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Transient response analysis of a steel beam with vacuum packed particles

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ABSTRACT

In this paper the method of semi-active damping of vibrations is presented. Free vibrations of a cantilever steel beam encapsulated in a sleeve, filled with the granular material are investigated. Various values of the partial vacuum generated in the granular structure allow to control the global dissipative properties of the discussed system. The loose grains encapsulated in the hermetic, polyvinyl chloride (PVC) envelope transform into a rigid, viscoplastic body as the jamming mechanism occurs when the underpressure is generated. Such phenomenon enables original strategies for semi-active damping. A detailed discussion related to the experimental results concerning the amplitude of vibration, damping, stiffness, and frequency of the continuous granular beam system is provided. The simplified Finite Element Model succeeded in describing the dynamic response of the structure.

1. Introduction

Passive damping methods provide an efficient and cost-effective solution for overcoming the problem of vibrations. Passive control involves modification of the stiffness, mass or damping of the system to make it less susceptible to vibrations, without requiring an external power source to operate. One of the most commonly proposed solutions for the passive damping of the beam are the composite sandwich sheets in which a thin layer of viscoelastic material is placed between face layers. These methods were extensively described in papers on the passive Constrained Layer Damping (CLD) (Douglas and Yang, 1978; Cho et al., 2000) which were mainly devoted to axial and bending vibration of the sandwich beams, predicting the energy dissipation of the layers.

Another method for passive vibration attenuation is based on the dissipative nature of particle collisions in the granular material. The motion of the loose grains inside the enclosure causes the dissipation of part of the energy through non-conservative collisions. This mechanism was applied in linear particle dampers (Sanchez et al., 2012; Saeki, 2002), and further used for the damping of the beams. Park and Palumbo (2009) described the structural vibration damping capabilities of the loose, lightweight particles, filling cavities in aluminum sandwich beams. The vibration of the structure induces vibration of the micro particles in the cavities, which dissipate energy into the heat due to the internal damping. McDaniel and Dupont (2000) investigated the vibration damping of beams filled with tightly packed elastomeric beads. In (Nayfeh et al., 2002) authors described a set of experiments in which aluminum beams are filled with granular material, whose total mass is only 3% of that of the unfilled beam, and the average particle diameter is 65 microns. In all of the mentioned studies it was shown that the conduction of energy into the micro-sized granular material and the following dissipation increases the vibration damping significantly.

The problem addressed in this article deals with damping of beam vibrations by means of the granular medium, although it is notably different from the solutions in the publications mentioned above, and uses different principles. Particularly, this paper aims to shed light on the mechanics of the complex beam with the semi-active control method, exploiting the properties of the specially designed granular structure subjected to underpressure.

Semi-active control utilizes the motion of the structure to develop the control forces, so the energy requirement is smaller than in the typical active damping treatment (Azvinet et al., 1995; Snamina et al., 2012). The real time parameters of the system, such as the stiffness or the coefficients of damping, can be controlled. The semi-active methods of damping of the beams typically use modified piezo-actuators (Ramaratnam et al., 2004) or magnetorheological materials (Nakate and Pawar, 2013), but utilizing

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properties of the granular structure subjected to a partial vacuum seems unique.

The proposed structure exploits fluid-like to solid-like reversible phase transition of the granular material, known as jamming (Chakraborty and Behringer, 2009). Unlike in the mentioned paper, the particles are rather large, with a diameter of several millimeters. For the considered size of the particles, the phase transition is temperature-independent. The transition can be forced by subjecting the structure to underpressure, and properties of the structure can be controlled by precisely adjusting the value of the partial vacuum. The detailed construction of the beam is discussed in Section 2.

The properties of tailor made, light weight granular materials give possibility to manufacture low-cost and efficient damping devices for beams, rods, plates, etc. Loeve et al. (2010), described the vacuum granular shaft used as a flexible endoscope guide with controllable rigidity. The vacuum packed particles are also being used in medical pillows, mattresses and splints which form a firm, uniform support for all parts of the body and stabilize the broken limbs of hospitalized patients (Luscombe and Williams, 2003). In Steltz et al. (2010) and Brown et al. (2010) the authors describe soft robots and a universal robot gripper with elastic cells filled with granules that allow control of the motion of the devices.

In this study, transient dynamic analysis was used to determine the time–history response and the parameters of the complex beam under time dependent loads. The necessary experiments were performed to determine the coefficients for the modified equations of motion. The dynamic behavior of the structure was modeled, taking into consideration the influence of the underpressure on the response of the system. To the authors' knowledge, there are no devices using granular materials subjected to underpressure for controlled vibration damping, so the proposed concept can be a substantial contribution.

