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On the efficacy of friction damping in the presence of nonlinear modal interactions

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ABSTRACT

This work addresses friction-induced modal interactions in jointed structures, and their effects on the passive mitigation of vibrations by means of friction damping. Under the condition of (nearly) commensurable natural frequencies, the nonlinear character of friction can cause so-called nonlinear modal interactions. If harmonic forcing near the natural frequency of a specific mode is applied, for instance, another mode may be excited due to nonlinear energy transfer and thus contribute considerably to the vibration response. We investigate how this phenomenon affects the performance of friction damping. To this end, we study the steady-state, periodic forced vibrations of a system of two beams connected via a local mechanical friction joint. The system can be tuned to continuously adjust the ratio between the first two natural frequencies in the range around the 1:3 internal resonance, in order to trigger or suppress the emergence of modal interactions. Due to the re-distribution of the vibration energy, the vibration level can in fact be reduced in certain situations. However, in other situations, the multi-harmonic character of the vibration has detrimental effects on the effective damping provided by the friction joint. The resulting response level can be significantly larger than in the absence of modal interactions. Moreover, it is shown that the vibration behavior is highly sensitive in the neighborhood of internal resonances. It is thus concluded that the condition of internal resonance should be avoided in the design of friction-damped systems.

1. Introduction

Friction damping is a well-known means of achieving vibration reduction. The damping effect is due to the dissipative character of dry friction occurring in mechanical joints. For this purpose, friction interfaces may be either newly introduced to the structure or may already exist e.g. in the form of bolted or riveted joints. Friction damping is particularly suited for the passive vibration reduction of lightly damped flexible structures. Various applications can be found in the field of aerospace structures, combustion engines or turbomachinery blades [1,2].

Dry friction is a nonlinear phenomenon: depending on the vibration level of a jointed structure, the behavior in the local contact interfaces may range from sticking via micro-slip to macro-sliding. Hence, dry friction may induce the common

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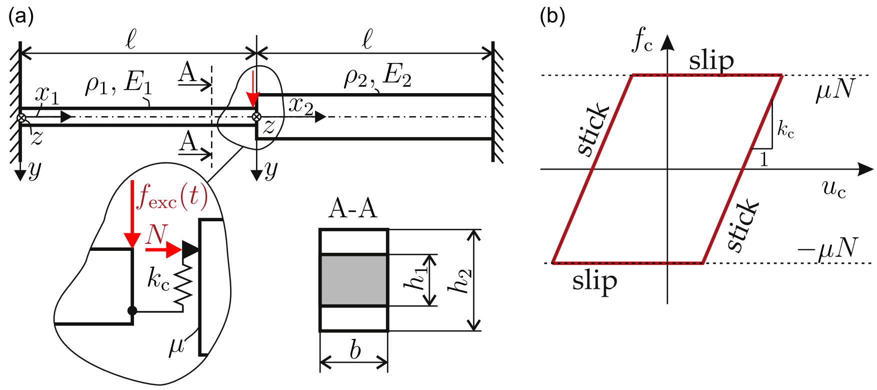

Fig. 1. Investigated model: (a) two beams connected via friction joint and (b) elastic Coulomb friction model; $E_1 = 6 \cdot 10^6 = E_2$, $\rho_1 = 2500 = \rho_2$, $l_1 = 1.0 = l_2$, $b_1 = 0.02 = b_2$, and $h_1 = 0.02$.

nonlinear phenomena. In the context of steady-state harmonically forced vibrations, these phenomena include (a) the dependence of the resonance frequency and the effective damping on the vibration level, (b) the loss of stability of the fundamental periodic response giving rise to sub-harmonic, quasi-periodic or chaotic vibrations, and (c) the occurrence of the so-called nonlinear modal interactions.

Nonlinear modal interactions refer to energy exchanges between two or more of a structure's modes of vibration caused by nonlinear effects. Thus, a mode that is not directly forced by an external source may be excited indirectly by the action of nonlinear forces, and therefore contribute significantly to the overall vibration response. This occurs when the natural frequency of the indirectly forced mode is in a rational relation with the natural frequency of a directly forced mode [3], i.e., when the two modes are in *internal resonance*. Under this condition, a suitable nonlinearity can initiate *mode mixing* caused by energy transfers between the modes, even if their frequencies are well separated. Note that the necessary condition of internal resonance does not have to hold for the natural frequencies of the linearized system, but this condition can be satisfied for larger vibration levels of the nonlinear system when the natural frequencies change accordingly.

In the context of friction damping, numerical and experimental evidence of nonlinear modal interactions was reported, e.g., in [4–8]. Specifically, an important effect on the steady-state forced vibration response in the excitation frequency range around a particular natural frequency is commonly reported: the response of the indirectly forced mode assumes a local maximum. At the same time, the expected pronounced peak in the amplitude-frequency curve of the directly forced mode transforms to a double peak with a local minimum in between two local maxima. This phenomenon appears to be more profound if the joint's normal load fluctuates and the joint undergoes lift off/impacts as a consequence of vibrations [6–8]. Ferri et al. explored the energy transfers from low to high frequencies of friction damped systems under the condition of internal resonances, both in the steady-state forced response and the free vibrations [9–11].

Although nonlinear modal interactions are known to occur in friction-damped systems, their influence on the vibration reduction performance is unknown and yet has to be studied. It should be noted that nonlinear modal interactions are known to play the essential role in the vibration control concept of targeted energy transfer [12]. The key of this concept is that the vibration energy is passively and irreversibly transferred from a primary mode to either a strongly nonlinear attachment or a higher-frequency modes, where it is dissipated more efficiently. The purpose of the present study is thus to investigate how nonlinear modal interactions affect the efficacy of friction damping. To this end, we study a system composed of two cantilevered beams connected via a friction joint, as presented in Section 2. The system can be tuned so that the beams' first bending modes are in 1:3 internal resonance. It is demonstrated in Section 3 how and under what conditions the friction nonlinearity induces the intended nonlinear modal interactions. The consequences for the vibration reduction performance are quantified and explained in Section 4. This paper ends with concluding remarks in Section 5.

2. Model description

2.1. Problem formulation

Consider the system of two beams connected via a friction joint, depicted in Fig. 1(a). Bending vibrations with the deflection $w(x,t)$ in the y-direction are considered. For convenience, the problem is divided into two sections, one for each beam, with local coordinates x_1 and x_2, respectively. In accordance with the classical Euler–Bernoulli beam theory,[1] the

[1] Small deflections, plane sections remain plane, constant length neutral axis, linear-elastic material.