Acoustic Metamaterials Memo for Term Project

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Topic

Using finite element methods, we will replicate a 2D acoustic metamaterial that hosts a Dirac-like cone, a feature in the dispersion relation that induces a simultaneously vanishing compressibility and density (a so-called "double-zero" metamaterial).

Specifically, we will replicate the results described in "Observation of acoustic Dirac-like cone and double zero refractive index," which reports "the first experimental realization of an impedance matched acoustic double zero refractive index material."[1]

We will discuss the significance of the Dirac cone,[2] drawing parallels between relativistic quantum mechanics[3] and acoustics. We will summarize perspectives presented by the condensed-matter physics community[4567] and interpret these perspectives in the context of acoustics.[8] We will also discuss the potential applications and future directions of double-zero acoustic metamaterials.[91011]

In addition to replicating the results of this paper and discussing the significance of its findings, we will explore the manufacturing limitations involved in production and determine a range of errors under which the Dirac cone can still be observed. We will also qualitatively (and numerically, time permitting) discuss how changing the unit cell geometry of the metamaterial alters the Dirac cone and double-zero properties.

Work distribution

C.G. will derive the dispersion relation[12] and numerically find the frequency at which the metamaterial hosts double-zero properties. C.G. will write the introduction and discussion, which will draw parallels between quantum mechanics and acoustics. C.G. will also discuss the potential applications and future directions of this technology.

R.W. has modeled the metamaterial's physical structure in SolidWorks and will import the model into COMSOL. R.W. will explore the manufacturing limitations/errors involved in production and determine a range of errors under which the Dirac cone can still be observed.

R.W. and A.N. will run the simulations in COMSOL. R.W. and A.N will calculate the transmission coefficient at a range of frequencies and compare to figure (2f) in the paper. R.W. and A.N. will replicate the Dirac cone structure at various frequencies and compare to figure (4a). A.N. will explore how changing the unit cell geometry of the metamaterial alters the Dirac cone and double-zero properties.

Logistics & Timeline

We will use **GitHub** for code and **Overleaf** for the report.

- 11/06: C.G. derives dispersion relation; R.W. imports geometry into COMSOL.
- 11/13: C.G. replicates figures (2a) & (2b) and identifies Dirac point frequency; R.W., A.N. replicate figure (2f).
- 11/20: R.W., A.N. replicate figure (4). A.N. explores different geometries.
- 11/27: C.G. completes QM $\Leftrightarrow$ acoustics discussion; R.W. explores limits.
- 12/4: C.G. completes discussion on potential application & future directions.
- 12/11: Term paper is completed; A.N., C.G., R.W. practice presentation.
- 12/14: A.N., C.G., R.W. present to class and submit report on Canvas.

Potential obstacles

C.G. may need help deriving the 2D dispersion relation and identifying the Dirac point. As a group, we do not understanding figure (3) in the paper; is this something we should replicate? Should we also attempt to replicate Supplementary Movies 1-3?

Notes

[1]Dubois, M., Shi, C. Zhu, X., Wang, Y., Zhang, X. Observation of acoustic Dirac-like cone and double zero refractive index. *Nature Communications.* 8,14871 (2017).

[2]Geim, A., Novoselov, K. The rise of graphene. *Nature Mater* **6**, 183–191 (2007).

[3]Dirac, Paul A.M. *Principles of Quantum Mechanics.* International Series of Monographs on Physics (4th ed.). *Oxford University Press* (1958).

[4]Huang, X., Lai, Y., Hang, Z. H., Zheng, H. Chan, C. T. Dirac cones induced by accidental degeneracy in photonic crystals and zero-refractive-index materials. *Nat. Mater.* **10**, 582–586 (2011).

[5]Liu, F., Huang, X. Chan, C. T. Dirac cones at $k = 0$ in acoustic crystals and zero refractive index acoustic materials. *Appl. Phys. Lett.* **100**, 071911 (2012).

[6]Moitra, P. et al. Realization of an all-dielectric zero-index optical metamaterial. *Nat. Photon.* **7**, 791–795 (2013).

[7]Li, Y. et al. On-chip zero-index metamaterials. *Nat. Photon.* **9**, 738–742 (2015).

[8]Nassar, H., Yousefzadeh, B., Fleury, R. *et al.* Nonreciprocity in acoustic and elastic materials. *Nat Rev Mater* **5**, 667–685 (2020).

[9]Xinxin Yan, Wei Wei, Ni Hu, Fengming Liu, Splitting of acoustic energy by zero index metamaterials, *Physics Letters A*, 2147-2149 (2015).

[10]Zhao, W., Yang, Y., Tao, Z., Zhi, H. H. Tunable transmission and deterministic interface states in double-zero-index acoustic metamaterials. *Scientific Reports (Nature Publisher Group)* **8**, 1-9 (2018).

[11]Wang, X.; Luo X., *et al.* Acoustic perfect absorption and broadband insulation achieved

by double-zero metamaterials. *Appl. Phys. Lett.* **112**, 021901 (2018).

[12]The supplementary information includes important derivations and details about the experiment.