Active acoustic metamaterials

Xulong Wang (王绪隆) [1,2], Guancong Ma (马冠聪) [1, 3†]

[1]Department of Physics, Hong Kong Baptist University, Kowloon Tong, Hong Kong, China
[2]Department of Physics, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[3]Shenzhen Institute for Research and Continuing Education, Hong Kong Baptist University, Shenzhen 518000, China

[†] Corresponding Email: phgcma@hkbu.edu.hk

Keywords: acoustics, acoustic metamaterials, active control

The history of acoustic metamaterials can be traced back to the turn of the 21st century, when local resonances of subwavelength structures were leveraged for acoustic properties unavailable in natural materials [1]. Over a quarter of a century, acoustic metamaterials have continued to thrive as numerous novel acoustic effects were explored and realized [2–6]. However, acoustic metamaterials were entirely passive in the early days, meaning that their functionalities were singular and were entirely determined at the fabrication stage. In addition, even at the effective-medium level, such passive metamaterials must obey fundamental laws such as time-reversal symmetry and causality. These limitations are overcome by employing active components in the metamaterials design. In this perspective, we survey the development, functionalities, and implications of active acoustic metamaterials.

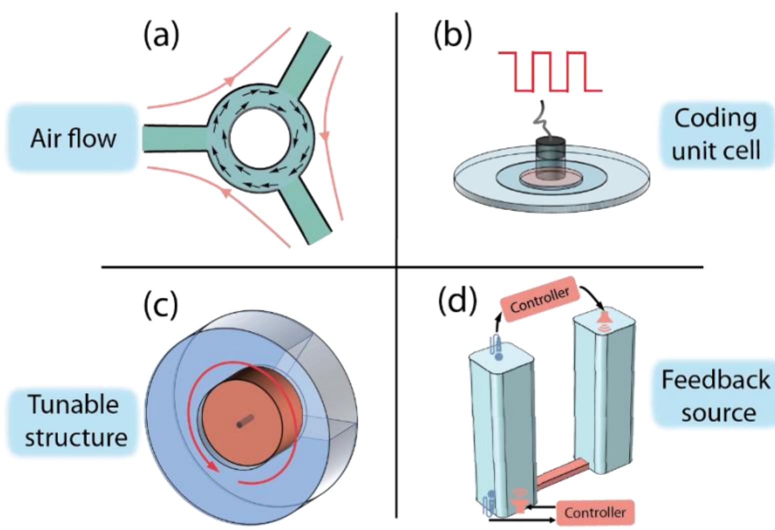

Fig. 1. Methods of active control in acoustic metamaterials. (a) Circulating airflow that breaks reciprocity in an acoustic cavity [8]. (b, c) Alternation of resonances via programmable electrical components, e.g., electromagnets [34] (b) and motorized structures [36] (c). (d) Programmable acoustic feedback [57].

Non-reciprocity via moving media

Linear time-invariant acoustic systems are time-reversal invariant and, therefore, obey reciprocity. This characteristic can be disrupted through the incorporation of moving media, which introduces the Doppler effect and breaks time-reversal symmetry [7]. A notable demonstration of this principle is the acoustic circulator, an annular acoustic resonator with a constant circulating airflow [8]. The cavity sustains two degenerate acoustic modes that are counter-propagating traveling waves. The presence of circulating airflow introduces the Doppler effect, raising (lowering) the resonant frequency of the mode traveling with (against) the airflow. This device functions as a three-port isolator and demonstrates non-reciprocal transmission among the ports. By modulating the hybrid junctions in a ring resonator, various non-reciprocal couplers, including rat-race couplers [9], can be effectively implemented. Besides, the moving media (airflow) can be modeled as a static external magnetic field in the wave equation. This analogy offers essential insights that link to the quantum Hall effect, which subsequently inspired a series of early adaptations of topological insulators in acoustics [10–12], which was later experimentally confirmed [13].

