On the Dynamics of Friction Based Tuned Mass Dampers

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Summary. Dynamics of three different types of friction based mass dampers are investigated analytically with the generalized averaging technique in order to understand their behaviour, identify appropriate application fields and provide an optimal tuning. It is shown that the simple lock-up mass damper cuts off the resonance peak of the main system without splitting its frequencies and achieving strong isolation in any frequency range. The mass damper with the normal force in the friction contact being proportional to the deformation of the spring shows properties similar to those of a tuned mass damper with linear viscous dissipation. Finally the tuned mass damper with the sequential friction-spring element combines advantages of the previous systems abolishing vibrations at the frequency of tuning and cutting off the side resonance peaks. All analytic results are confirmed by numerical simulations.

Introduction

Continuously increasing costs of fossil energy carriers and tightening legal regulations in the last years require high energy efficiency in all types of machinery. Consequently, in order to increase efficiency, friction and other damping influences are either eliminated or their impact is systematically reduced in any kind of mechanical machinery (e.g. powertrains, mechanisms, etc.). On the other hand, the strong trend to lightweight design makes mechanical structures extremely sensitive to any kind of vibrational excitation. Thus, regarding these trends which make structures prone to vibrations, it is necessary to introduce an effective and tightly focused vibration damping that doesn't decrease the mechanism's efficiency. One of the promising ideas in this area is to utilise the ability of dry friction to switch between sticking and sliding [1]. This effect has been systematically investigated for a 1 DOF oscillator in [2], both for forced vibrations as well as for self-excitation. It has been demonstrated that this effect used within the sequential friction-spring element enables very efficient suppression of the resonance. In contrast, less attention has been payed to the effects occurring in systems with many DOF; moreover, the corresponding results are mostly restricted to pure friction connectors [3] or resort to numerical analysis which do not offer deeper insight in the underlying mechanisms. Friction based realisations of a classical tuned mass damper are investigated in the present paper (cf. figure 1). The first one (fig.1a) is the standard tuned mass damper locked up by a dry friction element. In the second case (fig. 1b) the mass damper is attached to the main mass via a displacement dependent dry friction element [4] which is connected to the system parallel to the main tuned spring. In the last case (fig. 1c) the sequential friction-spring element [2] is used for the connection between the mass damper and the main system.

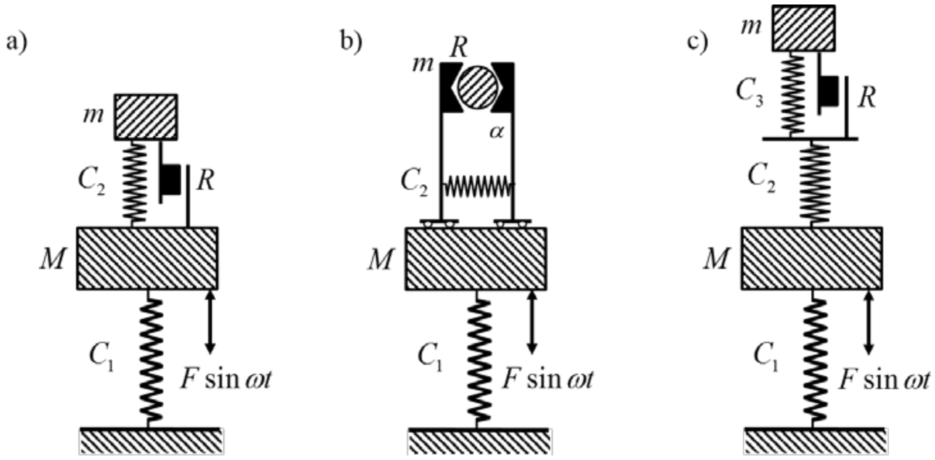

Fig. 1. Structure of the investigated tuned mass dampers, a) a simple friction locked-up mass damper; b) a mass damper with the displacement depending friction force; c) a mass damper with the sequential friction-spring connector.

