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Robust reliability-based design of liquid column mass dampers under earthquake excitation using an analytical reliability approximation

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Abstract

The robust reliability-based design of Tuned Liquid Column Dampers (TLCD) and Liquid Column Vibration Absorbers (LCVA) under earthquake excitation is studied. The design objective is the minimization of the probability of failure, where failure is defined as the first-passage of the dynamical system trajectory out of a hypercubic safe region in the space of the performance variables. These variables correspond to response characteristics of the system that are considered important. Versions of the approach are described for the case of a nominal model and the case considering model uncertainty. In the latter case the concept of robust probability of failure is employed which considers a set of possible models for the dynamic system. The nonlinear characteristics of the damper response are addressed by including the excitation intensity as an uncertain parameter in the system description. An analytical approximation is used for the reliability estimation that allows for computationally efficient, gradient-based design optimization. Numerical issues are discussed. The validity of the reliability approximation is checked by comparing the results to those derived through direct Monte Carlo simulation of the nonlinear model. Applications to dynamical systems with single and multiple degrees of freedom are presented. For the latter case, other standard control synthesis methods are also considered and significant differences are illustrated between them and robust reliability-based design. Although this study focuses on optimization of TLCDs and LCVAs, it shows the efficiency of the proposed methodology for other systems that also involve model uncertainty.

Keywords: Tuned liquid column damper; Liquid column vibration absorber; Tuned mass damper; Robust reliability-based design; Model uncertainty; Statistical linearization

1. Introduction

Liquid column mass dampers have been introduced [1,2] as an alternative to Tuned Mass Dampers (TMDs) as energy dissipation devices for suppression of structural vibrations. Some of their advantages are low cost, easy installation and easy adjustment of damper frequency. Two kinds of such dampers are considered in this study, the Tuned Liquid Column Damper (TLCD) [1] and the Liquid Column Vibration Absorber (LCVA) [2]. The TLCD consists of a U-shaped tube, with the same section diameter in its horizontal and vertical parts, filled with liquid, preferably water. At the center of the horizontal section of the tube an orifice plate exists, which causes energy dissipation in the vibration of the liquid. The motion of the liquid inside the tube counteracts the motion of the primary structure, producing the desired energy dissipation. The only additional feature that distinguishes the LCVA from the TLCD is that the cross section of the tube is non-uniform. The LCVA provides better architectural adaptability and versatility, since its natural frequency is a function not only of the length of the liquid column but also of the geometric configuration [3]. Both TLCD and LCVA belong to the general class of mass dampers and to the sub-class of liquid column mass dampers. The term *liquid column mass dampers* is used herein to refer to both of them.

TLCDs and LCVAs have been investigated and proved to be efficient, when properly tuned, for both wind and earthquake excitation [4–8]. The tuning refers typically to the adjustment of the natural frequency of the liquid column and the head-loss coefficient of the orifice plate to the dynamic characteristics of

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the coupled structure–damper system so that the mean square response is minimized. In contrast to TMDs, the governing equation for the damper motion is nonlinear because the dissipating force created by the orifice plate is nonlinear. This feature is the main point of distinction in the design of liquid column mass dampers and TMDs and in the end creates a dependence of the optimum head-loss coefficient on the excitation intensity [4,6]. This means that for intensities different than the nominal one used in the design, the tuning is going to be sub-optimal and the performance of the damper inferior [9]. For wind excitation, the slowly varying properties of the excitation input may allow for a semi-active adjustment of the head loss coefficient to the optimum value [10], but the same techniques may not be applicable to earthquake excitation.

The effect of structural model uncertainties on the design of TMDs has been investigated in [11] by considering a single output only. Since structural model uncertainties always exist, the concept of robust reliability against failure has been introduced in [12] and it serves as an important metric by which the quality of controlled systems may be judged. It should be noted that minimizing the mean square response does not necessarily correspond to the optimal design in terms of reliability, as has been reported in [11,13]. Failure, in both these studies and in the current one, is viewed as corresponding to the exceedance of some predefined serviceability or strength limit state by the structural performance variables that are of interest. The performance variables correspond to response characteristics of the system that are considered important in the design process, such as inter-story drifts or absolute accelerations. Under these considerations, reliability-based design is defined as the minimization of the probability of failure; if model uncertainties in the system description are included in the calculation of this probability, the latter is referred to as robust probability of failure [12], and the corresponding design, as robust reliability-based design. In this approach, information implying that some of the possible values of the model parameters are more probable than others is explicitly treated — contrary to other theoretically robust to uncertainties control methods such as H_∞ or μ-synthesis. When the information about the system can be updated [12, 14] during its life cycle, the robust reliability-based design may also be updated. This is particularly valuable for liquid column mass dampers because of the easy adjustment of their dynamical properties, which allows for low cost modification if necessary due to changes in design guidelines, or to changes in the structural system dynamic characteristics.

A robust reliability-based design is considered in this paper for liquid column mass dampers under earthquake excitation. The main contribution of this study is that it extends the reliability design of mass dampers to (1) a sub-class of systems that are nonlinear and to (2) multiple output of the system that are to be regulated. The nonlinearities of the system are considered by including the excitation intensity as an uncertain parameter and the multiple-output case is addressed by the application of a very efficient reliability approximation. This approximation has recently been developed for the reliability calculation of certain and uncertain linear dynamical systems with higher dimensional output [15,16] and it allows for computationally efficient optimization using gradient-based methods. A linearized model of the structure–damper interaction is used in the calculations. Because of the limitations of statistical linearization for estimation of reliability related quantities [17], the response of the damper is not considered as a performance variable in the present study. Comparisons with Monte Carlo simulation of the nonlinear system show that the suggested analytical approximation describes accurately the probability of failure for the response of the primary system. For MDOF (multi-degree-of-freedom) systems, the proposed design is compared with other standard stochastic-control synthesis methods that may be applied to multi-output systems.

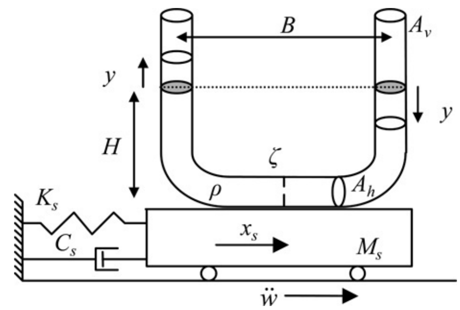

Fig. 1. Liquid column mass damper–structure interaction model.

2. Dynamic response model for damper–structure system

The state-space equations of motion are presented in this section for a structure under earthquake excitation with mass dampers distributed at various locations. A simple unified approach for the equations of motion for all TLCDs, LCVAs and TMDs is established with the introduction of only two auxiliary parameters. Some issues pertaining to optimal design and the efficiency are also clarified.

2.1. *Equation of the liquid column mass damper*

Consider a liquid column mass damper attached to a primary system under earthquake excitation as in Fig. 1. The displacements for the liquid column and the primary system are y and x_s, respectively, and the earthquake ground acceleration $\ddot{w}$. Let ρ, B, and H denote the density, horizontal length and initial height of the liquid column, respectively. A_v and A_h are the vertical and horizontal cross sectional areas of the liquid column, respectively, and ζ is the head-loss coefficient of the orifice. These parameters fully define the damper's characteristics. Define $r = A_v/A_h$ as the area ratio and consider the parameters shown in Table 1.

The distinction between nominal and effective values in Table 1 is introduced only for the case of the LCVA. For the TLCDs, those quantities are identical. It is straightforward to