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Semi-active control of a sandwich beam partially filled with magnetorheological elastomer

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ABSTRACT

The paper deals with the semi-active control of vibrations of structural elements. Elastomer composites with ferromagnetic particles that act as magnetorheological fluids are used. The damping coefficient and the shear modulus of the elastomer increases when it is exposed to an electro-magnetic field. The control of this process in time allows us to reduce vibrations more effectively than if the elastomer is permanently exposed to a magnetic field.

First the analytical solution for the vibrations of a sandwich beam filled with an elastomer is given. Then the control problem is defined and applied to the analytical formula. The numerical solution of the minimization problem results in a periodic, perfectly rectangular control function if free vibrations are considered. Such a temporarily acting magnetic field is more efficient than a constantly acting one. The surplus reaches 20–50% or more, depending on the filling ratio of the elastomer. The resulting control was verified experimentally in the vibrations of a cantilever sandwich beam.

The proposed semi-active control can be directly applied to engineering vibrating structural elements, for example helicopter rotors, aircraft wings, pads under machines, and vehicles.

1. Introduction

The constantly increasing requirements for the improvement of the comfort and safety of structures require innovative solutions that reduce adverse vibrations. The proposed semi-active approaches should significantly improve the dynamic properties of structures in comparison to their passive analogs. At the same time they should have low energy requirements, making them attractive alternatives to solutions based on forced control. Properly developed adaptive optimal control strategies will make it possible to both minimize oscillations and respond to instantaneous extreme states. The effective reduction of vibration is widely applied in modern technology, such as the aerospace, automotive, rail, and construction industries. In order to enhance vibro-isolation, solutions with controllable properties must be reached. Adaptive sandwich structures with an intelligent core should be used for the dynamic stabilization of various types of problems in structural engineering. The main aim is to elaborate an efficient semi-active control. According to current approachable solutions, electrorheological and magnetorheological materials can be used. Research into this group of materials has been extensively

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carried out. Dampers or clutches with magnetorheological fluids have been successfully used in the automotive industry and for the stabilization of high buildings vulnerable to seismic activity. Particularly noteworthy are magnetorheological elastomers in which the phenomenon of sedimentation of ferromagnetic particles is not observed. The constitutive models of magnetoelastic composites [1] and the macroscopic behavior of these materials [2,3] have been developed. Experimental work presenting new methods of production of smart elastomers [4] has also been carried out. In the literature, there are attempts to apply these new materials to engineering problems. One such is the development and evaluation by simulations of an isolator for controlling seat vibrations in order to improve the comfort and safety of passengers [5]. The use of layered structures with controllable materials is a natural way to meet the requirements imposed by innovative industries. A series of theoretical papers on smart sandwich structures have studied their parametric instability regions, natural frequencies, and loss factors for different values of the electric or magnetic fields [6–8]. In [9], the possibility of using electrorheological materials in the control of layered structures was demonstrated. A series of papers related to the finite element method have also been published. These papers concern the determination of the dynamic characteristics of particular sandwich structures. The influence of a magnetic field on the shear modulus [10,11], the natural frequency, and the loss factor [12–14] has been examined. Also, experimental work related to the assessment of the dynamic parameters of layered structures usingelectrorheological and magnetorheological materials with varying electric or magnetic field [15–18] has been carried out.

The dynamics of layered structures have been an object of study for many years. The pioneering work [19] refers to the transverse vibration of an infinitely long beam with a damping layer. In [20,21], the longitudinal free vibrations of a finite three-layer beam with a viscoelastic core were examined. The transversal oscillations of a sandwich beam of finite length excited by an external force were considered in [22]. The vast majority of further work has made use of the mathematical basis provided by the solutions referred to above, identifying the loss factor [23] or the stability of the system [24]. In [25] a non-uniform shear stress variation across the thickness of each layer was assumed. An analytical model that takes into account the compressional vibration of the layered beam was treated in [26]. Attempts to describe the sandwich beam with simple models were made in [27]. In order to take into account the large amplitude vibrations of sandwich structures, nonlinear modeling has also been carried out [28,29].

Smart damping of vibrations is widely undertaken in the literature. In [30] the bolted joint connections of large space structures were considered. Damping as a result of friction in joints has proved to be a major source of energy dissipation. A friction model with velocity-dependent dynamics is used to describe the friction phenomena. In order to improve the damping performance, the normal contact force related to friction was appropriately controlled. The verification of the control strategy was performed using a piezoelectric stack disc. A new method for the semi-active control of vibrating structures has been introduced in [31]. The proposed idea aims at releasing the strain energy accumulated in the structure during its deformation process. According to the Pre-stress Accumulation Release (PAR) strategy, the strain energy is converted into kinetic energy of higher modes of vibration, which is suppressed with damping. Numerical simulations and experimental results confirmed the effectiveness of the semi-active control strategy in the case of a free vibrations structure.

The aim of the present paper is to combine two components in a single entity: a layered structure with a core of variable dynamic properties and the concept of adaptive control. Optimal control in the dynamics of a structure is quite common. Most existing solutions are based on linear quadratic regulation (LQR), but these solutions are not satisfactory. Due to the absence of adequate theoretical solutions, there have been only a few attempts to use controlled magnetorheological elastomers in real technical applications. However, in many cases, in the field of the dynamics of the structure, the control of the system parameters in time is confused with a one-time selection.

2. Mathematical model

Theoretical analysis cannot be performed for arbitrary structures with equal simplicity. For an analytical solution, the simply supported beam was chosen as it is one of the most representative structures. The governing set of differential equations for the vibrating sandwich beam was derived in [22]. The necessary assumptions and simplifications of the analytical model are briefly described below. Let us consider a three-layered sandwich beam. Its cross-sectional geometry has a characteristic width b and the thicknesses of the three layers are h_1, h_2, and h_3 (Fig. 1). Longitudinal displacements u in the x direction and transversal displacements w in the z direction of the beam were taken into account. The face-plates are purely elastic, with Young's moduli of E_1 and E_3. The core is linearly viscoelastic and defined by shear modulus G. The mathematical model is obtained under some physically simplifying assumptions. The shear strains in the outer layers and

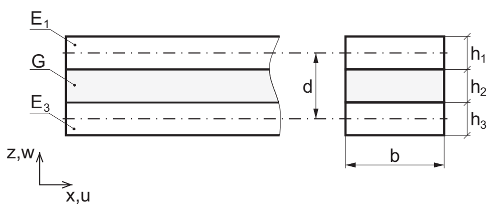

Fig. 1. Three-layered sandwich beam.