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Wave mode diffusion and propagation in structural wave guide under Varying Temperature

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ABSTRACT

A numerical approach is presented to study the guided wave propagation through periodic specimen with thermal dependence of material properties. There is a great interest in extending the skills of the wave finite element (WFE) method to figure out the variations in the wave propagation properties due to temperature fluctuations. Thermal effects on the dispersion curves thereby on group velocity are discussed. Comparisons between numerical results and analytical developments for various temperatures are given to prove the effectiveness of the proposed approach to predict the sensitivity of guided wave propagation characteristics in presence of temperature variations.

1. Introduction

Knowledge of the wave propagation properties in elastic media such as the dispersion curve (which refers to the relationship between the velocity and the wave frequency) and the mode shapes is one of the major questions. In fact, dispersion curves contain information on wave propagation characteristics in structure such as group velocity, wavelength, and wavenumber as a function of frequency. In addition, the dispersive characteristics of wave modes in a waveguide can be determined from the dispersion curves of the guided wave modes.

Indeed, guided wave structural health monitoring (SHM) is an inspection process which has received significant attention in the last decades [1]. It is finding wide industrial applications in various industries including petrochemical, pipelines, aerospace and civil engineering where the global inspection and surveying is beneficial for maintaining the safety and integrity of the structure. Of particular interest of this study, wave finite element (WFE) method is presented. Its target is to develop an accurate theoretical model of ultrasonic wave propagation predictions and wave scattering estimations. It has been investigated by a number of researchers and became one of the most powerful methods to examine the mechanical waveguide structures [2–4]. This technique combines standard finite element (FE) method with periodic structure theory. It has been used for the structural vibration analysis [5–8] and the wave propagation in elastic waveguides [9–11]. Houillon et al. [12] studied the dynamic problems of homogeneous thin-walled structures using this method, which has been shown to be successful when applied to structures with uniform cross-section. Duhamel et al. [13] used this method to investigate the vibrations of uniform waveguide structures, where it has been proved to be accurate with relatively low computational cost in comparison with the standard FE method.

Most of the work on temperature effects on guided wave has been experimental {see for instances [15,17–19]}. Lee et al. (2003) studied experimentally the effect of high temperature values at a range of 35–70 °C on the response of PZT patches in a pitch-catch configuration on an aluminum plate [14]. They suggested different feature extraction strategies that are sensitive to damage but not environmental changes and they depict that the effect of temperature variation was much more pronounced than the damage's defect. Raghavan and Cesnik studied the effect of thermal variation at a range of 20–150 °C on the response of piezo-ceramics (PZT-5A) on aluminum plate [16]. Some authors attempted to correlate modal properties with temperature and also to develop system identification models that could separate the influences of temperature from true indications of damage on dynamic modal parameters [20,21]. Many Researches have

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Nomenclature

α	linear thermal expansion	d	length of the structure at room temperature
γ	volumetric thermal expansion	$d(T)$	temperature dependent length of the structure
ρ	density of the structure at room temperature	E	Young modulus at room temperature
T	temperature	$E(T)$	temperature dependent Young modulus
$\rho(T)$	temperature dependent density	F	force field
$\mu(T)$	temperature dependent eigenvalue	$\mathbf{K}(T)$	temperature dependent stiffness matrix
ϕ	temperature dependent eigenvector	$k(T)$	temperature dependent wave number
$C_g(T)$	temperature dependent wave velocities	$\mathbf{M}(T)$	temperature dependent mass matrix
$\mathbf{D}(T)$	temperature dependent complex dynamic stiffness matrix	q	displacement field
		$\mathbf{S}(T)$	temperature dependent transfer matrix

extensively examined the causes of the temperature effects in order to predict the beam performance [22,23]. Some authors have been interested in studying the impact of thermal loading on the guided waves mode shape [24–26]. Schulz et al. [23] depict the piezo-ceramic performance such as free vibration sensors on aluminum beams. It is shown that the piezoelectric property of the sensor decreases with increasing temperature until the properties are almost completely lost at 240 °C, and also the piezoelectric properties return each time when the sensor is cooled. Useful research is reported on isotropic plates and shells. Among those researches, Jeyaraj et al. [27] studied the vibration and acoustic response of a composite plate in a thermal environment. Kadoli and Ganesan [28,29] have studied the dynamic behavior of composite and isotropic cylindrical shells with PZT layers under axisymmetric temperature variation.