Non-reciprocity induced by moving media has also become a productive approach for many innovative acoustic effects. Geometrically asymmetric structures introduce Willis coupling, which respects reciprocity and time reversal. Airflow can break time-reversal symmetry, enabling odd Willis coupling and non-reciprocal metagratings [14]. Furthermore, a resonant unit cell with a rotating inner core generates a bias through circulating fluid, allowing decoupled phase modulations. This approach could enable Janus acoustic metascreens [15]. Collectively, the foregoing studies illuminate new pathways for compact asymmetric sound wave engineering, with applications in biomedical imaging, sonar technology, and wavefront engineering rooted in the principles of pressure-velocity coupling.

Actively tunable acoustic resonances enabling reconfigurable and programmable metamaterials and metasurfaces

Although acoustic metamaterials and metasurfaces greatly expanded our wave-controlling capability, they cannot be altered after fabrication in the early days. In contrast to the interferences between acoustic modes in a ring resonator influenced by airflow, the active tuning of resonant units provides a more direct method for wave manipulation. The incorporation of active reconfigurability or programmability is a game changer, which not only enhances the adaptability of the designs but also opens unprecedented possibilities for sound control. Active metamaterials transcend material-based limitations by incorporating electronically controlled elements that afford precise manipulation of their acoustic characteristics [16–18]. Consequently, they exhibit a broad spectrum of effective parameters, showcasing their enhanced versatility and functionality. An initial experimental endeavor involved the integration of transducers and electronic circuits, which were designed to achieve negative refraction, negative effective mass density, bulk modulus, etc. [16] The coupling of sensing and driving transducers, along with the incorporation of electronic feedback loops, enabled the realization of advanced functionalities. Furthermore, the development of compact active meta-atoms has demonstrated adaptability and potential for novel applications, and the incorporation of additional feedback control mechanisms has introduced a new approach to achieving acoustic nonreciprocal transmission [19,20]. Subsequently, researchers shifted their focus to the programmability of resonant unit structures. The development of programmable and coded acoustic metasurfaces has demonstrated remarkable adaptability in sound manipulation, proving to be instrumental in the modulation of both wavefront phase and amplitude [21–25]. By incorporating tunable structures capable of operating across a wide frequency, researchers have expanded the novel functionalities of acoustic metamaterials, such as continuous steering of acoustic beams, precise modulation of acoustic energy flow, etc. [26–31] A notable example of this capability is the fine-tuning of acoustic cavity volumes, which enables precise and continuous control over the phase of acoustic waves transmitted through the associated metasurface. Such versatility permits a single sample to perform a variety of functions, including the adjustment of focal distances, the redirection of beam trajectories, and the generation of tweezer-like beams [32]. Another significant example is the integration of programmable circuits to modulate the unit cell configuration in phononic crystals, which facilitates the realization of reconfigurable topological edge states. This advancement substantially broadens the scope of applications for topological states [33,34].

Actively reconfigurable metasurfaces also play an essential role in extending the concept of adaptive wavefront shaping, a powerful technology for controlling multiple scattering light, to acoustics. The central component of adaptive wavefront shaping is an optical device called a spatial light modulator. A spatial light modulator is usually a liquid crystal array with individually controllable pixels, each capable of modulating the phase and/or the amplitude of the transmitted light. Spatial light modulators are commercially available, ready-to-use devices. However, the equivalent acoustic technology did not exist until actively reconfigurable metasurfaces emerged. Two examples of acoustic metasurfaces include those based on piezoelectric sheets and membrane resonators. The former employs thin piezoelectric sensors to create a flexible active array [35,36], enabling precise sound field control and promising applications in ultrasound diagnostics, therapy, and underwater communications. The latter utilizes electromagnets to switch membrane-type resonators between distinct resonant modes, thereby enabling the modulation of the transmitted sound wave's phase between 0 to π. Metasurfaces with hundreds of individually controllable resonator units controlled by a feedback-driven optimization protocol demonstrated that the reverberant sound field in a room can be locally shaped to generate quiet zones or hotspots [37]. Later, it was shown that the approach can even alter the room's impulse response, leading to the successful control of the spatiotemporal profile of the sound field [38]. Recently, reflection-type metasurfaces based on tunable Helmholtz resonators with electrically variable volumes have been used to further expand the functionality of complex sound field control by demonstrating crosstalk-free acoustic communications in a room [39].

