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Multiple spatially localized dynamical states in friction-excited oscillator chains

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ABSTRACT

Friction-induced vibrations are known to affect many engineering applications. Here, we study a chain of friction-excited oscillators with nearest neighbor elastic coupling. The excitation is provided by a moving belt which moves at a certain velocity v_d while friction is modelled with an exponentially decaying friction law. It is shown that in a certain range of driving velocities, multiple stable spatially localized solutions exist whose dynamical behavior (i.e. regular or irregular) depends on the number of oscillators involved in the vibration. The classical non-repeatability of friction-induced vibration problems can be interpreted in light of those multiple stable dynamical states. These states are found within a "snaking-like" bifurcation pattern. Contrary to the classical Anderson localization phenomenon, here the underlying linear system is perfectly homogeneous and localization is solely triggered by the friction nonlinearity.

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1. Introduction

Many engineering applications make use of frictional damping to dissipate energy. In particular, dry friction is commonly used as a cheap and convenient solution even in very hostile environments, as those where turbine blade rotors operate [1–5]. Also, many general engineering structures are assembled using different kinds of joints, which always introduce interfaces and thus dissipation (and damping) [6–11]. Nowadays many researchers are putting their effort in trying to control (or reduce) frictional resistance [12–15]. In turn, vibrations induced by friction are experienced in many systems too, like in friction brakes, where they generate discomfort and noise [16–19]. Similar phenomena have different names depending on the context: "chatter" in workpiece manufacturing, "brake squeal" and "groan" in automotive and railways industries, and other industrial problems are related to the interplay of frictional contact and system (nonlinear) dynamics [18–24]. Many lumped models have been introduced over time which have tried to capture the underlying phenomena that cause friction-excited stick-slip limit cycles – for example, there is a large literature on the classical mass-on-moving-belt system [25–28]. It has been shown that if at the mass-belt interface, a velocity exponential decaying friction law is assumed, the oscillator undergoes a subcritical Hopf bifurcations [29,30] which naturally implies a region of the control parameter (i.e. the belt velocity) where the system is bistable (i.e., has two stable solutions), and can approach a Steady-Sliding state (SS) with no vibrations, or a High Amplitude Limit Cycle (HALC) [31].

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The present work is devoted to study nonlinear localization phenomena in frictional systems particularly in the case where many elementary cells (the "unit cell") can be recognized, which are assembled together in a form of a chain of weakly coupled elements (see for example the high speed train brake pad in Fig. 1). The possibility for each of them to experience a twofold equilibrium opens the possibility of multi-stable spatially localized equilibrium states when these single components are elastically weakly linked together, allowing mutual interactions. Vakakis has studied weakly coupled chains extensively (see Ref. [32]) with various nonlinearities and forcing concepts, showing "nonlinear normal modes" (NNM) which localize in space and are a property of "weakly coupled" chains [32]. Recently, localized vibrating states have been observed in similar systems (both conservative and self-excited) with geometric nonlinearities [33–35] or nonlinear damping [36]. In the bifurcation diagram, patterns similar to the "snaking bifurcations" are encountered, which have been studied in different physics fields, from fluid dynamics [37–39] to optics [37].

In this study, we will consider a chain of linear oscillators placed on a frictional moving belt driven at a certain velocity. Friction will be described using an exponentially decaying friction law. We remark that the underlying linear system is perfectly homogeneous and with periodic boundary condition (i.e., the first and the last oscillator are also elastically linked), thus if localization arises, it is from the friction nonlinearity. This happens in contrast to the classical Anderson localization [40], which is a linear phenomenon well known in mechanical engineering under the name of "mistuning" [41,42].

The effect of the driving velocity and of the initial conditions is shown to affect the localization pattern.

2. The model: a chain of nonlinear oscillators

The model is an extension of the classical mass-on-moving-belt model. We consider a chain of N linear oscillators (each oscillator has one degree of freedom, see Fig. 2) which are elastically weakly coupled via a linear spring k_c. Each oscillator has mass m, stiffness k, viscous damping coefficient c and is pressed by a constant normal force P against the belt. The position of each oscillator is denoted with x, and a prime indicates differentiation with respect to time $\frac{d\square}{dt} = \square'$.

Friction between the oscillators and the belt is described using an exponential decaying friction law of the relative velocity $v_{rel} = x' - v_d$

$$\mu\left(v_{rel}\right) = \mu_d + \left(\mu_{st} - \mu_d\right)\exp\left(-\frac{|v_{rel}|}{v_0}\right) \tag{1}$$

where v_0 is a reference velocity, $\mu(0) = \mu_{st}$ is the static friction coefficient and $\mu\left(v_{rel} \to +\infty\right) = \mu_d$ is the dynamic friction coefficient, with $\mu_{st} > \mu_d$. Thus, the friction force is

$$\begin{cases} F = -P\mu\left(v_{rel}\right)\operatorname{sign}\left(v_{rel}\right) & v_{rel} \neq 0 \\ |F| < \mu_{st}P & v_{rel} = 0 \end{cases} \tag{2}$$

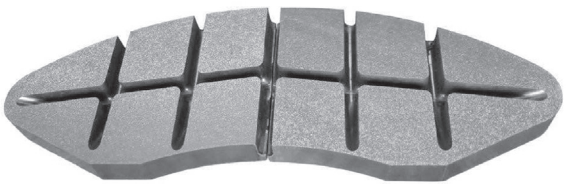

Fig. 1. A typical design for a high speed train brake pad. Deep grooves subdivide the lining material in multiple sectors.
source: http://www.huawu-brakes.com/products_detail/productId=147.html

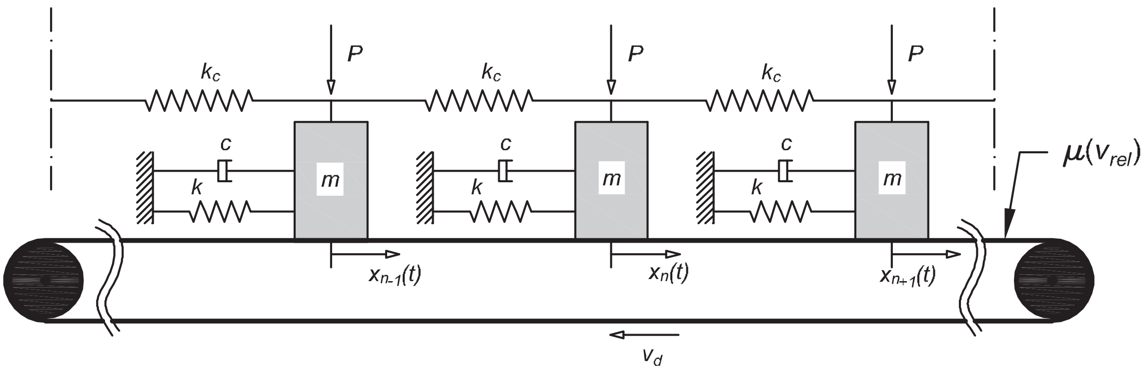

Fig. 2. Geometrical model. It consists of N weakly coupled nonlinear oscillators pressed against a frictional belt.

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