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Moving loads on beams on Winkler foundations with passive frictional damping devices

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ABSTRACT

This paper analyses the dynamic behavior of Euler-Bernoulli beams on elastic foundations of the Winkler type submitted to moving loads. In particular, the usefulness of passive frictional damping devices, that present ecological and economic advantages with respect to viscous ones, in the context of minimizing the consequences of resonance phenomena is studied.

A program in Matlab environment based on the finite element method (FEM) that simulates the dynamic behavior of the beam, foundation and frictional damping devices driven by a moving load, is developed and used to study the effect of the frictional dissipation on the values of the critical velocities and dynamic amplifications. The time integration of the global equations of the motion is performed using the nonsmooth contact dynamics method (NSCD) with persistent contact, especially conceived for friction problems which are governed by a nonsmooth constitutive law.

1. Introduction

In this paper the dynamic behavior of Euler-Bernoulli beams on elastic foundations of the Winkler type submitted to moving loads is analyzed. The usefulness and efficiency of passive frictional damping devices for the minimization of resonance phenomena is studied. The control of excessive vibrations is of special interest in the design and management of high-speed rail tracks. It is well know that for some velocity ranges the oscillation amplitudes may become very large, thus endangering the structural and passengers' safety. This amplification of the oscillations occurs usually for very high speeds. However, records of high dynamic amplifications in rail tracks exist for ordinary velocities ($v = 202$ km/h) due to the presence of soft foundation soils [1]. The most common solution for the control of excessive vibrations in structures has been the use of viscous dampers. In viscous dampers the damping force is proportional to the velocity of deformation while in frictional damping devices the damping force varies between a minimum and a maximum value depending on the sign of the velocity of deformation. Frictional damping presents ecological and economic advantages (cost and maintenance) with respect to viscous one [2,3] and has been successfully used in many civil and mechanical engineering applications, either in bladed disks [4], rotors [5], cables [6] or train suspension systems [7].

The dynamics of beams subjected to moving loads has been investigated over the years by several authors. From the initial analytical studies, it is worth mentioning the works by Krylov [8], Timoshenko [9], Inglis [10], Lowan [11] and Frýba [12]. The static problem of a beam on a linear elastic foundation was addressed by Hetenyi [13]. Later, Timoshenko et al. [14] analytically solved the free vibration problem of a beam on an elastic foundation. Various linear [15–19] and nonlinear [20–24] foundation models have been used and the response of beams resting on elastic foundations subjected to a moving mass or a moving oscillator has also been investigated [25–32]. The finite element method was also used to study the behavior of beams on elastic foundations subjected to moving loads [33–37].

When the velocity of the moving force becomes equal to the minimum phase velocity of the waves in the beam-foundation system a resonance phenomenon, characterized by an amplification of the beam's transverse displacements, occurs. This critical velocity in an infinite Euler-Bernoulli beam on a Winkler foundation is [12]

$$v_{cr} = \sqrt[4]{\frac{4kEI}{(\rho A)^2}}, \tag{1}$$

where EI and ρA are, respectively, the beam's bending stiffness and mass per unit length and k is the stiffness of the foundation. Dimitrovová and Rodrigues [38] determined analytically the critical velocities which cause resonance of finite beams under moving loads on uniform or non-uniform linear elastic Winkler foundations,

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with or without viscous damping. Using the FEM, Castro Jorge et al. [39,40] generalized the analyses in [38] for more realistic (nonlinear) foundation behaviors.

The objective of this paper is to study the effect of the frictional dissipation on the values of the critical velocities of the moving load and on the displacement and bending moment dynamic amplifications. Therefore, a program in Matlab environment based on the finite element method (FEM) that simulates the dynamic behavior of the beam, foundation and frictional damping devices driven by a moving load, was developed. In Section 2 the finite element method is formulated and in Section 3 the nonsmooth contact dynamics method (NSCD) [41–43], used in the time integration of the global equations of the motion, is presented. In Section 4 the results of the numerical simulations, namely the effect of the frictional dissipation on the values of the critical velocities and dynamic amplifications, are presented. Different solutions of passive frictional damping are compared and the problem of the optimization of the frictional force is also addressed. Finally, in Section 5 the main conclusions of this study are presented.

2. Finite element formulation

We consider an Euler-Bernoulli beam of length L, cross section area A and density ρ on a linear (visco)elastic foundation of the Winkler type in parallel with a set of discrete Coulomb type supports (frictional damping devices), subjected to a moving load with constant velocity v and magnitude F (Fig. 1). Different support conditions may be considered at the extremities of the beam as represented in Fig. 1. The Coulomb type supports are schematically represented in Fig. 2 and are designed in order to damp the vibrations of the beam.