Time modulation

While active or programmable acoustic metamaterials significantly expand the horizons of acoustic wave physics, the pursuit of novel wave–matter interactions has sparked a growing interest in exploring time as a new degree of freedom within metamaterials. Recent investigations into wave phenomena in the time domain have revealed a wealth of intriguing physical effects, facilitated by the application of explicit temporal modulations to the parameters of physical systems. Recent research notably draws parallels between temporal controlled acoustic resonance structures and tight-binding models in condensed matter physics. The realization of acoustic non-Abelian braiding and logic gate operations has been achieved through the implementation of flexible circuit designs that support adiabatic evolution [40]. Analogous to the concept of stimulated Raman adiabatic passage, these studies demonstrate robust and complete acoustic energy transfer along with non-reciprocal frequency conversion properties across different sites [41]. A unique class of strongly localized Floquet π modes has been observed in an acoustic temporal lattice featuring time-varying couplings. These modes are characterized by their gauge independence and can be robustly excited at frequencies within the nontrivial band gap [42]. Furthermore, temporal modulation has emerged as a viable alternative for achieving non-reciprocity. This approach effectively replicates the effects of moving media while mitigating associated drawbacks, such as extraneous noise, and is not limited to fluidic systems. For instance, dynamic adjustments to the bulk modulus in resonant cavity arrays have yielded promising simulation results, with acoustic isolation exceeding 40 dB while concurrently minimizing losses [43]. This approach, which introduces a non-reciprocal effect by modulating cavity volumes to simulate circulating airflow, is also frequency scalable and integrable in subwavelength devices. Subsequent experiments conducted in two coupled acoustic cavities employed a theoretical model based on the time-dependent Schrödinger-type differential equation, demonstrating the capacity for non-reciprocal acoustic transmission. This finding underscores the universality of temporal modulation as a method for achieving non-reciprocity in acoustic transmission [44]. In a waveguide model, an incoming acoustic wave interacts with a rotating elliptical blade, resulting in a scattering wave that undergoes harmonic frequency modulation. This interaction induces a frequency shift in a linear time-varying system. When combined with effective acoustic filtering, this mechanism facilitates unidirectional sound propagation at audible frequencies in two opposing directions [45].

In addition to the aforementioned modulation of mechanical structures, rapid spatiotemporal modulations via actively controlled circuits provide a novel approach for unidirectional amplification and the suppression of scattering. Effective medium theory applied to temporally modulated acoustic metamaterials, along with the temporal averaging of constitutive parameters such as compressibility, density, and Willis coupling terms, will enhance the control of time-varying metamaterials [46,47]. Related experiments have implemented programmable dynamic control of acoustic impedance by spatiotemporally modulating the coupling between an ultrathin membrane and external biasing electromagnetic fields [48]. These experiments demonstrate a range of non-reciprocal mode transitions and steering capabilities for airborne sound waves. Moreover, the breaking of continuous translational symmetry in time introduces an additional dimension in the design of acoustic metamaterials. This development enables the exploration of nonreciprocity, directional amplification, and efficient frequency conversion, among other advanced functionalities.

Non-Hermitian acoustics

Non-Hermitian systems are open systems in which energy exchange with external reservoirs is allowed. The dynamics of such systems do not conserve energy, thereby offering greater freedom for achieving new effects and phenomena that have no counterpart in Hermitian systems [49–51]. However, the realization and control of non-Hermitian effects demand control of energy flow, often in the forms of gain/loss or non-reciprocity, which poses significant experimental challenges across many different realms. Thanks to the development of active acoustics, acoustic-wave systems have become an invaluable platform for studying non-Hermitian physics [52,53].

