Robust nonreciprocal acoustic propagation in a compact acoustic circulator empowered by natural convection

Xingxing Liu, Xiaobing Cai, Qiuquan Guo and Jun Yang

Department of Mechanical and Materials Engineering, The University of Western Ontario, London, Ontario, N6A 5B9, Canada

E-mail: jyang@eng.uwo.ca

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Abstract

The development of the quantum Hall effect in condensed matter physics that breaks time-reversal symmetry by magnetic biasing has inspired its analog in classical nonreciprocal acoustics. Nonreciprocal acoustic propagation is highly desirable to control acoustics in isolation, broadband unidirectional transmission, and topologically robust to structural disorders or defects. So far, these fascinating properties have been investigated through fan-induced moving media, acoustic capacitance adjustment and acoustic metamaterials. However, these may be associated with disadvantages including extra noise and limited dynamic controlling performance. Here we overcome these limitations by introducing heat-induced natural convection into acoustic circulator, and demonstrate that the classical acoustic circulator with thermal management can realize robust nonreciprocal acoustic propagation. The concept of combining heat-induced natural convection and aeroacoustics creates a new practical paradigm and increases the feasibility for nonreciprocal acoustics due to merits of dynamic control, versatile topological structures, and miniaturization in the absence of moving parts.

1. Introduction

The exploration at the basis of the quantum Hall effect [1–3], has inspired many researchers in related fields of interest to investigate nonreciprocity and topologically non-trivial states [4–9]. Reciprocity [10,11] is a basic property in wave transmission process associated to the physical laws of time-reversal symmetry, which in return, makes the non-trivial band gaps attribute to the broken time-reversal symmetry [12,13]. For the electromagnetic nonreciprocity [14–16], the magnetic biasing is commonly employed to break reciprocity and achieve unidirectional mode with the local perturbation to the edge. Examples can be found in some photonic analogs, such as bianisotropic metamaterials [17], chiral waveguides [18,19], silicon-ring resonators [20,21] and photonic crystals [22–25].

However, for the nonreciprocal acoustics, the magnetic biasing is typically associated with a weak magneto-acoustic effect [26], which is only observable under large and impractical biasing structures. Inspired by using the external magnetic biasing to create the electromagnetic nonreciprocity due to the Zeeman effect [27], some analogous approaches are introduced by importing rotational motion [28–31] or angular momentum in specific acoustic resonators [13,32]. Alu et al [13,28] designed a circular resonator with flowing air rotating inside, together with three uniformly distributed ports for acoustic wave input/output. The flowing air works as the magnetic biasing counterpart and exhibits nonreciprocal acoustic propagation by breaking the time-reversal symmetry. Alu et al also proposed [12] the idea of acoustic Floquet topological insulators combining with the concept of capacitance adjustment in the trimer metamolecules, which realized broadband acoustic isolation and nonreciprocal acoustic emitters. Ni et al [32] investigated similar two-dimensional topologically one-way edge mode in networks of acoustic resonators with circulating air flow, which shows robust one-way edge transmission against structural disorders and defects. Moreover, in order to achieve unidirectional acoustic
transmission, acoustic metamaterials, sonic crystal structures\cite{30,33} and phononic crystals\cite{34,35} combining circulating flow, have been proposed to realize one-way propagation of pseudo-spin-dependent edge states under broken time-reversal symmetry or controlled propagation of acoustic wave in an arbitrary network pathway.

The previous studies have developed various acoustic devices or system-level configurations to demonstrate the concept of nonreciprocal acoustics by breaking time-reversal symmetry or parity symmetry. More work is demanded to advance this technology into more practical functions. Using fans or other rotating machines as the formation of circulating flow did create a valid gauge flow field to break the time-reversal symmetry, whereas introducing inevitable extra noise and difficulty in miniaturizing the whole structure due to the bulky angular momentum generator. For the case of acoustic capacitance adjustment\cite{12}, elastic material and piezoelectric actuators were employed, making it difficult to fabricate and realize dynamic control. For the acoustic metamaterial and sonic crystals, specific arrays or configurations often required relatively bulky structures that greatly limit their applications in a broad frequency range or concise dynamic control.

