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Vibration control of adjacent beams with pneumatic granular coupler: An experimental study

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ABSTRACT

A novel type of pneumatic device filled with granular material is proposed in the implementation of a switched control strategy to stabilize the vibration of slender structures. The analytically obtained control law for the airtight, elastic, granular coupler is implemented in a test structure with a relay-type control logic. In the experiment, the deformable granular coupler semi-actively damps an initially deflected pair of adjacent, aluminum beams. Two cases of initial excitation are considered, showing an improvement of up to 33% in vibration abatement efficiency compared to the passive case. Although this semi-active device is conceptually simple, its ease of operation and low cost should attract the attention of engineers who seek solutions that can be used to build new structures and upgrade existing ones.

1. Introduction

Typical damping techniques performed with granular materials have been studied in the literature over the years. In these techniques, a passive vibration suppression is obtained with particles placed in a container attached to the primary structure or packed in structural voids [1–3]. As the primary structure vibrates, the loose particles collide with each other and against the container walls. Non-conservative interactions such as momentum transfer, frictional deformation, internal energy dissipation, etc. facilitate the reduction in kinetic energy [4,5].

The damping method introduced in this paper is notably different from that of typical granular dampers, which operate in a fully passive manner. The main difference between them is the restricted movement of the particles, which are no longer loosely placed in a rigid container but tightly packed in an airtight, elastic sleeve (Fig. 1). The construction of a hermetic sleeve made of natural latex rubber allows controlling underpressure among tightly bounded granules. Many parameters like shape, size, material or mass ratio of the granules and sleeve may affect the efficiency, thus the issue of optimal constructional parameters is open. The dynamic control of the underpressure intensifies the jamming mechanism, allowing transition of the filling material from a fluid-like to a solid-like phase and enhancing the global rigidity of the ensemble [6]. In this paper, the authors describe the global damping properties of the granular coupler applying phenomenological approach, rather than analysing non-trivial particle interactions in the jammed state.

The proposed vibration mitigation system is composed of electromechanically controlled vacuum pump, displacement sensors and the granular dissipator. The principle of vibration abatement is based on a energy transmission controlled by sequentially coupling parallel structures of different dynamic characteristics to mistune their motion according to a state-feedback control law. The granular coupler in practice is a semi-active, deformable damper with time-dependant parameters of dissipation. The parametrical modification of the system, is often referred to as "switching times control" [7] or "prestress-accumulation-release" strategy [8]. Usually, the switching takes place between two extreme control values, as in the "bang-bang" type of control, or between two states of the actuator, as in on-off logic.

The controlled jamming of granular materials has rather rarely been explored in vibration attenuation, since morphing of the boundary walls of the container may be difficult to achieve. Author in [9] discusses the use of a cellular structure, shape memory alloys, or electromagnets to increase the static pressure among the granules and force the jamming transition. In [10] granules were placed inside a rigid container with an adjustable position of the top lid that allowed compressing the granules and obtaining a variable stiffness. The use of a pneumatic control to increase the static

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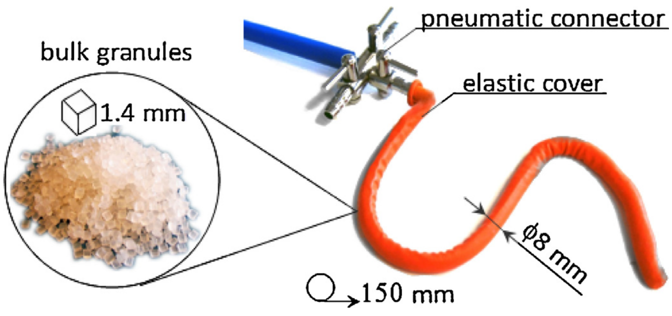

Fig. 1. Experimental granular coupler (length 150 mm, ϕ8 mm) filled with cubic ABS granules (1.4 mm × 1.4 mm × 1.4 mm).

pressure of a controllable granular structure covering steel beam was presented in [11]. In the following work, the concept of a new type, deformable, damping device filled with granules is presented. The obtained parametrical control policy of the pneumatically operated device is adapted for sequential coupling of slender beams, demonstrating the effectiveness of vibration abatement obtained with the prototype.

2. Investigated system

We will consider structures that can be represented by a set of linear elastic slender beams, as depicted in Fig. 2. For each beam we assume a constant rectangular cross-section A, length L_1 and L_2, cross-sectional inertia I, mass density ρ and elastic modulus E. To capture the dynamics of the beams, subjected to bending, we select the Euler model. This model provides high accuracy and is relatively simple for the control purposes. The imposed assumption of linear elasticity indicates that only small and moderate loads are considered.