Active acoustic components driven by feedback circuits are employed to modulate the non-Hermitian parameters of the system. For example, the instantaneous acoustic amplitude and phase measured by a small microphone are used to control the emission of a loudspeaker. The emitted sound can either supplement or counter the intrinsic loss in the system, effectively realizing gain and (additional) loss. This concept was initially demonstrated using invisible acoustic sensors based on parity-time (PT) symmetry, which consist of pairs of electro-acoustic resonators coupled with appropriately designed non-Foster electrical circuits, thereby forming a coherent perfect absorber coupled acoustic device [54]. Further experimental validation of this approach is evidenced by the observation of an exceptional point—a distinct non-Hermitian spectral singularity where two states coalesce at an identical eigenvalue [55]. Another notable example is the experimental realization of a one-way invisibility acoustic cloak, constructed from configurations of gain and lossy acoustic media, capable of concealing objects up to seven times larger than the acoustic wavelength [56]. The experimental approach can also be used to realize non-reciprocal coupling. For example, in a coupled-cavity configuration, the loudspeaker in a cavity can be set up to respond to the acoustic field in a neighboring unit, whereas the reversed response does not exist. This also provides an effective means to achieve long-range, complex-valued, and momentum-resolved couplings. Through the construction of a cavity-tube system, researchers have successfully demonstrated the existence of acoustic non-Hermitian Bloch braids and the topological transition states [57,58]. The experimental realization of non-Hermitian skin effect (NHSE) featuring twist non-Hermitian windings has been successfully demonstrated in acoustic crystals through the design of long-range non-reciprocal couplings [59]. Additionally, the implementation of two-dimensional nonreciprocal acoustic metamaterials has showcased the multi-polar NHSE and hybrid skin-topological effects, facilitating precise localization of sound fields at specific corners and boundaries in a frequency-selective manner [60]. Furthermore, researchers have explored an approach to isolate the intrinsic NHSE from a homogenous background loss [61]. Notably, the experimental observation of extended topological zero modes has been achieved in a one-dimensional non-Hermitian acoustic Su-Schrieffer-Heeger (SSH) model [62]. Consequently, active acoustics offers a convenient and effective avenue for the exploration of non-Hermitian physics. Furthermore, its integration with other forms of interaction, such as nonlinearity [63] and Anderson localization, is expected to foster significant advancements and vigorous development in the future.

Another interesting implementation of acoustic gain is using the thermoacoustic effect in carbon nanotube films. The thermoacoustic effect converts fluctuating Joule heating into sound. Building upon this foundation, a whispering-gallery insulator incorporating a phononic crystal has been developed, demonstrating the ability to support dissipationless topological valley edge states along its interface [64]. Additionally, anti-PT symmetry in an acoustic context has been achieved by introducing gain and loss components to the SSH lattice, providing a valuable platform for exploring topological properties within diverse PT-symmetric phases using sound [65].

Outlook

In summary, through the smart application of a wide range of physical phenomena and a large variety of ingenious designs, active acoustic components have already become an indispensable platform for fundamental physics research and a fertile ground for novel acoustic applications. The continued exploration of active acoustics is anticipated to yield substantial advancements in both theoretical understanding and practical implementations, ultimately broadening the scope and impact of this field.

Reference

[1] Liu Z, Zhang X, Mao Y, Zhu Y Y, Yang Z, Chan C T and Sheng P 2000 *Science* **289** 1734–6
[2] Cummer S A, Christensen J and Alù A 2016 *Nat. Rev. Mater.* **1** 16001
[3] Ma G and Sheng P 2016 *Sci. Adv.* **2** e1501595
[4] Assouar B, Liang B, Wu Y, Li Y, Cheng J-C and Jing Y 2018 *Nat. Rev. Mater.* **3** 460–72
[5] Zangeneh-Nejad F and Fleury R 2019 *Rev. Phys.* **4** 100031
[6] Nassar H, Yousefzadeh B, Fleury R, Ruzzene M, Alù A, Daraio C, Norris A N, Huang G and Haberman M R 2020 *Nat. Rev. Mater.* **5** 667–85
[7] Zangeneh-Nejad F and Fleury R 2018 *Appl. Sci.* **8** 1083
[8] Fleury R, Sounas D L, Sieck C F, Haberman M R and Alù A 2014 *Science* **343** 516–9
[9] Zangeneh-Nejad F and Fleury R 2019 *J. Acoust. Soc. Am.* **146** 843–9
[10] Ni X, He C, Sun X-C, Liu X, Lu M-H, Feng L and Chen Y-F 2015 *New J. Phys.* **17** 053016
[11] Yang Z, Gao F, Shi X, Lin X, Gao Z, Chong Y and Zhang B 2015 *Phys. Rev. Lett.* **114** 114301
[12] Chen Z-G and Wu Y 2016 *Phys. Rev. Appl.* **5** 054021
[13] Ding Y, Peng Y, Zhu Y, Fan X, Yang J, Liang B, Zhu X, Wan X and Cheng J 2019 *Phys. Rev. Lett.* **122** 014302
[14] Quan L, Yves S, Peng Y, Esfahlani H and Alù A 2021 *Nat. Commun.* **12** 2615
[15] Zhu Y, Cao L, Merkel A, Fan S-W, Vincent B and Assouar B 2021 *Nat. Commun.* **12** 7089
[16] Popa B-I, Zigoneanu L and Cummer S A 2013 *Phys. Rev. B* **88** 024303
[17] Popa B-I, Shinde D, Konneker A and Cummer S A 2015 *Phys. Rev. B* **91** 220303
[18] Cho C, Wen X, Park N and Li J 2020 *Nat. Commun.* **11** 251
[19] Geib N, Sasmal A, Wang Z, Zhai Y, Popa B-I and Grosh K 2021 *Phys. Rev. B* **103** 165427
[20] Wen X, Cho C, Zhu X, Park N and Li J 2024 *Sci. Adv.* **10** eadm9673
[21] Xie B, Tang K, Cheng H, Liu Z, Chen S and Tian J 2017 *Adv. Mater.* **29** 1603507