In this study, we propose a design of using heat-induced natural convection to form a steady air-flow circulation, which can break time-reversal symmetry and achieve robust nonreciprocal acoustic propagation in a ring resonator. In our geometry of analog, a circulator with 120° rotational symmetry of three-port coaxial cylinders associated with three corresponding rectangular waveguides is designed. Distribution of a temperature gradient in a vertically placed ring circulator creates a steady circulating air-flow field due to the existence of buoyancy force. Meanwhile, velocity and flow direction in the circulator can be easily tuned by adjusting temperature distribution. In this scenario, no extra noise would be generated as no moving components are employed in the whole setup, which can facilitate its applications by conducting more accurate control and miniaturizing the whole structure. Our design, a compact configuration without moving parts, creates a new paradigm for the application of nonreciprocal acoustics, which reduces the difficulty in device/material fabrication. Moreover, we further demonstrate that the nonreciprocal resonators with different interior circulator configurations, can exhibit excellent nonreciprocal acoustic propagation performance empowered by the heat-induced natural convection. This study also shows great potential for the insulation of any interior structures in acoustic circulators.

2. Prototype design and mode analysis

In the designed 3D nonreciprocal acoustic circulator, three-port subwavelength rectangular waveguides $(44 \times 178 \times 44$ mm) are connected by hard-walled coaxial cylinders ($r = 4.75$ mm, $h = 21$ mm), and the height of the whole structure is 44 mm. Three groups of thin heating layers are evenly distributed (spaced with 120° within the hollow ring circulator) to form a tri-symmetric structure and relatively uniform velocity distribution. Moreover, dynamic control of the velocity field can be realized by heating different groups of these thin heating layers. The inner and outer radii of the ring circulator are set as $R_i = 51$ mm and $R_e = 92$ mm, respectively. The fundamental waveguide mode for acoustic plane wave is supported in the studied frequency range. In figure 1(a), it can be found that the temperature distribution in the vertically placed circulator (buoyancy created by the lower left high temperature region) induces a steady circular velocity field by natural convection. Specifically, all the surfaces and two thin heating layers inside the hollow circulator of the red region are set as the high temperature region. Introducing this circular momentum to fill a subwavelength acoustic resonant ring circulator, the degenerate counter-propagating azimuthal resonant mode can be split. As is shown in figure 1(b), the pressure distribution in a peak frequency is displayed with all the dimensions labeled, which can visualize the nonreciprocal protection. A proper velocity distribution induced by natural convection and a suitable circulator design together can create giant nonreciprocity through modal interference.

As is shown in figures 1(c) and (d), the acoustic circulator with biasing angular momentum field can support clockwise and counterclockwise dipole modes\cite{32} with eigenfrequencies $w_\pm$. If the fluid inside the circulator is stationary, these modes would be degenerate with $w_0 = w_\pm$. When the biasing angular momentum in the form of air rotation is induced by natural convection, the degeneracy is lifted by $\Delta w = w_+ - w_\pm = 2\nu_0 / R_{eff}$, where $\nu_0$ represents the average air velocity and $R_{eff}$ is the effective radius of the circulator.

3. Velocity distribution of heat-induced natural convection

Natural convection is a heat transporting process, in which the fluid motion is not created by external sources but by the spatial density differences due to the temperature gradient. In the acoustic circulator with a controlled temperature distribution, the fluid in the heated region becomes less dense and rises, while the fluid in the cooler region moves downside forming an air-circulating cycle. In order to form a steady circulating velocity field, the high temperature and low temperature regions are controlled by specific heat fluxes to maintain relative
balanced temperature distribution. Normally, the internal driving force of natural convection comes from fluid density difference induced buoyancy, which would be affected by factors [36], such as temperature gradient, density difference, gravity, distance through the convective medium, diffusion rate and viscosity, through which dynamic control can be easily realized.

