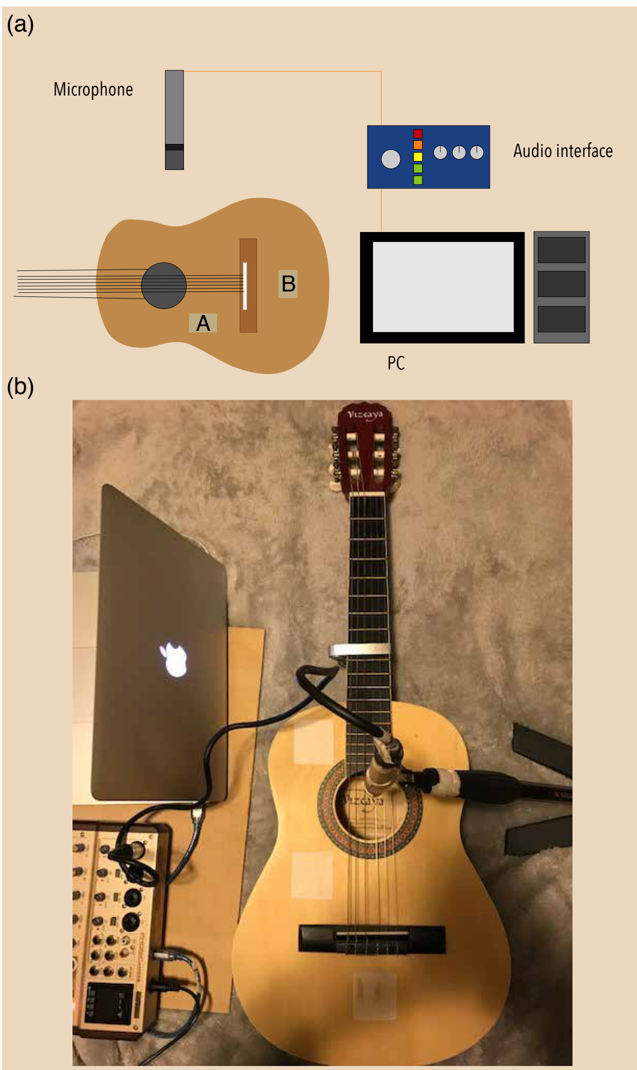

Figure 4: (a) Schematic of the experimental setup used for acoustic characterization of the influence of the metamaterial coupled to the sound box of an acoustic guitar. (b) Setup photography

4 METAMATERIAL APPLICATION

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 through a coupling gel, using the setup described in figure 4 to obtain and analyze its acoustic behavior. A string tuned to a convenient frequency is plucked, with and without the M1 sample coupled to the soundboard at different positions, and the sound is recorded for frequency analysis. A pencil condenser microphone Samson C02, with a sensitivity of 10 mV/Pa, and a Steinberg UR44 interface were used to perform the experiment. The metamaterial was coupled in positions A and B (see figure 4 (a)). Each measurement was performed five times in equal conditions.

5 RESULTS

Figure 5 (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 presents the ratio S1/S2.

In figure 5 (b) we observe the power spectral density of the sound signals produced by the acoustic guitar. The plucked string was

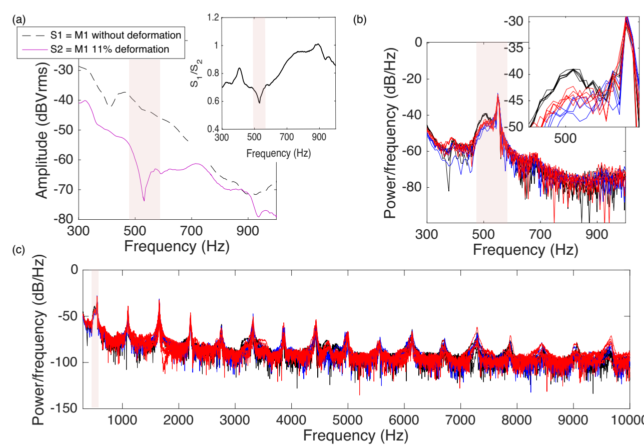

Figure 5: (a) Power spectral density for M1 response without deformation (S1, black dashed line) and with deformation of 11% (S2, pink line). Frequency response presents a band gap around 530 Hz. The insert figure presents the ratio S1/S2. (b) Power spectral density of the sound signal produced by the acoustic guitar. A string tuned to 554 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. The insert figure shows a zoom of the damped range. (c) Power spectral density of the sound signal produced by the acoustic guitar between 20 Hz and 10 kHz.

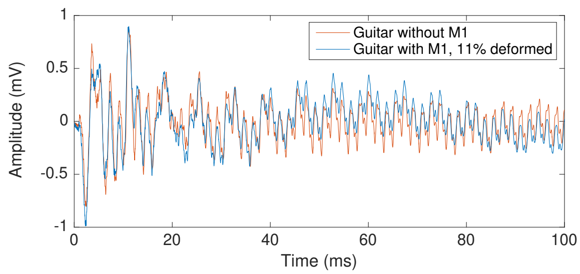

Figure 6: Example of audio signals of the sound produced by plucking the string without (orange line) and with (blue line) the M1 sample coupled to the guitar soundboard.

tuned in 554 Hz (approximately the frequency of the musical note $C_5^{\#}$). Black lines correspond to the results without coupling the M1 sample. Red lines are the results of the signals produced with M1 coupled in A position, with a deformation of 11%. Blue lines are the same case than red ones, but with M1 positioned in B. Each measurement was performed five times. A mean attenuation of 2.3 dB between the amplitude of the frequency measured around 554 Hz, without and with M1, was measured. Finally, figure 5 (c) shows the power spectral density of the sound produced by the guitar between 20 Hz and 10 kHz. We can observe that the effect of attenuation affects the frequency range around the measured band gap, and that it is not a general effect of damping. In figure 6, an example of signals of the sound produced without (orange line) and with (blue line) the M1 sample coupled to the guitar soundboard are shown. No changes in amplitude are observed.

Although the sounds produced by the guitar with and without metamaterial are indistinguishable, we can see these changes in the spectra originated by locally coupling to their soundboard a mechanical metamaterial. This means that this simple mechanism can be used to manipulate the frequency properties of a sound source. These preliminary results seem promising for future explorations that will allow us to change the timbre of musical instruments using metamaterials.

6 CONCLUSION

In this work, we have performed a mechano-acoustic characterization of a tunable mechanical metamaterial sample. We have measured a band gap in the deformed metamaterial and applied it to the soundboard of an acoustic guitar in order to observe their effect in the guitar sound production. Although the sounds produced by the guitar without and with the metamaterial were indistinguishable, we observed these changes in the spectra. These preliminary results are the first step to alter specific spectral properties, as the presence of a frequency component of a sound.

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