A tunable architectured core material exhibiting auxetic behaviour for sound transmission control

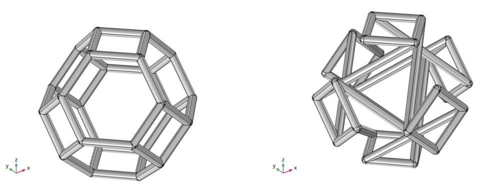
H. Mao[1,2], R. Rumpler[1,2], M. Gaborit[1,2], P. Göransson[1,2]

[1]The Marcus Wallenberg Laboratory for Sound and Vibration Research (MWL), Department of Engineering Mechanics, KTH Royal Institute of Technology, SE-100 44, Stockholm, Sweden
[2]The Centre for ECO2 Vehicle Design, SE-100 44 Stockholm, Sweden

Metamaterials, exhibiting exotic properties by artificial geometry design, have received increasing attention in the past decades. In this contribution, a tunable mechanical metamaterial exhibiting three-dimensional (3D) auxetic (negative Poisson's ratio) properties is proposed. The negative Poisson's ratio arises from the chirality of the cellular microstructures, which also leads to anisotropic elastic material properties to be characterised by an inverse estimation method developed by the authors. The results show that the anisotropic mechanical properties and the Poisson's ratios in all three dimensions are tunable by simply adjusting the cellular geometry. These adjustable properties offer broad potential for applications in the fields of sensors, tissue engineering, or vibro-acoustics. The paper mainly illustrates an application on sound transmission loss of a sandwich panel in the low frequency range. The simulated results highlight the potential of the proposed approach to control the design of structures with exceptional noise insulation properties.

1 3D auxetic cell and material modelling

An isometric Kelvin cell (KC) arrangement exhibiting cubic material symmetry is chosen as the reference micro-structure, see Fig. 1a. The geometrical modifications applied to the reference KC geometry are in the form of rigid body rotations of the square faces, while keeping these square undeformed during the rotation [2]. Fig. 1b shows an auxetic cell generated from twisting all six square faces with an angle of 90°. Topologically, the cell is not modified and all vertices remain connected through the same struts (with altered lengths) as in the KC geometry. The rotational angles applied on each pair of square faces are anti-symmetric, *i.e.* rotated with opposite angles, equal in absolute value. The twisted cell exhibits chirality with respect to each middle plane parallel to the pairs of twisted faces, see Fig. 1b. When a load is applied to the chiral structure, the non-centered force or non-affine deformation induce auxetic behavior where the lateral squares from any chosen pair of squares contract laterally under compression of the cell applied to the chosen pair.
The anisotropic elastic material properties associated with this KC geometry with rotated faces are characterised by an inverse estimation method developed by the authors [3]. The corresponding results show that the estimated Poisson's ratio of the twisted cell vary as a function of the twisting angle and geometry size. A negative Poisson's ratio is found for a twisting angle in the range $35° - 90°$ when twisting all six square faces anti-symmetrically with a same angle.



(a) (b)

Figure 1: a) Kelvin cell, b) twisted auxetic cell (90°).

2 Applications: an example in vibro-acoustics

In connection with the specific auxetic and chiral properties previously introduced, multiple applications are currently under study. Here we focus on an application in vibro-acoustics for sound insulation purposes, focusing on the sound transmission loss of a sandwich panel with a KC-based structural foam as core material. Fig. 2 shows three mode shapes of the auxetic single cell, which might be interesting for vibro-acoustics purposes. Fig. 2a shows a spring-mass-like functional mode shape which may be introduced to exhibit an internal-resonator-like behaviour, previously studied to design metamaterial sandwich structures for noise insulation purposes [1]. Fig. 2b shows an extension-torsion coupled mode shape, which may generate strong local damping effects. Fig. 2c shows the unit cell auxetic behaviour due to the chiral torsional effect under compression.