[22] Cao W K, Zhang C, Wu L T, Guo K Q, Ke J C, Cui T J and Cheng Q 2021 *Phys. Rev. Appl.* **15** 024026
[23] Gong K, Zhou X, Ouyang H and Mo J 2021 *J. Phys. Appl. Phys.* **54** 305302
[24] Zhang H, Xiao Y, Wen J, Yu D and Wen X 2016 *Appl. Phys. Lett.* **108** 141902
[25] Chen X, Xu X, Ai S, Chen H, Pei Y and Zhou X 2014 *Appl. Phys. Lett.* **105** 071913
[26] Fan S-W, Zhao S-D, Chen A-L, Wang Y-F, Assouar B and Wang Y-S 2019 *Phys. Rev. Appl.* **11** 044038
[27] Wang X-L, Yang J, Liang B and Cheng J-C 2019 *Appl. Phys. Express* **13** 014002
[28] Fan S-W, Zhu Y, Cao L, Wang Y-F, Chen A-L, Merkel A, Wang Y-S and Assouar B 2020 *Smart Mater. Struct.* **29** 105038
[29] Wang Y-F, Wang Y-Z, Wu B, Chen W and Wang Y-S 2020 *Appl. Mech. Rev.* **72**
[30] Choi C, Bansal S, Münzenrieder N and Subramanian S 2021 *Adv. Eng. Mater.* **23** 2000988
[31] Chen A-L, Wang Y-S, Wang Y-F, Zhou H-T and Yuan S-M 2022 *Appl. Mech. Rev.* **74**
[32] Tian Z, Shen C, Li J, Reit E, Gu Y, Fu H, Cummer S A and Huang T J 2019 *Adv. Funct. Mater.* **29** 1808489
[33] Xia J, Jia D, Sun H, Yuan S, Ge Y, Si Q and Liu X 2018 *Adv. Mater.* **30** 1805002
[34] Ge Y, Shi B, Xia J, Sun H, Yuan S, Xue H and Zhang B 2023 *Appl. Phys. Rev.* **10** 031403
[35] Shen Y, Zhu X, Cai F, Ma T, Li F, Xia X, Li Y, Wang C and Zheng H 2019 *Phys. Rev. Appl.* **11** 034009
[36] Li P-Q, Shen Y-X, Geng Z-G, Cao P-C, Peng Y-G and Zhu X-F 2020 *J. Phys. Appl. Phys.* **53** 155502
[37] Ma G, Fan X, Sheng P and Fink M 2018 *Proc. Natl. Acad. Sci.* **115** 6638–43
[38] Wang Q, Del Hougne P and Ma G 2022 *Phys. Rev. Appl.* **17** 044007
[39] Zhang H, Wang Q, Fink M and Ma G 2024 *Nat. Commun.* **15** 1270
[40] Chen Z, Ma L, Ge S, Chen Z-G, Lu M, Chen Y and Lu Y 2024 *Phys. Rev. Appl.* **21** L011001
[41] Chen Z-X, Peng Y-G, Chen Z-G, Liu Y, Chen P, Zhu X-F and Lu Y-Q 2024 *Nat. Commun.* **15** 1478
[42] Chen Z, Chen A, Peng Y-G, Li Z, Liang B, Yang J, Zhu X-F, Lu Y and Cheng J 2024 *Phys. Rev. B* **109** L020302
[43] Fleury R, Sounas D L and Alù A 2015 *Phys. Rev. B* **91** 174306
[44] Shen C, Zhu X, Li J and Cummer S A 2019 *Phys. Rev. B* **100** 054302
[45] Wang Q, Yang Y, Ni X, Xu Y-L, Sun X-C, Chen Z-G, Feng L, Liu X, Lu M-H and Chen Y-F 2015 *Sci. Rep.* **5** 10880
[46] Wen X, Zhu X, Wu H W and Li J 2021 *Phys. Rev. B* **104** L060304
[47] Zhu X, Wu H-W, Zhuo Y, Liu Z and Li J 2023 *Phys. Rev. B* **108** 104303
[48] Chen Z, Peng Y, Li H, Liu J, Ding Y, Liang B, Zhu X-F, Lu Y, Cheng J and Alù A 2021 *Sci. Adv.* **7** eabj1198
[49] El-Ganainy R, Makris K G, Khajavikhan M, Musslimani Z H, Rotter S and Christodoulides D N 2018 *Nat. Phys.* **14** 11–9
[50] Ashida Y, Gong Z and Ueda M 2020 *Adv. Phys.* **69** 249–435
[51] Ding K, Fang C and Ma G 2022 *Nat. Rev. Phys.* **4** 745–60
[52] Gu Z, Gao H, Cao P-C, Liu T, Zhu X-F and Zhu J 2021 *Phys. Rev. Appl.* **16** 057001
[53] Huang L, Huang S, Shen C, Yves S, Pilipchuk A S, Ni X, Kim S, Chiang Y K, Powell D A, Zhu J, Cheng Y, Li Y, Sadreev A F, Alù A and Miroshnichenko A E 2024 *Nat. Rev. Phys.* **6** 11–27
[54] Fleury R, Sounas D and Alù A 2015 *Nat. Commun.* **6** 5905
[55] Shi C, Dubois M, Chen Y, Cheng L, Ramezani H, Wang Y and Zhang X 2016 *Nat. Commun.* **7** 11110
[56] Li H, Rosendo-López M, Zhu Y, Fan X, Torrent D, Liang B, Cheng J and Christensen J 2019 *Research* **2019** 2019/8345683