2. Concept of the particular structure

The construction of the proposed complex beam incorporates a granular structure that allows changing the damping characteristics by varying the pressure value in the structure.

The structure comprises a core beam, made from spring steel, and a viscoelastic polyvinyl chloride (PVC) sleeve with homogeneous granular material filling, made of acrylonitrile butadiene styrene (ABS) (Fig. 1). The sleeve hermetically coats the steel beam. The main dimensions of the structure are presented in Figs. 1 and 2a. Two different types of granules were used to fill the sleeve: rollers ϕ 2.7 mm × 3 mm (density 700 kg/m^3) and spheres ϕ 6 mm (density 1132 kg/m^3).

The hose connector of the pressure valve is connected to the vacuum pump. When the pump is switched off, the granular structure is in a compliant state, and the beam can be easily bent, as the particles have space to move inside the sleeve (Fig. 2a). Evacuating the air from the sleeve allows triggering the jammed state of the granules (Fig. 2b). The distinctive feature of such a beam is the ability to control the amount of dissipation in the system by varying the control signal. Hence, it enables the reduction of the free transverse vibrations.

The negative pressure intensifies the mechanisms which enhance the rigidity of the structure and the energy of dissipation, like the friction and slips among particles and between particles and the enclosure (Pyrz and Zalewski, 2010; Jiang et al., 2012). Particle intrusion occurs when granules change their position or orientation. The particle can also be pushed over an underlying layer as particle hopping occurs (Cates et al., 1998). Particle deformation can promote or inhibit the total deformation (Loeve et al., 2010). The level of deformation of the particles depends on the hardness and stiffness of the granular material (Kadau et al., 2006). The stability of the packing and the probability distributions of forces depends on the number of layers up to a certain limit, and were examined in (Aguirre et al., 2001).

3. Experimental results

Based on the uniaxial tensile and compression test, the reasonable possibility of controlling the elastic range of deformations of the considered granular structure was stated as −0.01 to −0.095 MPa (Zalewski, 2010; Zalewski and Pyrz, 2010, 2013). Outside this range, the influence of underpressure change on the system parameters diminishes. The observed benefits of the "jamming" mechanism occurring in mentioned vacuum packed particles encouraged authors to apply discussed structures for a semi-active damping of vibrations.

The main part of the research was devoted to the longitudinal vibrations of a 0.42 m long beam, in a clamped-free configuration (Fig. 1), which vibrates freely by displacing the tip by 0.03 m. The initial displacement of the end of the beam was realized by a thin thread tensioned until a predetermined deflection was achieved. After setting up the data acquisition, the system was released by burning out the thread. The vibrating structure was allowed to come to rest while the oscillations were recorded.

The negative pressure inside the sleeve was set individually before every measurement, and remained constant during the vibrations. Measurements with no vacuum were not performed, as the structure requires at least some of the underpressure to keep the granules locked in place and to retain the rectangular shape of the cross section of the complex beam. The minimum negative pressure that keeps the particles in place and prevents shape distortion is −0.01 MPa. This means that all of the measurements were performed after the initial jamming phase transition. The shape of the vibration mode reaches maximum at the beam's tip. The amplitude of the displacement of this point was recorded with the 2D CMOS laser distance measurement system, with an accuracy of 40 μm at 520 Hz sampling frequency.

The history of the amplitude of the displacement of the beam's tip is presented in Fig. 3a and b for spherical and roller shaped particles, respectively. These two cases illustrate the effect of different underpressure applied in the structure on the response of the beam. A significant reduction of the amplitude of the vibrations is observed for increasing underpressure. For a better clearance, the envelopes of the curves were plotted.

The envelopes were analyzed for 5 s of vibration, and were approximated by the exponentially modulated decay curves. The fitting algorithm gave a very good agreement with the experimental and fitted curves.

After 5 s of vibration, the amplitude of the displacement was below 0.002 m, which was out of the interest of the study. Separating this part allowed the quantification of the damping with the logarithmic decrement δ or the damping ratio ζ, which is typically used for systems with the viscous damping.

The logarithmic decrement value is defined as:

$$\delta = \frac{1}{N} \ln \frac{x_n}{x_{n+N}} \tag{1}$$

where x_n and x_{n+N} are the amplitude of vibration of n and $n+N$ cycles, respectively, N is the number of cycles.

The logarithmic decrement and the damping ratio can be connected by the expression:

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{2}$$

The obtained experimental damping ratio value is plotted on the graphs of the frequency response of the beam (Fig. 4). The