Journal of Sound and Vibration 429 (2018) 162–175

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

One-way energy insulation using time-space modulated structures

Kaijun Yi *, Sami Karkar, Manuel Collet

Univ Lyon, Ecole Centrale de Lyon, ENISE, ENTPE, CNRS, Laboratoire de Tribologie et Dynamique des Systèmes LTDS UMR5513, F-69134 Ecully, France

ARTICLE INFO

Article history:
Received 14 August 2017
Revised 9 May 2018
Accepted 11 May 2018
Available online XXX
Handling Editor: G. Degrande

Keywords:
Time-space modulation
One-way energy insulation
Non-reciprocity
Scattering matrix method

ABSTRACT

The one-way energy insulation using time-space modulated structures is theoretically studied in this paper. Specifically, the time-space modulated structure in our studies possesses a traveling wave-like modulation. An extended scattering matrix method is developed and verified by comparing to the finite element method. The wave transmission through finite time-space modulated structures is studied using the proposed method. Results show that within the whole stop bands of the two fundamental Bloch modes of time-space modulated structures, one-way wave transmission is achievable. This non-reciprocal phenomenon can be exploited to realize one-way energy isolation in equivalent infinite or semi-infinite systems, which can be found in practice. The one-way energy isolation fails in finite systems due to a frequency conversion phenomenon resulting from the reflection.

1. Introduction

Time-space modulated structures are those whose properties are changed both in time and space. The modulation can be either coupled [1] or uncoupled [2] between time and space. In this paper, special attention is payed to the coupled case, which means the modulation acts like a traveling wave in the media. Real time-space modulated structures can be found in many engineering equipments. For example, the axially moving string [3] or rotating ring [4]. They essentially possess space periodicity, the move or rotation further introduces a time periodicity which is coupled with the space one. Also time-space modulated structures can be artificially realized using smart materials like piezoelectric materials, since their effective material properties can be changed by tuning the shunt impedance [5]. This tunable feature has been widely exploited in building metamaterials with tunable band gaps [6–9] and devices with gradient space-varying properties [10–13].

Wave propagation in time-space modulated structures is non-reciprocal. In conventional media, wave motion obeys the reciprocity, which guarantees that if waves can travel from a source to an observer, the opposite propagation path, from the observer to the source, is equally possible [14]. This property is violated in time-space modulated structures. The non-reciprocity of them is implied by the symmetry breaking of the dispersion diagram, which has been observed in real axially moving strings [3], rotating rings [4] and structures possessing artificially time-space modulated properties [1,15–18]. Due to the symmetry breaking of the dispersion diagram, stop bands of the fundamental Bloch modes in time-space modulated structures occupy different frequency ranges [1,16]. Unidirectional wave propagation was numerically demonstrated at individual frequencies

* Corresponding author. Current address: Univ. Bourgogne Franch-Comté, FEMTO-ST Institute, CNRS/UFC/ENSMM/UTBM, Department of Applied Mechanics, 24 rue de l'épitaphe, 25000 Besançon, France.

E-mail address: kaijun.yi@femto-st.fr (K. Yi).

https://doi.org/10.1016/j.jsv.2018.05.017
0022-460X/

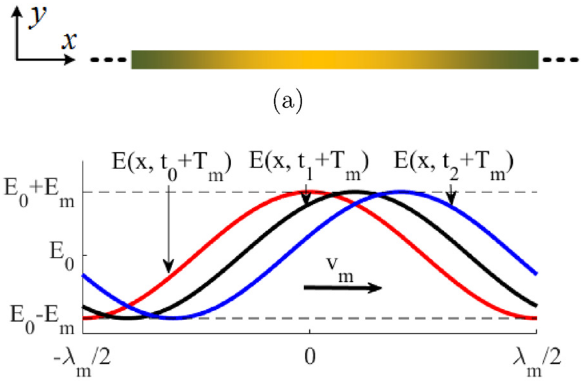

Fig. 1. (a) A slender modulated rod lying along the x axis. (b) The wave-like time-space modulation of the Young's modulus defined by $E(x,t) = E_0 + E_m \cos(\omega_m t - k_m x)$. The time period is $T_m = 2\pi/\omega_m$, the wavelength (space period) is $\lambda_m = 2\pi/k_m$ and the wave speed is $v_m = \omega_m/k_m$.

within these stop bands.

Apart from the above mentioned works, unidirectional wave propagation in time-space modulated structures were also studied by using homogenization methods. K. Lurie [19] designed an array composed of cells with two segments, the properties of these segments are changing in time and space, like the whole array is moving with a constant velocity. He obtained the effective material parameters of the dynamic array and predicted that by appropriately designing the activated array, unidirectional wave propagation can be observed. Following K. Lurie's work, S. Weekes [20] validated his homogenization results by performing direct numerical simulations. L. Shui et al. [21] used an improved multi-scale homogenization method to obtain the effective material parameters of the time-space modulated material. According to the homogenization results, they predicted asymmetric wave propagation in the modulated material and numerically demonstrated it.

In brief, the above introduction indicates that the one-way wave propagation is common in diverse time-space modulated structures. This property is desired in achieving one-way energy insulation, which can be used in many engineering applications, such as underwater one-way communication, one-way vibration/noise manipulation, etc. Consequently, time-space modulated structures have drawn and are continuously drawing attention from many researchers in acoustics and mechanics. However, the one-way wave propagation/transmission in them were mainly demonstrated by using numerical methods, such as finite element method [1] and finite-difference time domain method [15], at specific individual frequencies. Limited by the numerical methods, the properties of one-way transmission of acoustic or elastic waves impinging on time-space modulated structures have not been clearly uncovered yet, also the possibility of exploiting time-space modulated structures to realize one-way energy insulation has not been fully discussed.

In this paper, we propose a theoretical method to study the wave transmission through one-dimensional finite time-space modulated structures, and discuss the feasibility of one-way energy isolation. We have the intention of making our works reach out to both acoustical and mechanical engineers. Therefore, the longitudinal motion in slender rods is considered. Our studies can be easily extended to other types of waves, like acoustic waves in air and water, flexural waves in beams, etc. In what follows, time-space modulated structures will be simply called modulated structures. Section 2 studies the dispersion relations and Block modes in modulated rods by using the plane wave expansion (PWE) method. Section 3 proposes a theoretical method to study the reflection and transmission of waves incident on modulated rods. Section 4 presents the results. The proposed theoretical method is verified in Section 4.1. The properties of wave transmission are studied in Section 4.2. The feasibility of using modulated structures to realize one-way energy insulation is discussed in Section 4.3. Finally, Section 5 summaries important conclusions.

2. Dispersion relations and Bloch modes in modulated rods

The rod lying along the x axis in Fig. 1(a) is studied. The density of the rod ρ_0 is constant and homogeneous, while the Young's modulus is modulated in time and space according to a cosine wave function:

$$E(x,t) = E_0 + E_m \cos(\omega_m t - k_m x) \tag{1}$$

in which, E_0 is the Young's modulus when there is no modulation, E_m is the modulation amplitude, ω_m and k_m are respectively the angular frequency and wavenumber of the modulation wave, whose wavelength is $\lambda_m = 2\pi/k_m$. The modulation wave propagates along the rod with the speed $v_m = \omega_m/k_m$, as illustrated in Fig. 1(b).