Indeed, the WFE method is used to show the thermal influence on the wave characteristics (i.e. dispersion curves and group velocity). Temperature variations affect various mechanical properties of the structure such as elasticity modulus and density. The modeling of the structure under thermal environment is still a subject of intensive research in several engineering areas.

Studying the material behavior following a thermal variability and evaluating its high-temperature and mechanical properties has been the subject of many researches [30]. The quantification of the material properties variation plays a crucial role in establishing the credibility of the underlying numerical model. The effect of tempering temperature on the microstructure and mechanical properties of steel was investigated in different works [31–34]. The experimental test results for the mechanical properties of the studied steel at fire temperatures are presented in [35]. The test results were used to determine the temperature dependencies of the mechanical properties, i.e. yield strength, modulus of elasticity and thermal elongation, of the studied steel material. A large disagreement exists in the test results, mainly owing to the different techniques used for tensile tests under temperature. There are, in fact, two ways of doing this: In the first one, the tensile load increases until the destruction of the specimen by keeping the temperature constant [36]. And in the second technique, the temperature increases until failure of the specimen by keeping the tensile load constant [36]. The speed of loading and temperature increase play a main role in identifying the mechanical properties. The effect of temperature on mechanical properties of pre-damaged steel reinforcing bars exposed to elevated temperatures are reported in Ref. [37] towards understanding the behavior of such bars in a fire. Referring to [38], the authors report the results of an investigation of the environmental temperature effect on mechanical properties of multi-walled carbon Nano-tubes. The obtained results reveal that the Young's modulus and Poisson's ratio decrease significantly with the increase of environmental temperatures. A mathematical framework based on finite element method (FEM) which capable of predicting temperature history, evolution of phases and internal stresses during thermal treatment of metals and alloys was developed [39].

The current study extends the mentioned works to survey thermal effect on the wave propagation. The mechanical properties are influenced by the temperature increment which will affect the scattering wave in the structure. The main objective of this work is the treatment of the wave characteristics as a function of the temperature in order to study the thermal effect on the wave finite element method. The originality of this paper is the formulation of the thermal wave finite element method (TWFE) based on the elastic guided wave propagation in periodic structure in presence of thermal variations.

The remainder of this paper is organized as follows. Section 2 introduces the thermal effect on the structural parameters. A general formulation of TWFE is offered in Section 3. The results are represented for longitudinal and flexural wave propagation cases and are given in Section 4. In Section 5, the multimodal wave propagation through the thermal wave finite element method is examined. Concluding remarks are made in Section 6.

2. Thermal effect on the structural parameters

The thermal effects in elastic media are captured at the material level. Thereby, its properties vary with temperature, consequently, the wave characteristics change. The material properties govern the wave propagation in the considered structure. The traveling modes dispersion curves and velocity depend on the material properties (in particular to the Young modulus) and the geometry of the studied structure.

Consider how the material properties change if there is a change to a different temperature where $T = T_0 + \Delta T$ (with $T_0 = 25\,^\circ$C is the room temperature). In our case, the chosen material is the steel. The temperature is introduced as state variable, allowing it to be modeled as variable field. In the following, the temperature dependent material parameters are identified in the temperature range from 25 °C to 1000 °C (see for instance Ref. [36]).

2.1. Young modulus

According to [36], the variation of the Young modulus of the steel at a range of 25–1000 °C, can be estimated by the following equation:

$$\frac{E(T)}{E} = 1 + \frac{T}{2000Log\left(\frac{T}{1100}\right)} \quad (1)$$

where T is the temperature, E is the Young modulus at room temperature and $E(T)$ is the temperature dependent Young modulus.