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One-dimensional linear elastic waves at moving property interface

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HIGHLIGHTS

- Proposed a moving property interface model.
- Proposed a novel method to study the waves at moving property interface.
- Property interface motion and wave velocity can influence the wave propagation.
- There may exist shock waves at moving property interface.
- Property interface motion has an impact on the wave frequency and energy.

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ABSTRACT

Smart materials exhibit time-varying properties while time-varying external field is applied. To investigate the one-dimensional (1-D) homogeneous time-varying properties, a moving property interface (MPI) model is proposed, and the propagation of linear elastic waves at 1-D MPI is studied in this paper. Based on the idea of weak solutions and an infinity approximation, a novel method to deal with the difficulties in using the continuities to study the waves at MPI is also proposed. Some interesting phenomena are revealed: (i) besides wave impedance, the property interface motion and wave velocity are also very important factors that influence the wave propagation; (ii) at MPI, there may exist shock waves; (iii) the property interface motion has a significant impact on the wave frequency and energy. This research provides a theoretical viewpoint in the study of smart materials with a time-dependent mechanical properties at different loading conditions.

1. Introduction

For their smart features, such as sensing, feedback, information recognition and accumulation, self-recovery, self-adjusting and so on, smart materials are widely used in the multi-sensor, precision driving, vibration isolation/excitation and many other fields [1,2]. Smart materials exhibit time-varying properties while time-varying external field is applied, such as the shear modulus of the piezoelectric material [3] and electro rheological (ER) materials [4] experiencing time-varying electric field, material damping of the magnetostrictive material [5] and magneto rheological fluid [6] experiencing time-varying magnetic field, and modulus of the shape-memory material (SMA) [7] experiencing time-varying temperature field. The time-varying properties of smart materials can be realized through precise control of the external fields.

Using the time-varying properties, the smart composites and structures gained a lot of new applications. Ruzzene, Baz et al. [8–13] applied the SMA and the piezoelectric material to the design of period structures considering the time-varying modulus. Such structures demonstrate excellent active vibration performances. Wu [14] and Yang [15] respectively

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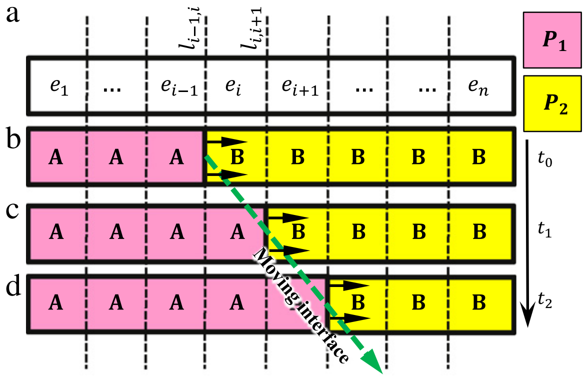

Fig. 1. The moving interface in smart materials: (a) cell division of 1-D structure; (b) distribution of the property at time t_0; (c) distribution of the property at time t_1; (d) distribution of the property at time t_2.

used the dielectric elastomer with time-varying properties to design the 1-D and 2-D phononic crystals. These phononic crystals have an adjustable band-gap. Wright and Cobbold [16,17] studied the band-gap characteristics of the phononic crystals with time-varying scatterer, and extended the multiple scattering theory to time-varying structures. Luo and Wang [18,19] designed left-handed metamaterials with actively modulated left-handed transmission peak and electrically tunable negative permeability metamaterials based on ER fluids considering time-varying properties. Most of these researches are focused on applications of a specific smart material with time-varying properties. Few of them involve general theoretical study.

Generally, there are two methods, which are wave propagation method and frequency domain analysis method, to research the mesoscopic physical mechanism and the transient response of smart structures with time-varying properties. The variance of the wave frequency in materials with time-varying properties makes the frequency domain analysis method unavailable. Thus the wave propagation method is a better choice to study the time-varying materials. A series of work has been reported on waves in time-varying materials [20–23]. This work on wave propagation in materials with time-varying properties will reveal interesting phenomenon different from the waves in static or moving media.

This paper focuses on the propagation of linear elastic waves at 1-D moving property interface (MPI). MPI is a model that can sufficiently reflect the characteristics of a material with 1-D time-varying properties. Usually, the continuities are powerful and sufficient in gaining the wave propagation law at property interface. However, there are obstacles in using the continuities to study the waves at MPI. Hence we proposed a novel method, which is based on the idea of weak solutions and infinity approximation, to deal with the difficulties, and the propagation law of linear elastic waves at 1-D MPI is achieved.

Specifically, the MPI model will be described based on the property variability of smart materials in Section 2. The movement mechanism of the property will be revealed in this section. In Section 3, according to the propagation characteristics of the wave when the property interface moving with different velocities, the wave propagation at MPI is classified. A complete discussion of the propagation law of the waves at MPI will be given in Sections 4 and 5. In Section 6, simulations will be conducted to verify the results obtained in previous sections. Section 7 is the summary of the whole work in this paper. In addition, the wavelength, wave frequency and energy characteristics of the waves on the MPI will be analyzed in Section 7. In Section 8, i.e. the last section, some conclusions will be made.

2. Moving property interface (MPI)

We will find out a representative model which can sufficiently reflect the characteristics of materials with time-varying properties. This needs to take an in-deep understanding of the materials with time-varying properties, first.

As well known, the application of the smart material is mainly based on the property controllability. The properties variance of smart materials is due to the time-varying external field. On the other hand, the edge effect, device-specific or human-induced inhomogeneity of external field, and some other factors, may lead to the spatial inhomogeneity of the property of smart materials. As a result, variable properties of smart materials are functions of time and space.

A general variable property should be inhomogeneous in time and space. However, a homogeneous variable property is a basic model which can be used to describe an inhomogeneous one by integration. In the following, we put forward a 1-D wave model to describe the 1-D homogeneous variable property which named MPI.

As shown in Fig. 1(a), the space in the 1-D structure is divided into a series of small cells: $e_1, e_2, \ldots, e_i, \ldots, e_n$, and $l_{i-1,i}$ represents the interface between the adjacent cells e_{i-1}, e_i. Assume that the property of the material is $\boldsymbol{P}_1$ when the external field $\boldsymbol{A}$ acts on the material, and the property is $\boldsymbol{P}_2$ when field $\boldsymbol{B}$ is applied. $\boldsymbol{P}_1$ and $\boldsymbol{P}_2$ in Fig. 1(b)–(d) are expressed by pink and yellow respectively. At the initial time t_0 (Fig. 1(b)), field $\boldsymbol{A}$ acts on cells $e_1, \ldots, e_{i-1}$ and field $\boldsymbol{B}$ on $e_i, \ldots, e_n$. After a time interval, at time t_1 (Fig. 1(c)), the field on cell e_i switches from $\boldsymbol{B}$ to $\boldsymbol{A}$. Hence the property of cell e_i switches from $\boldsymbol{P}_2$ to $\boldsymbol{P}_1$, which means that the property interface moves rightward by a cell length and reaches $l_{i,i+1}$. So repeatedly the MPI can be formed. Considering infinitesimal cells, the movement of the interface will be continuous.