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Mechanical circulator for elastic waves by using the nonreciprocity of flexible rotating rings

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ABSTRACT

Circulators have a wide range of applications in wave manipulation. They provide a nonreciprocal response by breaking the time-reversal symmetry. In the mechanical field, nonlinear isolators and ferromagnetic circulators can be used for this objective. However, they require high power and high volumes. Herein, a flexible rotating ring is used to break the time-reversal symmetry as a result of the combined effect of Coriolis acceleration and material damping. Complete asymmetry of oscillating and evanescent components of wavenumbers is achieved. The elastic ring produces a nonreciprocal response that is used to design a three port mechanical circulator. The rotational speed for maximum transmission in one port and isolation in the other one is determined using analytical equations. A spectral element formulation is used to compute the complex dispersion diagrams and the forced response. Waveguides that support longitudinal and flexural waves are investigated. In this case, the ring nonreciprocity is modulated by the waveguide reciprocal response and the transmission coefficients can be affected. The proposed device is compact, nonferromagnetic, and may open new directions for elastic wave manipulation.

1. Introduction

Wave control and manipulation is a topic that raises enthusiasm among researchers of fields such as electromagnetism, acoustics, mechanics, and material science as it opens new avenues for the development of applications in modern communication, energy harvesting, and sensing. Recently, the possibility of engineering devices with strongly nonreciprocal responses has offered new possibilities for wave control [1]. Reciprocity is the fundamental property of most wave phenomena observed in everyday life, which results from the time-reversible property of conventional media. It guarantees that the wave propagation between source and receiver or vice versa is symmetric [2]. However, in various situations, nonreciprocal wave phenomena are highly desirable as, for instance, to separate waves propagating in opposite directions, to create one-way propagation, or to isolate different media [3]. In addition, it has also been shown that breaking time-reversal symmetry plays an important role in bringing about topological edge states. The main feature of topological states, at first believed as a quantum Hall effect, is their immunity against wave scattering by disorder [4,5].

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Nonreciprocal devices, namely isolators and circulators, have initially been proposed in electromagnetism [6,7]. In isolators, nonlinear structures associated with linear periodic structures are employed, whereas in circulators, linear media in the presence of magnetic or Coriolis forces produce a nonsymmetrical propagation that breaks the time-reversal symmetry [8]. Moreover, an isolator can be constructed using circulators by impedance matching one of the ports. In this work, the objective is to show that flexible rotating rings have the inherent property of breaking the symmetry of forward and backward traveling waves producing a nonreciprocal response. Hence, they can be regarded as the mechanical wave counterpart to the devices recently proposed and demonstrated in electromagnetism [6], acoustics [9], and nonlinear dynamics [10–12]. Indeed, the flexible rotating ring is the mechanical analogue to the acoustic circulator proposed in Fleury et al. [13]. In magneto-optical media, the magnetic field interacts with light, as a result of the Faraday phenomenon, which splits the spectral lines, resulting in Zeeman's electronic effect [14]. In acoustic media, angular momentum due to rotational fluid movement induce nonreciprocity by splitting the resonance frequencies of an acoustic cavity. Here, the Coriolis forces acting on the ring split the elastic waves and induce high interference phenomena.

The first realization of a nonreciprocal elastic wave device was the object of a patent deposed by Comstock [15]. It consists of a magnetized disk of ferromagnetic material having gyromagnetic properties. Recently, the Coriolis effect was used to break the time-reversal symmetry in topological active metamaterials. By using gyroscopes attached to a honeycomb lattice structure, one-way longitudinal and transverse wave propagation immune to backscattering is obtained [16]. For the same configuration, Nash et al. [4] showed that gyroscopic metamaterials allow one-way wave propagation even in the presence of defects. Indeed, the unidirectional transport is a result of topological mechanical modes, which are analogues to the quantum Hall effect. Besides, Wang et al. [5] showed that a nonsymmetrical response due to Coriolis forces can also be induced when a two-dimensional honeycomb lattice of masses and springs is on constant rotation. Later, one-way propagation in beams and rods was achieved using material modulation in time and space [17].

The present work shows that the Coriolis effect can also induce time-reversal symmetry breaking in a homogeneous and continuous flexible ring under rotation. The dynamics of a flexible rotating ring was studied by many authors [18–20] motivated by the need of understanding gear and tire vibrations. However, from the best of the authors knowledge, the nonreciprocal feature of such structures and their use for the design of mechanical circulators have not been addressed so far.

This paper is organized as follows. In Section 2, the fundamental basis to demonstrate that time-reversal symmetry is broken in flexible rotating rings is presented. The equations of motion for an element of flexible rotating ring in an Eulerian reference frame, corresponding dispersion relations and dynamic stiffness matrix are shown. Using the spectral element (SE) method, dispersion diagrams and forced response solutions are obtained. In Section 3, the nonreciprocal mechanical circulator is studied, and analytical equations and numerical simulations verifying the physical phenomenon are shown. More complex examples with waveguides that can support longitudinal or flexural vibration are discussed in Section 4. Finally, in Section 5, the conclusions are drawn. In addition, four appendices are included. In Appendix A, the equations of motion for a rotating ring are provided. In Appendix B, the theoretical background to develop a spectral element from the equations of motion is presented. Free and forced analytical solution for the rotating ring are shown in Appendices C and D, respectively.

2. Wave propagation in an Eulerian reference frame

2.1. Theoretical background

The use of an Eulerian (spatial) description is convenient to solve coupled mechanical systems involving rotating parts, which is the case in this paper. In this section, the theoretical formulation for the rotating ring (see Fig. 1) in an Eulerian reference frame is derived from the Lagrangian equivalent description, which is briefly recalled in Appendix A for the purpose of clarity. The governing equations of motion for a flexible rotating ring in a Lagrangian reference system can be written in compact form as:

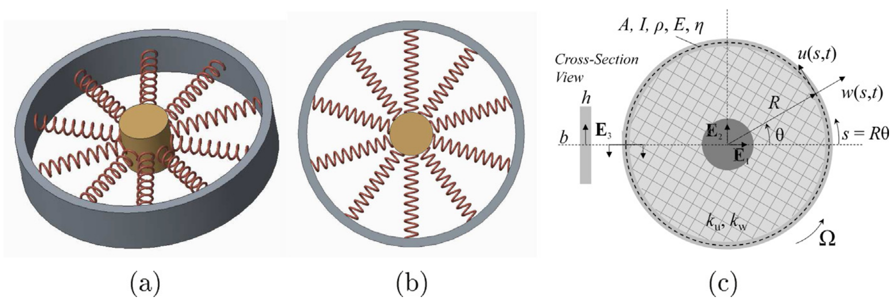

Fig. 1. Schematic representations of a flexible rotating ring supported on an elastic foundation: (a) 3D CAD view, (b) top view and (c) 2D model including reference axes, model parameters which are defined in Appendix A; the distributed elastic foundation is represented by the hatched area.