Characterization of biphasic architectured media towards ultrasound monitoring applications

M Gattin, N Bochud, G Rosi, Q Grossman, D Ruffoni, S Naili

Characterization of biphasic architectured media towards ultrasound monitoring applications

M. Gattin[1], **N. Bochud**[1], **G. Rosi**[1], **Q. Grossman**[2], **D. Ruffoni**[2], **and S. Naili**[1]

1. *Univ Paris Est Creteil, Univ Gustave Eiffel, CNRS, UMR 8208, MSME, F-94010 Créteil, France*
max.gattin@u-pec.fr, nicolas.bochud@u-pec.fr, giuseppe.rosi@u-pec.fr, naili@u-pec.fr
2. *Mechanics of Biological and Bioinspired Materials Laboratory, Department of Aerospace and Mechanical Engineering, University of Liège, Quartier Polytech 1, Allée de la Découverte 9, B-4000 Liège, Belgium*
quentin.grossman@uliege.be, druffoni@uliege.be

Abstract: Multi-material additive manufacturing is receiving growing attention in the field of acoustics, in particular for the design of micro-architectured periodic media used to obtain programmable ultrasonic responses. In this context, there is a need to develop wave propagation models to predict and optimize the impact of both the material properties and the spatial arrangement of the printed constituents. This work aims to investigate the transmission of longitudinal ultrasonic waves through periodic biphasic media that display viscoelastic constituent material properties. Thereby, we apply Bloch-Floquet analysis to unravel the relative contributions of viscoelasticity and periodicity on ultrasonic signatures, such as dispersion, attenuation, and bandgap characteristics. The impact of the finite size of such structures is also assessed by comparing the results from Bloch-Floquet analysis to those obtained using a transfer matrix formalism. The modelling outcomes, expressed in terms of frequency-dependent phase velocity and attenuation, are finally compared with experiments carried out on 3D-printed samples, which exhibit a 1D or 2D periodicity at a few hundred of micrometres length-scale. Altogether, the results provide insights into the modelling characteristics that must be accounted for to accurately predict the complex acoustic behaviour of periodic media in the ultrasonic regime.

Biological tissues are inherently heterogeneous materials with a multiscale hierarchical organization[1], whose singular properties are extremely difficult to replicate. From a mechanical viewpoint, their outstanding properties at the tissue scale are hypothesized to result from the combination of two main factors[2]: (i) the contribution of multiple constituent materials (soft and rigid) and (ii) the presence of a structural organization (periodic microstructure, functional gradients of mechanical properties, etc.). In this context, the rational design of architectured orthopaedic implants possessing an acoustic signature linked to their microstructure could open the way towards the ultrasound monitoring of their integration to the surrounding biological environment. To this end, it is necessary to have a precise knowledge of the acoustic properties of the constitutive media, as well as to accurately model the effect of the microstructure on the ultrasonic signatures.

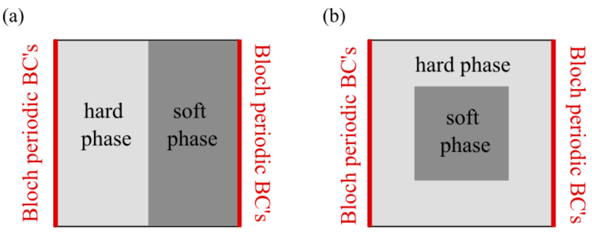

Figure 1: Schematic representation of biphasic (a) 1D unit cell, and (b) 2D unit cell.

In this work, we investigate the capability of multi-material 3D printing (*polyjet* technology) to design micro-architectured periodic media with programmable ultrasonic responses in a controlled laboratory environment. Our study focuses on simplified periodic structures made of 1D or 2D unit cells (see Fig. 1) to disentangle the roles played by viscoelasticity, finite size nature of the sample, and periodicity on the modelled ultrasonic responses. In a former study by our group[3], the viscoelastic properties of the constituent materials (soft and hard phases) were shown to exhibit dispersive losses, which could be described using a frequency power law

