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Radial vibration analysis of pseudoelastic shape memory alloy thin cylindrical shells by the differential quadrature method

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ABSTRACT

This paper represents the radial vibrations of simply supported pseudoelastic shape memory alloy cylindrical shells under time-dependant internal pressure based on Donnell-type classical shell theory. The material behavior is simulated via the Boyd–Lagoudas model. The Hamilton's principle, Differential Quadrature, and Newmark method are employed to obtain and solve the equations of motion. The phase transformation effects are studied on the time and frequency responses of the shell. Results show that the frequency response peak points have a shift to the left with respect to the natural frequencies of the linear system (pure austenitic phase) due to the phase transformation.

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1. Introduction

Over the past recent decades, unique characteristics of shape memory alloys (SMAs) have attracted the attention of many researchers to use these materials in the various applications such as attenuating undesired vibrations of mechanical systems, sensing and actuating. The SMAs application spans a wide variety of industrial sectors like aerospace, automotive, biomedical, and oil exploration [1].

SMAs are a class of shape memory materials which have two crystallographic phases. One is the high temperature phase called austenite and the other is the low temperature phase called martensite. The reversible martensitic transformations from one structure to the other occur through diffusion-less transformations which lead to two remarkable phenomena: the shape memory effect and the pseudoelasticity [2].

The pseudoelastic effect occurs when the martensitic phase transformation is stress-induced at a constant temperature and the shape memory effect is the result of thermally induced crystallographic phase changes that refers to the ability of the material to recover its original shape via increasing the temperature.

High dissipation capacity due to the hysteretic behavior of pseudoelastic SMAs and thermomechanical properties can be mentioned as very interesting characteristics to be explored in passive vibration isolation systems [3]. Many researchers have studied the complex dynamical response of SMA systems, including the free and forced vibration behavior of bars, beams and composite plates embedded with SMA wires.

Seelecke [4], for example, studied the single degree of freedom vibration of a rigid mass suspended by a shape memory alloy tube under torsional loading. An improved version of the Muller–Achenbach model was applied to consider the SMA behavior for the cases of quasiplasticity and pseudoelasticity. Both, free and forced vibrations were analyzed. The analysis of the free vibration showed that the quasiplastic case exhibits larger damping. Hashemi and khadem [5] presented a mathematical model based on Auricchio model, considering asymmetry in tension and compression and also temperature effects on hysteresis at superelastic conditions. They also analyzed the dynamical behavior of a NiTi beam under free vibration as well as application of sinusoidal and impulse loads upon free-clamped and simply supported conditions. Machado [3] investigated the nonlinear dynamics of a passive vibration isolation and damping device through numerical simulations and experimental correlations. The considered device was a mass connected to a frame through SMA wires subjected to a series of continuous acceleration functions in the form of a sine sweep. A modified version of the constitutive model proposed by Boyd and Lagoudas, which considers the thermomechanical coupling, was used to predict the behavior of the SMA elements of the oscillator. Jafari and Ghiasvand [6] presented the dynamic response of multi-span pseudoelastic shape memory alloy beams subjected to a concentrated moving load. The Auricchio–Muller extended model and Lagrange's equations with the polynomial

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form trial function representing the deflection of the beam were applied by them. Zbiciak [7] presented a formulation of initial-boundary-value problem for the dynamic analysis of a Bernoulli–Euler beam made of pseudoelastic shape memory alloy. The finite difference method and the Runge–Kutta method were employed to solve the problem. Shiau et al. [8] investigated the effect of shape memory alloys on the free vibration behavior of buckled cross-ply and angle-ply laminates by varying the SMA fiber spacing using the finite element method. According to their study, the increase of SMA fiber volume fraction will decrease the post-buckling deflections of the plate and modify the natural frequencies of the plate significantly. Wang et al. [9] designed a robust SMA-based oscillator such that it is able to operate in a rather wide range of frequencies. Their system consists of a SMA rod and an end-mass. They proposed a dynamic nonlinear model and an efficient numerical methodology for the vibration analysis of the system. The results showed that at low temperatures, the SMA oscillator behaves as a regular damper. Asadi et al. [10] studied the large amplitude vibration and thermal post-buckling of shape memory alloy fiber reinforced hybrid composite beams with symmetric and asymmetric lay-up by utilizing the Euler–Bernoulli beam theory and the one-dimensional Brinson SMA model. A closed-form solution was obtained for the thermal post-buckling and nonlinear free vibration analysis of such beams. Asadi et al. [11] investigated the free vibration of shape memory alloy hybrid composite beams in thermally pre/post-buckled domains by using the first-order shear deformation theory and the Brinson model. They presented exact closed-form solutions for the buckling temperature, post-buckling deformation and temperature-deformation equilibrium path of these symmetric and asymmetric simply supported beams under uniform temperature rise and an analytical solution for the free vibration of the symmetric beam around the first buckled configuration. Khalili et al. [12] studied a non-linear dynamic response of a continuous sandwich beam with SMA hybrid composite face sheets and flexible core for the case of pseudoelasticity. The Brinson model and a higher order finite element theory were used. Khalili et al. [13] presented a new nonlinear finite element model using a unified formulation for dynamic analysis of multilayer composite plate embedded with SMA wires based on the Brinson's SMA constitutive equation. Khalili et al. [14] analyzed the dynamic response of a continuous pseudoelastic SMA hybrid composite beam subjected to impulse load using the Brinson model, a transient finite element and the Newmark time integration method. Shariyat et al. [15] proposed an enhanced model for forced and transient vibration analysis of rectangular composite plates with SMA wires. The modified Brinson's model, the first-order shear-deformation plate theory and the finite element method were employed. They conclude that the fundamental natural frequency is both load- and time-dependent. Damanpack et al. [16] examined the vibration control capability of shape memory alloy (SMA) composite beams subjected to impulsive loads based on a one-dimensional constitutive model to reproduce pseudo-elasticity, martensite transformation/orientation and ferro-elasticity effects. The equivalent single layer theory of Rayleigh–Euler–Bernoulli, Newmark and Newton–Raphson methods were utilized. They showed that SMA layers with high pre-strain have a passive vibration control capability in low temperatures.