The contours and vectors of velocity field distributions in different temperature gradients are illustrated in figure 2. The obtained velocity field is then used to calculate acoustic transmission in this biasing circulator by Aeroacoustics Module in COMSOL. As is shown in figure 2, the high temperature region is placed in the lower left corner, which takes up a quarter of this circulator, and the rest blue area is set as a balanced temperature 273.15 K. (b) The acoustic pressure distribution in the condition of the optimal nonreciprocal performance with all the dimensions labeled. The pressure distribution of the clockwise (c) and counterclockwise (d) dipole modes of the acoustic circulator corresponding to the azimuthal order to be \( m = 1 \).

![Figure 1. Model configuration and pressure distribution.](image)

**Figure 1.** Model configuration and pressure distribution. (a) Geometrical top view of cross-section at \( H = 22 \) mm. The red region is specified as high temperature region is heated at a given temperature that is 373.15 K, 423.15 K, 473.15 K, 523.15 K, 573.15 K and 623.15 K, respectively. The rest blue area is set as a balanced temperature 273.15 K. (b) The acoustic pressure distribution in the condition of the optimal nonreciprocal performance with all the dimensions labeled. The pressure distribution of the clockwise (c) and counterclockwise (d) dipole modes of the acoustic circulator corresponding to the azimuthal order to be \( m = 1 \).

4. Nonreciprocal performance

Modeling of the complex coupling of air flow and acoustics can be achieved by COMSOL Multiphysics and the add-on Acoustics Module using the linearized Navier–Stokes module interfaces, which allows robust simulation
of complex flow-acoustics interaction that leads to flow-dependent acoustic property change. This Acoustic Module offers a detailed analysis of turbulent and non-isothermal flow that influences the acoustic field in this system. This module takes all the energy dissipation from viscous loss and thermal loss into account, while do not include flow-induced noise source terms. Basically, the full linear perturbation to the general equations of CFD (computational fluid dynamics)-mass, momentum, and energy conservation can be solved using the equations (1)–(3).

The linearized Navier–Stokes equations represent a linearization to the full set of governing equations for a compressible, viscous, and non-isothermal flow [37]. Here, it is performed as the first-order perturbation around the steady-state background flow defined by its pressure, velocity, temperature, and density ($p_0$, $u_0$, $T_0$, and $\rho_0$). This yields the governing equations for the propagation of small acoustic perturbations in the pressure, velocity, and temperature ($p'$, $u'$, and $T'$). In the perturbation theory, a superscript ' is used to denote variables of the first-order perturbations. The governing equations (with subscript 0 on the background fields) are:

$$\rho_0 C_p \left( \frac{\partial T'}{\partial t} + u' \cdot \nabla T_0 + u_0 \cdot \nabla T' \right) + (\rho C_p)$$

$$u_0 \cdot \nabla T_0 - \alpha_p T_0 \left( \frac{\partial p'}{\partial t} + u' \cdot \nabla p_0 + u_0 \cdot \nabla p' \right)$$

$$- (\alpha_p T') u_0 \cdot \nabla p_0 = \nabla \cdot (k \nabla T') + \Phi + Q, \quad (1)$$

$$\rho_0 \left[ \frac{\partial u'}{\partial t} + (u' \cdot \nabla) u_0 + (u_0 \cdot \nabla) u' \right] + p'(u_0 \cdot \nabla)$$

$$u_0 = \Delta \cdot \sigma + F - u_0 M, \quad \text{(2)}$$

$$\frac{\partial p'}{\partial t} + \nabla \cdot (\rho' u_0 + \rho_0 u') = M, \quad \text{(3)}$$

where $M$, $F$, and $Q$ represent different source terms, $\Phi$ is the viscous dissipation function, $\sigma$ is the stress tensor, and normally in frequency domain, the time derivative $\partial / \partial t$ can be denoted by harmonic dependence $iw$, and $w$ is defined as frequency. The standard hard wall boundary conditions and perfectly matching layers have been assigned in the simulation process.