The continuum system is governed by the partial differential inclusion

$$\rho A\ddot{w}(x,t) + EIw''''(x,t) + kw(x,t) \in -\rho gA + F\delta(x - vt) + \sum_{i=1}^{n_d} R(\dot{w}(x_i,t))\delta(x - x_i), \quad (2)$$

where $w(x,t)$ denotes the transverse displacement at abcissa x in instant t, $\dot{(\,)}$ and $(\,)'$ denote first order partial derivatives with respect to t and to x, respectively, and $\delta(\,)$ is the Dirac delta "function". Each one of the Coulomb frictional damping devices located at abcissa x_i applies a concentrated force R on the beam that is related to the velocity of the beam's cross section at the device location by the inclusion

$$R(t) \in -F_u \mathrm{Sign}(\dot{w}(x_i,t)), \quad (3)$$

where F_u is the maximum frictional force of the device and the multi-application $\mathrm{Sign}(z)$ is defined by

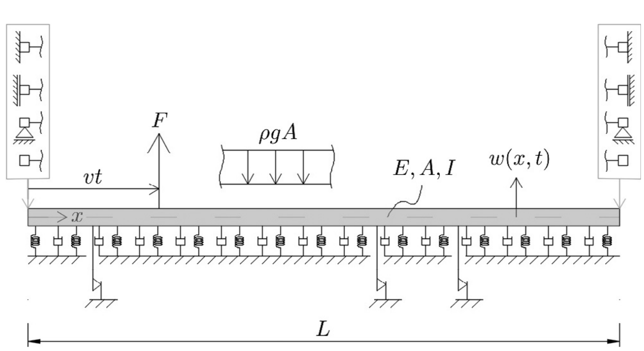

Fig. 1. Euler-Bernoulli beam on a (visco)elastic foundation of the Winkler type in parallel with a set of discrete Coulomb type supports.

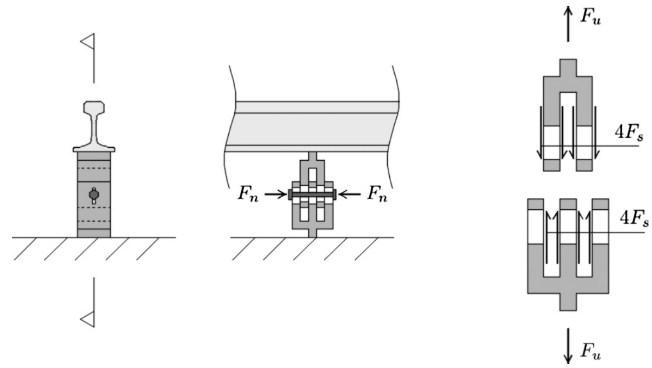

Fig. 2. Schematic representation of a frictional damping device with four bolted sliding surfaces ($n_s = 4$). The existence of ovalized holes allows the relative sliding of the contacting surfaces and the development of a frictional force.

$$\mathrm{Sign}(z) = \begin{cases} -1, & z < 0 \\ [-1,+1], & z = 0 \\ +1, & z > 0 \end{cases}. \quad (4)$$

Inclusion (3), schematically represented in Fig. 3, corresponds to Coulomb's friction law: (a) when the velocity of the beam's cross section above the device is zero ($\dot{w} = 0$), the absolute value of the force applied by the device is smaller than the maximum frictional force F_u, (b) when $\dot{w} \neq 0$, the force applied by the device on the beam has magnitude F_u and is opposed to the motion. The maximum frictional force developed at the device is given by

$$F_u = n_s F_s \quad \text{with} \quad F_s = \mu F_n, \quad (5)$$

where n_s is the number of contact sliding surfaces bolted together in the frictional device, F_s is the maximum frictional force developed at each surface, μ is the friction coefficient and F_n is the bolt force. In Fig. 2 a frictional damping device with $n_s = 4$ is schematically represented.

Inclusion (3) is equivalent to

$$R = \mathrm{proj}_{[-F_u,+F_u]}(R - c\dot{w}) \quad (6)$$

where the projection operator is defined by

$$\mathrm{proj}_{[a,b]}(z) = \begin{cases} a, & z < a \\ z, & z \in [a,b] \\ b, & z > b \end{cases}, \quad (7)$$

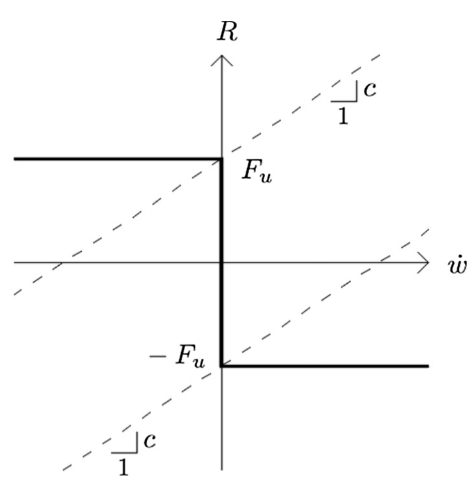

Fig. 3. Graph of the frictional damping device constitutive law. The two dashed lines separate the regions of different behavior in space $R - \dot{w}$: upward sliding ($\dot{w} > 0$), no sliding ($\dot{w} = 0$) and downward sliding ($\dot{w} < 0$).