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Vibration analysis of an axially moving sandwich beam with multiscale composite facings in thermal environment

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ABSTRACT

An axially moving sandwich beam with two nanotube-reinforced metallic facings and thick viscoelastic core in thermal environment is analyzed. Using the frequency-temperature equivalence principle, both the covers and the core are modeled using four-parameter fractional rheological model in the frequency domain.. The tuning of the two characteristics in the frequency domain made it possible to determine the partial equation of motion of the axially moving beam. The Galerkin method is used to solve the governing partial differential equation. Beryllium copper and 2024-T4 aluminum alloy, are taken into numerical investigations as the matrix materials in facings. The effect of the transport speed and the cover parameters on the dynamic behavior of the moving system is investigated in under-critical range of transport speed.

1. Introduction

The axially moving composite structures are involved in many engineering applications. Paper and textile webs during production, processing and printing, parts of high-speed trains during operation, and flat objects moving at high speeds in space are examples of these applications. Many factors influence the dynamic behavior of the moving plants. The most important are: transport speed, tension, material properties and influence of external environment. Among the external factors affecting the dynamics, temperature plays an important role. Current literature review on dynamics of axially moving systems can be found in the work Marynowski and Kapitaniak [19].

On the other hand, the contemporary development of composite materials is strictly associated with the growing demand various industries for lightweight and durable materials, which could be replaced steel and other metals. At the turn of the centuries composite materials began to appear particularly in the aerospace, maritime and space industries because they offer a number of advantageous mechanical properties. These properties include resistance to electrochemical corrosion, high strength and rigidity with less weight than conventional materials. In many cases, the viscoelastic properties of these materials are highly desirable. This happens for example in the aerospace and automotive industries, where the reduction of structural vibrations by the application of surface damping is a frequent practice.

Studies of dynamics in the field of composite are carried out for a long time. In the fifties of the twentieth century a method of damping of flexural vibration of the beam by means of viscoelastic laminate layers was presented by Ross et al. [22]. In sandwich configuration, the damping of the plate is caused by elongation and shear of viscoelastic layers. Theoretical and experimental analysis of the effectiveness of different configurations of viscoelastic damping layers was presented. The method presented in [22], known in the literature as the RKU method was verified and used later in the works of many researchers (e.g. [1, 13, 15]).

The appearance at the end of the last century many new laminates caused interest in dynamics of layered composites with viscoelastic cores. To describe the viscoelastic properties of the core both classical rheological models and fractional rheological models were used. For example in the study by Bagley and Torvik [2] three-layer beam with fractional internal damping is analyzed by using both a continuum formulation and a finite element formulation. In the study by Cupiał and Nizioł [7], three-layer plate with a viscoelastic middle layer is analyzed. To describe the viscoelastic properties of the core a complex shear modulus determined from classical rheological models is used in this study.

The inaccuracy of the classical rheological models can be observed in the frequency domain, where the slope of the experimental amplitude curves is always smaller than that of the curves predicted by these models. The reason for this inaccuracy can be found in the stress-strain relationship defined in the time-domain by a linear differential equation of integer order. By replacing the integer order derivatives in the standard rheological model with fractional order ones, the four-parameter rheological model with fractional derivatives was introduced in the study by Pritz [21]. The effect of the parameters on the frequency curves was demonstrated in this study. It is shown that there is a strict relation between the dispersion of the dynamic modules, the loss peak and the slope of the frequency curves of the viscoelastic material. Since

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that time, the fractional model was used in many works (e.g. Beda and Chevalier [4]; Cortes and Elejabarrieta [5,6]; De Espindola et al. [8]; Monje et al. [20]; Ghanbari and Haeri, [10]). Overview of publications in this field, together with a critical analysis of, applications of fractional derivatives in modeling of mechanical systems, can be found at the study of Rossikhin and Shitikova [23]. The state of researches in the dynamics of laminated composite and sandwich plates in the paper by Sayyad and Ghugal [24] is presented.

In contrast to the case of stationary laminated composites, the literature on dynamic analysis of axially moving composite systems is rather limited. Two studies by Hatami et al. [11,12] devoted to free vibrations of axially moving multi-span composite plates were published in recent decade. To model visoelastic properties of moving plate, two parameters Kelvin-Voigt rheological model was used in these papers. A simple model to study the dynamic behaviors of the axially moving sandwich beams with viscoelastic core, which is described by Kelvin–Voigt rheological model was proposed by Marynowski in the study [17]. Free vibrations and stability of an axially moving rectangular antisymmetric cross-ply composite plate are investigated by Yang et al. in the study [30]. The state of researches in the field of axially moving viscoelastic plates in the book by Banichuk et al. [3] is presented.

Recently, due to their outstanding properties sandwich structures are likely to play a great role in the construction of reusable transportation systems as well as in the construction of micro-electromechanical systems. Moreover, sandwich construction has become even more attractive to the introduction of advanced composite materials for the face sheets, e.g. fiber-reinforced composites, or functionally graded ceramic–metal materials (e.g. [28, 31]). It has been shown that carbon nanotubes (CNTs) have extraordinary mechanical properties over carbon fibers [26]. The considerable advantages offered by carbon nanotube-reinforced composites (CNTRCs) over carbon fiber-reinforced composites have prompted an increased use of sandwich structures with CNTRC facings.