Numerical simulations of the heat-induced natural convection based acoustic circulator in dipole mode are performed to investigate nonreciprocal acoustic propagation. As is shown in figure 3(a), the acoustic pressure

![Figure 2](image-url)
amplitude of transmission coefficient at Port 2 and Port 3 in the absence of angular-momentum biasing at two output ports are identical and equal to 0.691 due to the symmetric splitting circular structure, with the remaining 1/9 of acoustic power being reflected or dissipated. Figure 3(a) nevertheless displays, in the condition of the acoustic circulator with angular-momentum biasing, the transmission coefficient of output Port 3 is proportional to the temperature in high temperature region and could reach a maximum value of more than 0.9 at 623.15 K. On the contrary, the related transmission coefficients of output Port 2 decreases, and can be less than 0.1. Actually the velocity field created by the heat-induced natural convection can lead to robust nonreciprocal acoustic transmission, even by a small temperature gradient, indicating that the proposed acoustic nonreciprocal circulator is robust.

In figure 3(b), all the full-wave simulation and theoretical results are compared with the experimental results, which show good agreement, once the average value of the heat-induced velocity distribution matches the value from Alu's model [28]. As stated above, by varying the heating temperature, different interior velocity distributions can be easily obtained and the optimal nonreciprocal effect can be achieved when the temperature of the heated region is 623.15 K. The optimal velocity predicted by the analytical model coincides well with the average value of the velocity field. As predicted in the former analytical theory, the transmission to Port 2 can be reduced to zero at the operating frequency \( w_0 \), whereas the transmission to Port 3 is close to unity, which indicates almost all the acoustic power is transmitted to Port 3. These results show the correct amount of acoustic Zeeman splitting to achieve well-performed acoustic circulators with natural convection by a wide range of temperature gradients, enabling the dynamic control with minor temperature gradient for robust nonreciprocal acoustic transmission in specific structures.

The acoustic pressure distributions in an unbiased condition (supplementary figure S1(b)) and the biased conditions induced by natural convection (figures 1(c) and (d)) are compared to fully understand the mechanism of the proposed design. For the unbiased condition, the resonant dipole modes are degenerate and evenly excited, resulting in a symmetric acoustic pressure distribution with respect to the axes of three ports in this cavity. While for the biased condition, the resonant dipole modes are split to produce an asymmetric field distribution for all the output ports. Specifically, the acoustic transmission in Port 2 is very small, whereas it in Port 3 is close to 1, which confirms a robust nonreciprocal acoustic transmission in the proposed acoustic circulator design. In addition, the selection of heated regions and temperature ranges can be adjusted to realize dynamic control of acoustic transmission direction and its nonreciprocal performance. In this scenario, the acoustic energy is routed exclusively in one direction and is easy to realize dynamic control without any moving components.

5. Coupled-mode theory for an acoustic circulator by angular-momentum bias

The modified coupled-mode theory [13, 38, 39] is developed as an analytical solution to describe the acoustic propagation in the circulator under angular-momentum bias considering acoustic energy dissipation, which agrees well with the full-wave simulation results conducted by COMSOL Multiphysics. Based on the model of an azimuthally symmetric acoustic circulator under angular-momentum bias, the scattering parameters
\[ S_3 = S_1 - e^{-i\omega t} \] can be achieved according to equations (4)–(6), which represent reflection coefficient and transmission coefficients for Ports 1, 2 and 3, respectively, as:

\[ S_{11} = -1 + e^{i\varphi} \left( \frac{2\gamma_1}{3} \alpha_+ + \frac{2\gamma_2}{3} \alpha_- \right) \] (4)

\[ S_{21} = e^{i\varphi} \left( \frac{2\gamma_1}{3} \alpha_+ + e^{-i\varphi} \frac{2\gamma_2}{3} \alpha_- \right) \] (5)

\[ S_{31} = e^{i\varphi} \left( \frac{2\gamma_1}{3} \alpha_+ + e^{-i\varphi} \frac{2\gamma_2}{3} \alpha_- \right) \] (6)