A survey of works previously published shows that, although shell structures are widely used in vibration systems, no research on the vibration analysis of SMA thin cylindrical shells has been reported based on the 3D proposed models of the SMA material response yet. Hence in this paper, the vibration behavior of pseudoelastic SMA cylindrical shells based on Donnell-type classical deformation shell theory is investigated. The main idea of this work is to present a fast and suitable solution procedure to consider the effects of material nonlinearity on the forced radial vibrations of simply supported SMA cylindrical shells under harmonic internal pressure. The behavior of pseudoelastic SMA is simulated via the Boyd–Lagoudas constitutive model numerically implemented by the Convex Cutting Plane Mapping algorithm. The Hamilton's principle is employed to obtain the equations of motion. Differential Quadrature Method (DQM) and Newmark time integration scheme are applied to obtain the radial time and frequency responses of the shell. Also, the natural frequencies of the model are obtained by using DQM for the case of pure austenitic phase to study the frequency response around them during the material phase transformation. In addition, a finite element (FE) model is created to validate the results taken by the present solution procedure.

2. Shape memory alloy Modeling

2.1. Constitutive relations

The constitutive model for polycrystalline shape memory alloys proposed by Boyd and Lagoudas [1] is based on the Gibbs free energy which is given as a function of Cauchy stress tensor ($\boldsymbol{\sigma}$), temperature (T), martensitic volume fraction (ξ) and transformation strain tensor ($\boldsymbol{\varepsilon}^{\mathbf{t}}$) by the following form:

$$G(\boldsymbol{\sigma}, T, \xi, \boldsymbol{\varepsilon}^{\mathbf{t}}) = -\frac{1}{2\rho}\boldsymbol{\sigma} : \mathbf{S} : \boldsymbol{\sigma} - \frac{1}{\rho}\boldsymbol{\sigma} : [\boldsymbol{\alpha}(T-T_0) + \boldsymbol{\varepsilon}^{\mathbf{t}}] + c\left[(T-T_0) - T\ln\left(\frac{T}{T_0}\right)\right] - s_0 T + u_0 + \frac{1}{\rho}f(\xi) \quad (1)$$

where T_0 is a reference temperature and sign (:) signifies the Frobenius inner product of two tensors. The material parameters $\mathbf{S}$, $\boldsymbol{\alpha}$, c, s_0, u_0 and ρ are the effective compliance tensor, the effective thermal expansion tensor, the effective specific heat, the effective specific entropy at the reference state, the effective specific internal energy at the reference state, and density, respectively. The effective material properties can be determined in terms of the martensitic volume fraction and the properties for the pure phases as follows:

$$\begin{aligned}
\mathbf{S}(\xi) &= \mathbf{S}^A + \xi(\mathbf{S}^M - \mathbf{S}^A) = \mathbf{S}^A + \xi\Delta\mathbf{S} \\
\boldsymbol{\alpha}(\xi) &= \boldsymbol{\alpha}^A + \xi(\boldsymbol{\alpha}^M - \boldsymbol{\alpha}^A) = \boldsymbol{\alpha}^A + \xi\Delta\boldsymbol{\alpha} \\
c(\xi) &= c^A + \xi(c^M - c^A) = c^A + \xi\Delta c \\
s_0(\xi) &= {s_0}^A + \xi({s_0}^M - {s_0}^A) = {s_0}^A + \xi\Delta s_0 \\
u_0(\xi) &= {u_0}^A + \xi({u_0}^M - {u_0}^A) = {u_0}^A + \xi\Delta u_0
\end{aligned} \quad (2)$$

where the superscripts A and M denote the austenitic and martensitic phases, respectively.

The function $f(\xi)$ is a transformation hardening function which is used to account for the interactions between the austenitic phase and the martensitic phase, and also among the martensitic variants themselves. A second-order polynomial form of this function is expressed as [1]

$$f(\xi) = \begin{cases} \frac{1}{2}\rho b^M \xi^2 + (\mu_1 + \mu_2)\xi; & \dot{\xi} > 0 \\ \frac{1}{2}\rho b^A \xi^2 + (\mu_1 - \mu_2)\xi; & \dot{\xi} < 0 \end{cases} \quad (3)$$

where the sign $(\dot{\ })$ indicates the first time derivative. The first condition ($\dot{\xi} > 0$) represents the forward phase transformation ($A \to M$) and the second one ($\dot{\xi} < 0$) is the reverse phase transformation ($M \to A$) (see Fig. 1 which depicts a typical pseudoelastic SMA response).

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