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Design of adjustable Tuned Mass Dampers using elastomeric O-rings

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ABSTRACT

Tuned mass dampers (TMDs) are widely used in passive vibration control, and have been implemented on many engineering structures. In general, the design of TMDs is unique to each application; the choice of damping material and its in-situ performance are key issues that can affect design and prototyping costs. The present contribution demonstrates that TMDs can be built using ubiquitous and low-cost elastomeric O-rings. It is shown that the damping and stiffness characteristics of the O-ring can be predicted a priori, in order to achieve an initial design that is fit for purpose. Furthermore, it is shown that the nonlinear characteristics of the O-ring enable the device to be easily tuned in-situ, in order to optimise the final system. Finally, the simple configuration of the device makes it well suited to through-mounting or surface-mounting on thin-walled flexible structures such as beams and plates.

1. Introduction

Polymeric materials are frequently used as the energy dissipating element in vibration control strategies as they are reliable and inexpensive. Elastomeric anti-vibration mounts are widely used for isolation while free and constrained layer dampers are highly effective for flexible plates and shells. These classic damping technologies are less effective for structures where the dynamic strains, in comparison to the vibration level, are very low or are localised to inaccessible regions. One possible solution for vibration mitigation in these conditions is the Tuned Mass Damper(TMD).

A TMD, first described publicly by Den Hartog [1], is a damped oscillator that is attached to a vibrating structure. The vibration energy of the primary structure is then transferred to this secondary oscillator or dissipated by the incorporated damping. Passive TMDs are always attractive as they are easy to use, low cost and reliable. However, they suffer from a narrow working frequency band and can usually only target one single resonance. Many studies have been carried out to improve the performance of the conventional TMD [2,3] and recently there has been growing interest techniques where the moving mass in the secondary oscillator is replaced by either an inerter [4,5] or part of the host structure itself (non-conventional TMD [6] which causes a reduction of the overall system mass. One approach that aims to address wider working frequencies is to incorporate variable stiffness TMDs [7,8] but these devices suffer from high additional weight. Other approaches have included the development of semi-active or active control strategies [9–12] what have resulted in TMDs that suppress multi-mode vibration. However, use of these devices is limited because of the additional volume and complex circuitry involved.

Simple yet adjustable TMDs can be constructed if the spring and damper elements are formed by one or more O-rings made from elastomers such as nitrile or natural rubber. Modification of the stiffness can by achieved by altering the axial deformation

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of an O-ring. Energy dissipation occurs as the elastomer is subjected to dynamic strains and is dominated by relaxation and recovery processes that occur within and between the long chain molecules that form the material [13]. Consequently, in order to design an effective O-ring TMD, it is necessary to be able to predict the stiffness and damping properties of the O-ring itself. For elastomeric O-rings, Lindley [14] derived the load-deflection relationship in the tensile-compressive direction. However, there has been limited research to establish analytical models for O-rings, subjected to transverse shear or rocking. This becomes important when the O-ring is used in a TMD configuration, because for simple designs there is no mechanical constraint to inhibit off-axis motion.

This paper develops a design procedure for elastomeric O-ring TMDs, considering how the stiffness can be tuned in-situ. Then, the influence of multi-degree-of-freedom behaviour (tension-compression and rocking) is evaluated, because this could be detrimental or advantageous for vibration control of practical flexible structures. Section 2 begins by illustrating the proposed TMD design, and using Finite Element Analysis (FEA) to illustrate its behaviour. Section 3 presents experimental analysis of O-rings to demonstrate their dynamic stiffness and damping characteristics. The influence of static compression is considered in order to explore whether in-situ TMD tuning is possible. Section 4 develops an analytical model of the O-ring performance that could be used for device design purposes. This is then validated against experimental data in Section 5. Section 6 then demonstrates a practical application of the approach on an engineering structure, exploring MDOF effects and demonstrating the tuning capabilities. Section 7 briefly considers additional design considerations for practical applications while Section 8 draws some conclusions.

2. Configuration and initial evaluations of TMD incorporating O-rings

The configuration of the proposed adjustable O-ring TMD is shown in Fig. 1. This damper uses two identical circular discs and elastomeric O-rings that are mechanically attached to host structure. Two threaded holes are made in the middle of these discs. The two halves of the TMD are clamped onto the host structure using a threaded rod that passes through the host structure without touching it. The static compression of the O-rings can be adjusted using the threaded rod resulting in a simple device that minimises interface friction. In this design therefore, the O-rings not only provide the stiffness and damping for the system, they isolate the threaded rod, which serves as part of the TMD mass. Consequently, there are no redundant components in the design. Furthermore, the circular cross-section of the O-ring means that static compression applied using the threaded rod is expected to influence the O-ring stiffness. Thus, if the stiffness and damping can be predicted, then the designer is able to follow a very simple methodology, namely:

1. selection of the threaded rod and attached discs based on the desired TMD mass;
2. choice of O-ring material, diameter, and wire diameter (i.e. diameter of the O-ring's solid section), in order to achieve desired damping and stiffness;
3. final adjustment of the static compression to optimise the resonance frequencies.

Before developing this methodology, the behaviour of an example device is explored using FEA. The dimensions of the device are given in Table 1.

2.1. Numerical model

An initial numerical study was conducted in order to identify the vibration modes typically occurring in such devices. The analysis first needed to obtain the deformed condition caused by the static pre-load, which in practice, is always required in order to hold the damper to the host structure. To minimise computational effort, the deformed shape for the O-ring cross-section was first obtained using a 2D axisymmetric finite strain analysis using a high density mesh. This deformed shape was

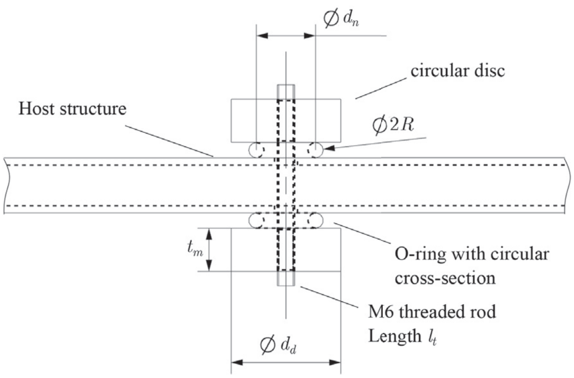

Fig. 1. Adjustable TMD using elastomer O-ring.