where, \( \gamma_\pm \) denotes the inverse of decay times to the output Ports 1, 2 and 3, which are located at the equally distributed positions \( \varphi = 0, \frac{2\pi}{3}, \) and \( \frac{4\pi}{3}, \) respectively, which normally can be denoted as \( \gamma_+ = \gamma_- = \gamma \) owing to symmetry. The coefficient \( \alpha_\pm \) is \( \alpha_\pm = \frac{\gamma_\pm}{\gamma_0} = \frac{\gamma}{\gamma_0} \). Here the eigenfrequencies of the right and left-handed modes are given by \( \omega_\pm = \omega_0 \pm \gamma c_{\text{heat}} / R_{\text{eff}} \), where \( \gamma \) is the resonance frequency and \( R_{\text{eff}} \) comes from the calculation of \( \gamma_0 = c_{\text{heat}} / R_{\text{eff}} \), where effective acoustic speed changes with air temperature in the form of \( \sqrt{k^' \cdot c / \rho} \), as \( k^' \) is the ratio of specific heat. Optimal nonreciprocal performance can be achieved at \( \omega_0 = \omega_0 \pm \sqrt[4]{3} \). Moreover, considering the acoustic energy dissipation generated by the non-uniform velocity and temperature distribution, related damping coefficients \( \varphi_{1p}, \varphi_{2p}, \) and \( \varphi_{31} \) are substituted in the transmission equations (4)–(6). More details can be found in supplementary material.

6. Robust nonreciprocal acoustic circulator with other interior configurations

We have designed different interior structures to confirm that the heat-induced natural convection can form a robust nonreciprocal acoustic transmission in this type of acoustic circulator. As is shown in figures 4(a)–(d), the interior structures of triangle, Y-parallel triangles, hexagon and hexagram are placed vertically with a well-adjusted high temperature region and a low temperature region, which can form a steady velocity field therein. The triangle structure achieves a maximum velocity distribution, whereas the Y-parallel triangle structure gets a minimum velocity distribution. In figure 4(e), the interior configurations of hexagon and hexagram obtain the best nonreciprocal performance, although their velocities are not the maximum ones. We can conclude that nonreciprocal performance is not only determined by the velocity distribution, but also the specific geometrical configuration. Moreover, in this type of acoustic circulator, the differences for transmission coefficients of two output ports are still big enough to obtain excellent nonreciprocal performance.

7. Discussion

We have reported that the heat-induced natural convection can be easily incorporated into acoustic circulators to realize nonreciprocal acoustic propagation in compact configurations without using moving components that may generate extra noise, taking a significant step towards the realization of nonreciprocal acoustics for practical applications. In many applied scenarios, compared to other methods of adopting external biasing variables, manipulating temperature gradient is convenient to realize and can be controlled more concisely. Our design confirms that the classical yet simple acoustic circulator with different temperature distributions can realize robust nonreciprocal acoustic propagation. Moreover, in order to demonstrate that the heat-induced natural convection is a facile way of generating steady velocity field in various structural configurations to realize nonreciprocal acoustic propagation, four types of interior structures are designed to verify the versatility and robustness in these circulator configurations. The simulation results show excellent nonreciprocal performance for the protection of interior structures, which also certifies the feasibility and reliability at the basis of coupling thermal control with nonreciprocal acoustics.

This work, by combining the concept of natural convection and aeroacoustics, opens a new practical paradigm in nonreciprocal acoustics, particularly for practical applications. Due to its noiseless, controllable, structurally flexible and size-compact merits, such acoustic nonreciprocal design will also lead to new applications in the miniaturization of nonreciprocal acoustic-related applications, such as ultrasonic components, MEMS devices and sound attenuation in circumstances with temperature control capability, which provides alternative and practical option for the design of nonreciprocal acoustics based on existing external flow-driven basing model.
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ORCID iDs

Xiaobing Cai https://orcid.org/0000-0002-4894-1892

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Figure 4. The velocity contours and nonreciprocal performance of acoustic circulators with four types of interior configurations, where temperature of the high temperature region is 523.15 K. The velocity contours and vector arrows for (a) triangle structure, (b) Y-parallel triangles structure, (c) Hexagon structure, (d) Hexagram structure. (e) Transmission coefficients for Port 2 (curves with lower peak values) and Port 3 (curves with higher peak values).
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