[57] Zhang Q, Li Y, Sun H, Liu X, Zhao L, Feng X, Fan X and Qiu C 2023 *Phys. Rev. Lett.* **130** 017201
[58] Zhang Q, Zhao L, Liu X, Feng X, Xiong L, Wu W and Qiu C 2023 *Phys. Rev. Res.* **5** L022050
[59] Zhang L, Yang Y, Ge Y, Guan Y-J, Chen Q, Yan Q, Chen F, Xi R, Li Y, Jia D, Yuan S-Q, Sun H-X, Chen H and Zhang B 2021 *Nat. Commun.* **12** 6297
[60] Zhang Q, Leng Y, Xiong L, Li Y, Zhang K, Qi L and Qiu C 2024 *Adv. Mater.* **36** 2403108
[61] Xiong L, Zhang Q, Feng X, Leng Y, Pi M, Tong S and Qiu C 2023 arXiv:2312.11490[cond-mat.other]
[62] Wang X, Wang W and Ma G 2023 *AAPPS Bull.* **33** 23
[63] Guo X, Lissek H and Fleury R 2023 *Commun. Phys.* **6** 93
[64] Hu B, Zhang Z, Zhang H, Zheng L, Xiong W, Yue Z, Wang X, Xu J, Cheng Y, Liu X and Christensen J 2021 *Nature* **597** 655–9
[65] Hu B, Zhang Z, Yue Z, Liao D, Liu Y, Zhang H, Cheng Y, Liu X and Christensen J 2023 *Phys. Rev. Lett.* **131** 066601