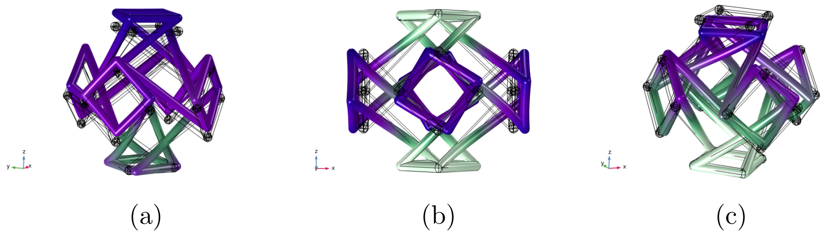


Figure 2: Selected interesting mode shapes of a single twisted cell: a) a spring-mass-like system, b) extension-torsion coupling in transverse direction, c) chiral torsional mode shape with auxetic effect.

Introducing such structural foams as a core material, Fig. 3a shows the finite element model of a metamaterial, periodic sandwich plate with infinite lateral dimensions. A cellular array consisting of two auxetic cells in the thickness are assembled as a meta-structure core material of the sandwich plate. Fig. 3b illustrate the resulting trend of the STL in the frequency range up to 5000 Hz. The case without internal resonator is plotted in solid line, and the potential associated with the addition of the Kelvin Cell array corresponds to the dashed line. The coincidence region is clearly visible on the reference calculation without the cellular array. A tuned cell array offers the possibility to imrove the STL in this region, at the expense of an additional deep, which itself may be mitigated by a specifically tuned resonator. Such configurations will be further demonstrated by controlling microstructure properties such as twisting angles, size and material properties of the struts.

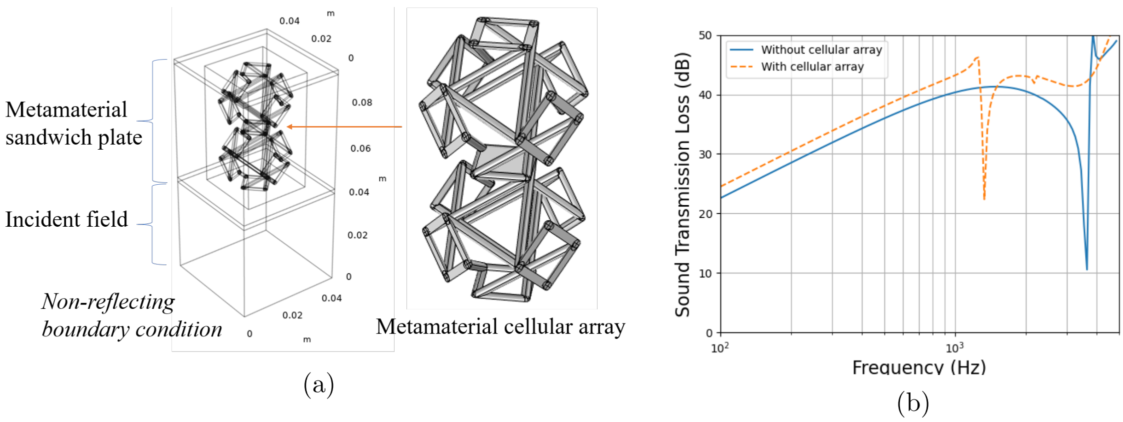


Figure 3: The finite element model of the metamaterial sandwich plate, b) Sound transmission loss (STL) of the metamaterial single-layer plate.

References

[1] Zibo Liu, Romain Rumpler, and Leping Feng. Broadband locally resonant metamaterial sandwich plate for improved noise insulation in the coincidence region. *Composite structures*, 200:165–172, 2018.

[2] Huina Mao, Romain Rumpler, Mathieu Gaborit, Peter Göransson, John Kennedy, Daragh O'Connor, Daniel Trimble, and Henry Rice. Twist, tilt and stretch: From isometric kelvin cells to anisotropic cellular materials. *Materials & Design*, 193:108855, 2020.

[3] Huina Mao, Romain Rumpler, and Peter Göransson. An inverse method for characterisation of the static elastic Hooke's tensors of solid frame of anisotropic open-cell materials. *International Journal of Engineering Science*, 147:103198, 2020.