Among the external factors affecting the dynamics of multiscale composites, temperature plays an important role. Accurate identification of the temperature effect on the dynamics is important to properly control these very often expensive devices (e.g. [25]). However, the literature review shows that the dynamic studies of axially moving multiscale composites in thermal environment are very limited. On the basis of the frequency-temperature equivalence principle and the elastic–viscoelastic equivalence, free vibration analysis of the moving orthotropic multiscale composite plate was presented by Marynowski in the study [18]. To describe thermomechanical properties of the plate material, viscoelastic properties of multiscale fiber reinforced stationary composites presented in literature were taken into account. The effects of transport speed, internal damping and the volume fraction of fibers in the plate material on natural frequencies are presented in this study.

The objective of this study is vibration analysis of the axially moving sandwich beam with two nanotube-reinforced metallic facings and thick viscoelastic core in thermal environment. To describe thermomechanical properties of the beam materials, properties of stationary composites presented in literature are taken into account. Fractional standard rheological models both of the core and the face material as the functions of reduced frequency depended on the temperature are taken into considerations. The effects of temperature, transport speed, and volume fraction of CNTs in metallic facings on natural frequencies and critical transport speed are analyzed.

2. Temperature – frequency equivalence

It is known that most viscoelastic materials exhibit dynamic behavior which depends strongly on frequency and temperature. When such a material is subjected to periodic load, the induced deformation is also periodic out of phase. Then the stress-strain relationship can be characterized by complex modulus given in the frequency domain by

$$G_c(\omega) = G(\omega)(1 + i\,\eta(\omega)), \tag{1}$$

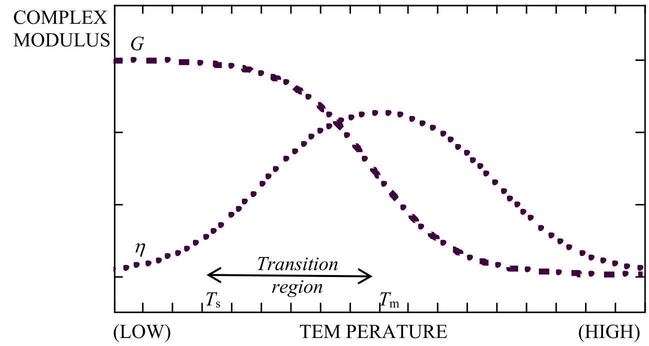

Fig. 1. Effect of temperature on complex modules behavior.

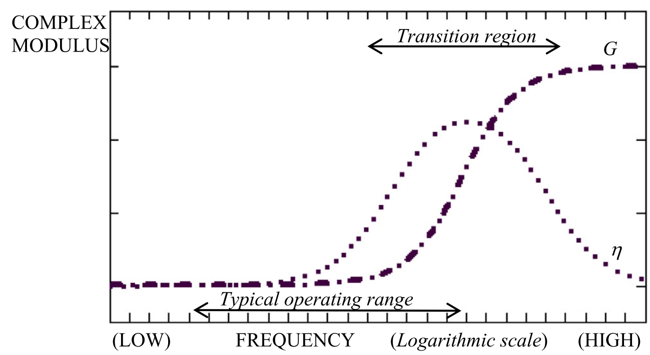

Fig. 2. Effect of frequency on complex modules behavior.

where $G(\omega)$ is the Kirchhoff's modulus, and $\eta(\omega)$ is the loss factor.

Polymers, as the material of the core in the sandwich structure, are composed of long intertwined and cross-linked molecular chains, each containing very many atoms. The internal molecular interactions which occur during vibration leads to energy dissipation and damping. If the polymers are homogenous and isotropic, the stiffness and damping characteristics vary with temperature and frequency. The shear and extensional moduli are closely related to each other for homogenous and isotropic polymers [13].

The complex modules properties of polymers vary strongly with temperature, in ways particular to each polymer composition. Fig. 1 illustrates nonlinear behavior of some typical polymers.

Fig. 1 shows that above softening temperature T_s in the transition region, the shear modulus decreases rapidly and the loss factor rises to a maximum in the temperature T_m and then falls again. In temperatures above the transition region, the modulus is low, and as the temperature continues to rise, the material disintegrates. Meanwhile the effect of frequency for many polymers is the inverse of the effect of temperature. Increasing frequency is similar to the effect of decreasing temperature, but at much different rates, as Fig. 2 illustrates. The difference is very significant. While the temperature may vary by a few hundred degrees to reach the transition region, the corresponding change of frequency encompass many orders of magnitude. In this range the frequency can vary from 10^{-8} Hz to 10^{8} Hz or more. For low frequencies the loss factor and shear modulus increase slightly. In transition region one can observe strong increase of loss factor, which takes maximal value and then significantly decreases. In this region the shear modulus increases. Above the transient region one can notice further decrease of loss factor and slight increase of the shear modulus, which takes maximal value.

Meanwhile, it is well known that at small stresses and at low temperatures far below the melting point most metals behave in a nearly elastic manner. Viscoelastic effects in metals, used as covers in sandwich structures, are usually much smaller than those in polymers. Viscoelasticity manifests itself in the form of a small, but nonzero value of the loss fac-