Analytic approach based on the generalised averaging

Asymptotic analysis of these systems requires several different techniques. Whereas the system shown in Fig. 1b can be treated with the standard averaging, the system shown in Fig. 1a needs a special approach. It is based on the averaging for systems with strong dissipation [5] combined with the following *Proposition* on the validity of averaging results in systems with simple dry friction:

Consider a system with n degrees of freedom with external excitation. Suppose that the only nonlinearity in this system is dry friction with constant friction coefficient μ.

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\mathbf{x} = a\mathbf{f}(t) + \mu\mathbf{r}\,\mathrm{Sgn}\left(\mathbf{b}\dot{\mathbf{x}}\right) \tag{1}$$

M and **C** here are mass- and stiffness-matrixes respectively, **f** is the vector of external excitation forces scaled by the factor *a*, **b** is a constant vector determining between which degrees of freedom the dry friction force acts and **r** is a constant vector distributing the action of the dry friction.

If it is possible to obtain averaging results under the assumption that the amplitude of the excitation $a \ll 1$ and the friction coefficient $\mu \ll 1$are small parameters of the same magnitude order, then this result remains valid also for non-small excitation amplitude and friction coefficient $a = O(1)$, $\mu = O(1)$.

Analysis of the system shown in Fig. 1c can be performed using a combination of both techniques similar to [2].

Main properties of the friction based mass dampers

The characteristic behaviour of the friction based mass dampers is shown if Fig. 2.

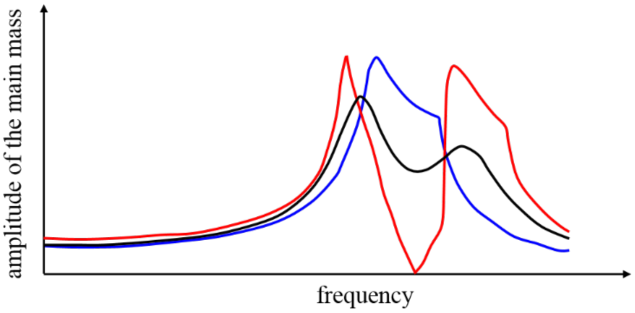

Fig. 2. Amplitude response of the main mass; blue line – the simple locked-up mass damper; black line - the mass damper with the displacement depending friction force; red line - the mass damper with the sequential friction-spring connector.

The simple locked-up mass damper limits the amplitude of the main mass in a wide range of parameters without any viscous damping. Its effect is very similar to that of the sequential friction-spring damper in a 1 DOF system [2]: it doesn’t dissipate energy if the vibration’s amplitude is sufficiently small (due to sticking in the lock-up friction) and starts to slide and to dissipate energy only if necessary. However the current solution has got the advantage that it can be used as an add-on element which is not necessarily integrated in the main structure. The performance of the mass damper with the displacement proportional friction force is very similar to the standard tuned mass damper with viscous dissipation, i.e. the amplitudes of the side resonances are limited but the isolation at the tuned frequency is not perfect due to the unavoidable phase shift between the excitation and the response of the mass damper. Finally the mass damper with the sequential friction-spring connector combines advantages of both systems. Its amplitude at the side resonances is limited and the isolation at the frequency of tuning is perfect. The last effect can be achieved, because the friction element is sticking for sufficiently small forces and it is the case in the vicinity of the tuning frequency. Thus the system works in this area as a damping free tuned mass damper. In the vicinity of the resonances on the contrary the friction element is sliding, it dissipated energy and limits the amplitude similar to the simple locked-up mass damper.

Conclusions

Three types of the friction based tuned mass dampers are investigated both analytically and numerically using the generalized averaging technique. It is shown that the results obtained under the assumption of small friction and small excitation remain valid also for the large parameters being of the same magnitude order. Concerning the applicability of the considered systems the mass damper with the displacement proportional friction force shows the best overall performance concerning the maximal amplitudes in the whole frequency range. The lock-up mass damper cuts off the resonance without diminishing the amplitude at the tuning frequency. Finally the mass damper with the sequential friction-spring element enables to extinguish vibrations perfectly at the tuning frequency and to limit the amplitudes at the side resonances. This behaviour makes the last technical solution advantageous for the applications in machines having a certain operation frequency but requiring limited vibrations while acceleration and coasting down. Analytical solutions enable optimal choice of the parameters for each system depending on the expected application requirements.

References

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