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Using a damper amplification factor to increase energy dissipation in structures

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ABSTRACT

Fluid dampers are an important tool for dissipating unwanted vibrations in a range of engineering structures. This paper examines the effects of amplifying the displacements transferred to a non-linear damper, to increase the effectiveness of the damper in a range of situations commonly encountered in civil engineering structures. These include, (i) the ability to "fine tune" the required damping for a particular size damper, (ii) the ability to have a set of the same size dampers, but with different amplification factors to achieve a specific damping task, and (iii) to increase the sensitivity of the damper to small movements which effectively extends the range over which the damper works. Through numerical simulations and experimental tests conducted on a non-linear damper, we quantify the potential advantages of adding an amplification factor and the range of parameters where the benefit to this device is significant. The example of a two-storey structure is used as a test case and real-time dynamic substructuring tests are used to assess the complete system performance using a range of different amplification factors. The results show that the structural performance is most improved for frequencies close to resonance and that the amplification factor has an effective limit that for the case considered in this study is of approximately 3. The effects of the mechanism compliance are also assessed.

1. Introduction

The elimination of unwanted vibrations from civil engineering structures has been of growing importance in recent years, particularly for slender or otherwise flexible structures. This is important, not only for reducing the dynamic response of structures under extreme loads, but also for increasing the system reliability and ensuring human comfort during everyday dynamic loads [1]. Over recent decades improvement in damper technology have been seen. It is typical to split such technologies into three classes; (i) passive, (ii) active and (iii) semi-active devices [2]. In this paper, the focus is on using passive fluid dampers, in combination with a motion amplification mechanism. The purpose of the amplification factor is to increase the sensitivity of the damper and therefore extend its range of operation [3]. It can also be used to "tune" the required damping value of a single or multiple dampers.

In practice, the amplification factor can be achieved by using a variety of in-built mechanisms. In [3] for instance, dampers are connected to the structure through lever arms and double chevron braces. By selecting suitable lever arm ratios, the authors highlight that a single size of damper can be used throughout a building while still achieving the optimal response performance associated with using a range of damper sizes. However, the use of a chevron brace can be visually intrusive. A similar lever arm and chevron brace setup, this time utilising two dampers, is reported in [4], where the effects of brace stiffness is discussed. In [5] a brace system in which tensioned cables impose amplified structural displacements on dampers is presented. It is reported that this system can efficiently enhance damping without modifying the structural stiffness. However due to geometric limitations, the scheme is only able to deliver relatively low amplification. In [6] pre-tensioned diagonal bracing bars are connected to angular lever arms located at the lower corners of each bay. While offering a relatively unobtrusive solution, the performance is shown to be highly dependent on both the brace stiffness and its angle of inclination.

A toggle-brace-damper was proposed by Taylor Devices inc. in [7] and analysed in [8]. Despite being particularly sensitive to the brace stiffness, toggles can offer relatively high amplification factors. However, due to geometry considerations, the authors suggest a practical amplitude range of between 2 and 5. The use of MR dampers in conjunction with the toggle configuration is

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discussed in [9]. They observed that the toggle configuration is likely to raise the structural stiffness. Scissor-jack-damper systems offer a compact method for high amplification, see for example the detailed assessment in [10]. However they also add stiffness and are sensitive to both pivot movement and elastic deformation. Another approach involves the use of gears. For example, a device constructed by coupling together two rack and two pinions having differing radii is described in [11]. The authors claim compactness and high amplification capability for the system. A further attractive approach, Hwang et al. [12], combines rotational inertia dampers with toggle bracing. In this case the amplification system is not only compact but also able to decrease the effective mass and stiffness of the structure.

Note that all of the mechanisms reported above have been modelled in the literature as constant amplification factors, i.e., coefficients that linearly scale the velocity transferred from the structure to the damper.

Here we are interested in the use of an amplifier in conjunction with a nonlinear damper for vibration suppression. Rather than studying a particular amplification mechanism, we wish to analyse how the combined nonlinearity and amplification changes the effectiveness of the vibration suppression. A further question is whether this behaviour results in an amplification limit beyond which no significant performance gain is obtained. Knowledge of this limit is needed to ensure well-behaved and cost-effective amplification mechanisms. As such we consider a generic amplifier capable of linearly scaling the displacement.