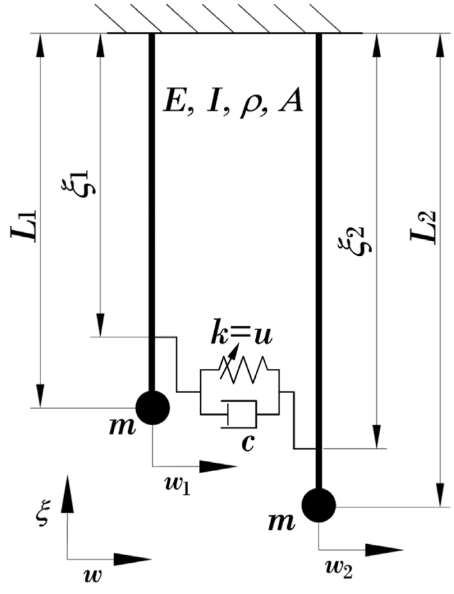

Fig. 2. The investigated system of adjacent beams with Kelvin–Voigt mathematical model of the granular coupler.

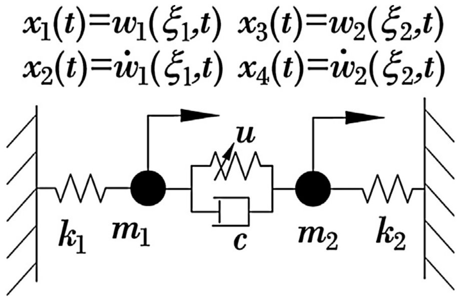

Fig. 3. The reduced system of combined cantilever beams represented by coupled oscillators.

The granular coupler is located at the positions ξ_1 and ξ_2 and joins the adjacent beams. As we shall demonstrate later, the selection of $\xi_1 \neq \xi_2$ is required to provide high performance for the stabilising controller. For the mathematical description, the granular coupler is represented by the Kelvin–Voigt (K–V) model, which consists of a purely viscous damper c and a purely elastic spring k. As discussed in [12], the K–V model provides a good approximation of the experimental data for a wide range of granular materials subjected to underpressure, and is easy to adapt to control and optimisation problems. A variable stiffness k is assumed for the control parameter and later denoted by u.

Let w_1 and w_2 stand for the transverse deflections of the beams (which are later measured experimentally). The system is governed by the following set of partial differential equations:

$$\begin{aligned}
&\rho A\ddot{w}_1 + EIw_1'''' + \delta(\xi-\xi_1)[c\dot{w}_1 + k(t)w_1] - \delta(\xi-\xi_2)[c\dot{w}_2 + k(t)w_2] + \delta(\xi-L_1)m\ddot{w}_1 = 0,\\
&\rho A\ddot{w}_2 + EIw_2'''' + \delta(\xi-\xi_2)[c\dot{w}_2 + k(t)w_2] - \delta(\xi-\xi_1)[c\dot{w}_1 + k(t)w_1] + \delta(\xi-L_2)m\ddot{w}_2 = 0.
\end{aligned} \tag{1}$$

Here, dot and prime denote differentiation with respect to time t and the space coordinate ξ, respectively. The ends of the beams that are fixed impose the following boundary conditions: $w_i(0,t) = w'_i(0,t) = w''_i(L_i,t) = w'''_i(L_i,t) = 0, i = 1, 2$. For the initial conditions, we assume non-zero initial deflections w^0 and initial velocities $\dot{w}^0$: $w_i(\xi,0) = w_i^0(\xi)$, $\dot{w}_i(\xi,0) = \dot{w}_i^0(\xi)$, $i = 1, 2$.

3. Control design

The stabilising controller will be based on a practical state-dependent switching law. The control strategy design and synchronisation analysis will be carried out employing the first modal approximation to (1). The reduced size of the system will enable us to perform the experimental tests with the available equipment. The proposed general methodology can be implemented in multimodal systems.

3.1. Model reduction

Let us consider the system depicted in Fig. 3. Referring to Fig. 2 each beam is now represented by a simple oscillator, and joined by the controlled pneumatic coupler.

The parameters of the oscillators mimic the dynamics of the first natural modes of the beams. Denoting by ω the first natural frequency of the cantilever, the stiffness and the mass of the reduced system can be computed as: $k_1(\xi_1) = 3EI/\xi_1^3$, $m_1(\xi_1) = k_1(\xi_1)/\omega^2$,

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