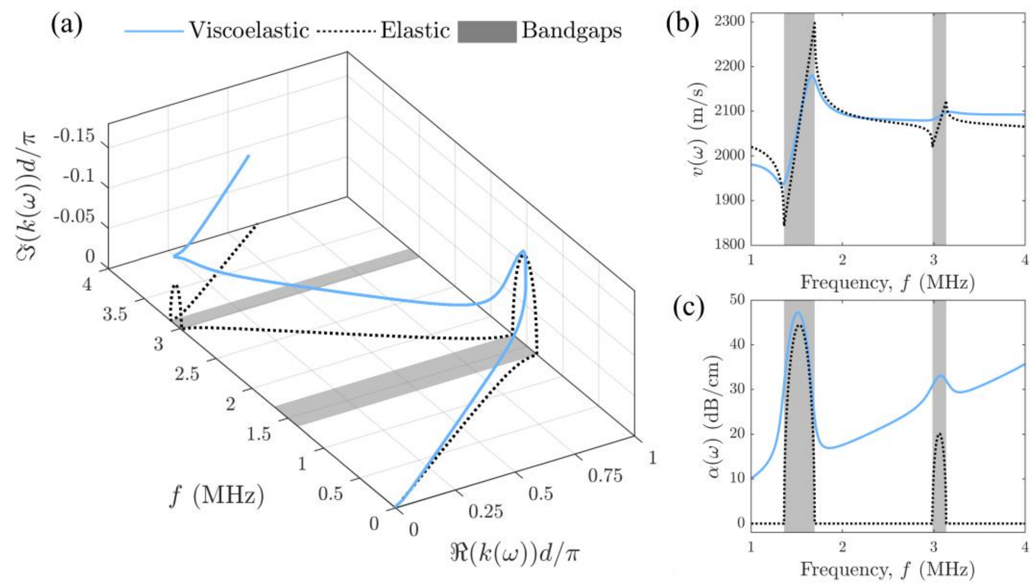

Figure 2: Normalized dispersion curve for an infinite 1D-periodic medium, displayed for the pure elastic (dotted black lines) and viscoelastic (continuous light blue lines) cases: (a) Complex Bloch wave number $k(\omega)$ as a function of the frequency f in the first Brillouin zone; (b) phase velocity $v(\omega)$; and (c) attenuation $\alpha(\omega)$. The light grey areas display the positions and widths of the bandgaps for the elastic case.

model[4]. The reported properties are here used to feed models of the transmission of longitudinal ultrasound waves through periodic biphasic samples. Applying Bloch-Floquet analysis to a 677 µm-thick 1D unit cell with either elastic or viscoelastic constituent materials allows recovering the dispersion curves and the corresponding phase velocities and attenuations depicted in Fig. 2, which underline the significant differences between the pure elastic and viscoelastic cases[5]. The impact of the finite size nature of these structures is then assessed by using a modelling approach based on the transfer matrix formalism. To serve as an example, Fig. 3 shows the comparison between the frequency-dependent phase velocities and attenuations derived from both modelling approaches, as well as an experimental validation for a 3D-printed sample consisting of 12 replicated 1D unit cells. As Bloch-Floquet analysis is valid for an infinite medium only, it fails in accurately capturing the variations of the ultrasonic characteristics when the number of unit cells is low. Similar evidences, which are not shown here for the sake of conciseness, were also observed for measurements performed on samples made of 2D unit cells. Altogether, the reported findings provide a basis for future research towards the development of ultrasound monitoring techniques for periodic biomaterials with more complex geometric topologies, such as scaffolds used in orthopaedic applications.

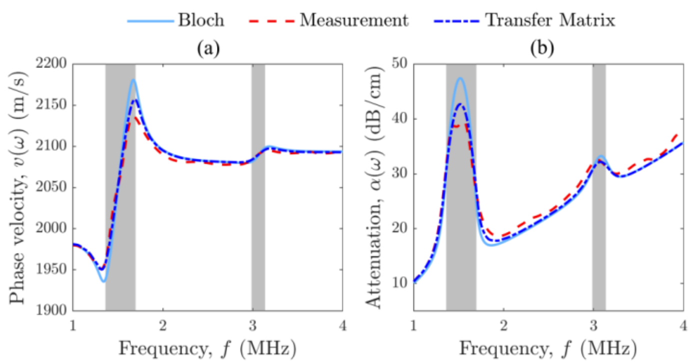

Figure 3: Ultrasound characteristics obtained using Bloch-Floquet analysis (continuous light blue lines), the transfer matrix formalism (dotted blue lines), and measurements (dashed red lines): (a) Phase velocity $v(\omega)$ and (b) attenuation $\alpha(\omega)$.

References

[1] P. Fratzl and R. Weinkamer, *Prog. Mater. Sci.*, **52(8)**, 1263–1334 (2007).
[2] A. A. Zadpoor, *Biomater. Sci.*, ***8*(1)**, 18–38 (2020).
[3] M. Gattin, N. Bochud, G. Rosi, Q. Grossman, D. Ruffoni, and S. Naili, *J. Acoust. Soc. Am.*, ***152*(3)**, 1901–1912 (2022)
[4] T. L. Szabo and J. Wu, J., *J. Acoust. Soc. Am*., **107(5)**, 2437–2446 (2000).
[5] M. Gattin, N. Bochud, G. Rosi, Q. Grossman, D. Ruffoni, and S. Naili, *Ultrasonics*, **131**, 106951 (2023).