By considering a wide range of amplification factors and several loading conditions, we show both numerically and experimentally the advantages of amplifying the structural velocity transmitted to a small-scale non-linear damper. Using this approach we can identify the range of parameters where the most benefit is achieved when an amplification mechanism is added to the structure. We use the example of a two-storey structure to assess a whole system performance by considering a small non-linear damper attached to an amplification mechanism within the structure. A particular issue we consider is that of using an amplification mechanism-damper system with a smaller damper, to reduce the amount of stiction caused by large damper seals. The effects of the mechanism compliance are also assessed.

This paper is organised as follows. Section 2 introduces the structural model and highlights the effects of amplifying the velocity transferred to the non-linear dampers via numerical simulations. Section 3 presents details of the real-time dynamic substructuring, the experimental testing technique that has been used in this work. The numerical findings are validated experimentally through a series of experiments that physically test a real non-linear damper in Section 4. Finally, the conclusions and further remarks of this work are presented in Section 5.

2. Energy dissipation in dampers and the amplification factor

A basic approach for reducing structural vibration in buildings is to fit some supplemental damping devices into the structure. This concept takes advantage of the structure's own motion to produce relative movement within the damping devices. In response, those devices are expected to develop considerable local damping forces that act to dissipate a significant amount of energy—see for example [13] and references therein. If the relative motion of the damper can be amplified, then for small structural movements, a larger damping force can be achieved. Or, the same damping force can be achieved, but using a smaller damper.

Typical fluid dampers have a piston/plunger within a cylinder and two sets of seals. The seals are designed to maintain alignment of the damper and stop the fluid from leaking. In terms of damper performance the seals act as sources of non-linearity and friction effects. One consequence of the seals is that static friction will restrict the range of velocities when the damper will move. This results in two different types of behaviour (i) sticking when the force is below the static friction level and (ii) a slipping phase, after the damper is mobilised, where energy is effectively dissipated. It should be noted that negligible energy is dissipated in the damper during sticking and if there is a large range where this behaviour occurs the damper performance is degraded.

The major seismic building codes impose strict limits on the maximum permissible inter-storey drift of buildings when subject to earthquake excitation. While structural safety is the primary driver for these limits, minimising damage to non structural elements is also a factor when considering moderate or minor earthquakes. In fact, during moderate seismic events, structures are expected to exhibit just small lateral displacements. If the damper has been designed for a large event, small deformation may not even mobilise the damper, due to the internal friction forces that must be overcome prior to mobilisation of the damper.

Since energy is dissipated during the slipping phase rather than a sticking phase, one advantage of amplifying the structure's motion is to use a smaller dampers with lower static friction so that the slipping phase occurs at lower displacements (and velocities). The concept is illustrated in Fig. 1, which shows experimental results from a large-scale non-linear viscous fluid damper (NLD). Two experimental tests, one over a low and the other a high displacement range are shown. It can be seen that no slip occurs over the low range and hence the NLD effectively acts as a nonlinear spring rather than as an energy dissipator. The NLD has a peak force of 60 kN and a maximum stroke of ±15 mm [14]. When acting at a range of low displacements, the damper behaves as a very stiff spring, meanwhile at large displacements the damper goes into the slipping phase, describing the well-known hysteretic loop and dissipating energy. Therefore, in this situation, using smaller dampers and amplifying the structural motion transferred to them could significantly increase the dampers efficacy.

2.1. Two-storey example

As an example structure we consider a symmetric two-storey building with two NLD attached at the first floor as shown in Fig. 2a. The structure and damper size were tuned to produce an equivalent additional damping of approximately 20% of the critical damping ratio when the system oscillating at the frequency of the first linear mode. We note that this damper configuration may not

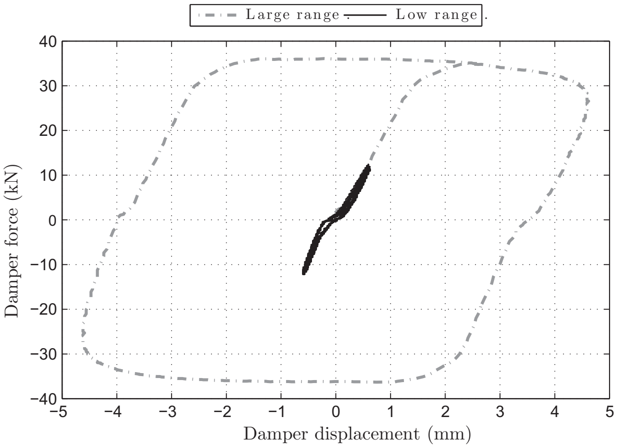

Fig. 1. Experimental data from a non-linear viscous fluid damper at low level (solid line) and large (dashed line) regime of displacements.