Journal of Sound and Vibration ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Optimization under uncertainty of parallel nonlinear energy sinks

Ethan Boroson [a], Samy Missoum [a,*], Pierre-Olivier Mattei [b], Christophe Vergez [b]

[a] Aerospace and Mechanical Engineering Department, University of Arizona, Tucson, AZ 85721, United States
[b] Laboratoire de Mécanique et d'Acoustique, CNRS, Marseille 13453, France

ARTICLE INFO

Article history:
Received 9 September 2016
Received in revised form
9 December 2016
Accepted 29 December 2016
Handling Editor: A.V. Metrikine

Keywords:
Parallel nonlinear energy sinks
Optimization under uncertainty
Activation threshold

ABSTRACT

Nonlinear Energy Sinks (NESs) are a promising technique for passively reducing the amplitude of vibrations. Through nonlinear stiffness properties, a NES is able to passively and irreversibly absorb energy. Unlike the traditional Tuned Mass Damper (TMD), NESs do not require a specific tuning and absorb energy over a wider range of frequencies. Nevertheless, they are still only efficient over a limited range of excitations. In order to mitigate this limitation and maximize the efficiency range, this work investigates the optimization of multiple NESs configured in parallel. It is well known that the efficiency of a NES is extremely sensitive to small perturbations in loading conditions or design parameters. In fact, the efficiency of a NES has been shown to be nearly discontinuous in the neighborhood of its activation threshold. For this reason, uncertainties must be taken into account in the design optimization of NESs. In addition, the discontinuities require a specific treatment during the optimization process. In this work, the objective of the optimization is to maximize the expected value of the efficiency of NESs in parallel. The optimization algorithm is able to tackle design variables with uncertainty (e.g., nonlinear stiffness coefficients) as well as aleatory variables such as the initial velocity of the main system. The optimal design of several parallel NES configurations for maximum mean efficiency is investigated. Specifically, NES nonlinear stiffness properties, considered random design variables, are optimized for cases with 1, 2, 3, 4, 5, and 10 NESs in parallel. The distributions of efficiency for the optimal parallel configurations are compared to distributions of efficiencies of non-optimized NESs. It is observed that the optimization enables a sharp increase in the mean value of efficiency while reducing the corresponding variance, thus leading to more robust NES designs.

1. Introduction

Passive mitigation of vibrations is an important research field in many areas including earthquake engineering, aeroelasticity, and vibro-acoustics. Tuned Mass Dampers (TMDs), which are tuned to the natural frequencies of a system, such as a building or wing, have historically been the most widely used devices [1]. TMDs can efficiently dissipate energy, but they need to be tuned to the natural frequency of the system to which they are attached in order to be effective [2]. When a TMD becomes detuned from the main system through a change in natural frequencies of either system, the effectiveness of the TMD drops considerably [3].

* Corresponding author.
E-mail address: smissoum@email.arizona.edu (S. Missoum).

http://dx.doi.org/10.1016/j.jsv.2016.12.043
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In recent years, an alternative to TMDs, referred to as Nonlinear Energy Sinks (NESs), has emerged as a promising method to achieve the same goals. NESs are able to irreversibly capture and dissipate energy through a nonlinear, typically cubic, stiffness property [4,5]. NESs have been applied to systems such as buildings under seismic loading [3,2] as well as in aeroelasticity [6], and acoustics [7,8]. NESs, unlike TMDs, do not need to be tuned to a particular frequency in order to dissipate energy effectively. Instead, NESs absorb energy from a wider range of frequencies [2,9] and, therefore, are more robust than TMDs.

A NES, however, still absorbs energy over a limited range of excitations to the system. It has been shown that a NES is characterized by an "activation" threshold below which the energy is not effectively dissipated [2,10]. In addition, beyond this activation threshold, further increases in excitation lead to decreasingly efficient NES performance. This leaves a relatively narrow range of excitations for which each NES is most effective. In order to overcome this limitation, this paper investigates the optimization of NESs configured in parallel [8,11–13] so as to widen the range of excitations within which the NES can absorb energy efficiently. Earlier studies on the dynamics and performance of NESs combined in parallel can be found in [12,13].

It has also been shown that uncertainties might play an important role in the behavior and efficiency of the NES [14] and several uncertainty quantification techniques such as polynomial chaos expansions have been used [15]. The efficiency of a NES can be very sensitive to slight perturbations of the design parameters [2,14,10] and loading. For instance, a NES can switch from a very high to a very low efficiency with just a small change in those parameters. The extreme sensitivity results in near-discontinuous NES efficiency as a function of the design parameters or loading conditions. Although the behavior is not truly discontinuous in a mathematical sense, it may still present problems for gradient-based optimization approaches and dictates the need to account for uncertainty. In many cases, a deterministic optimization for the maximization of efficiency would locate the optimum at the boundary between higher and lower efficiency regions thus resulting in a design with a high probability of performing less efficiently than expected due to small perturbations in design parameters [14,10].

This study makes use of previous work by the first two authors that introduced a stochastic optimization algorithm to design NESs [16]. The algorithm makes use of a support vector machine (SVM) classifier, clustering, Kriging approximations, and a dedicated adaptive sampling scheme referred to as "generalized max–min" [17]. It involves local refinements of the SVM classifier and two Kriging approximations trained on two levels of NES efficiencies as identified through clustering. In addition, the algorithm is able to tackle random design variables (e.g., the cubic stiffness coefficient of the NES) as well as aleatory variables such as loading conditions of the main system.

The optimization under uncertainty scheme developed by the authors provides an essential tool to investigate the optimal design of parallel NESs. Specifically, this paper investigates the maximization of the expected value (i.e., mean) of NES efficiency. The optimization variables considered are the NES nonlinear stiffness coefficients, considered random design variables. The excitation of the main system to which the NESs are attached is treated as an aleatory variable over a relatively wide range. The corresponding gains in efficiency and its distribution around the optimum are studied and compared to cases where the NESs are not optimized. These studies also provide a way to gauge the robustness of the parallel NES designs obtained through optimization under uncertainty.

The paper is constructed as follows: in Section 2, an introduction to NES dynamics is provided, including parallel NESs. Important notions about activation thresholds and discontinuities are presented. Section 3 describes the optimization problem under uncertainty formulation and the proposed algorithm for maximization of the mean efficiency. The section also introduces important tools such as generalized max–min sampling, Kriging, and Support Vector Machines. In Section 4 the optimization of several systems with varying numbers of NESs in parallel (ranging from 1 to 10) is presented. Finally, Section 5 will discuss the effect of optimization on activation thresholds and the relation between amount of dissipated energy and time to dissipate it.

2. Nonlinear Energy Sink (NES)

The NES configuration used in this article is depicted in Fig. 1. The system is composed of a main system (with angular eigenfrequency ω and damping γ) and a NES with nonlinear stiffness α, damping λ, and mass ratio (NES mass divided by

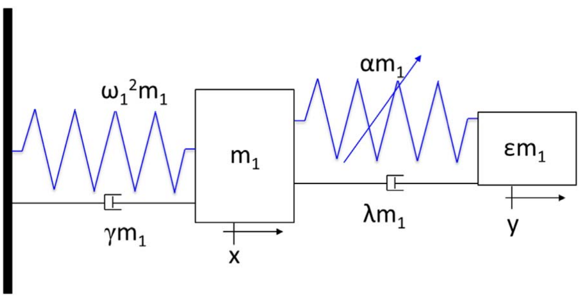

Fig. 1. One NES system with all parameters labeled.

Please cite this article as: E. Boroson, et al., Optimization under uncertainty of parallel nonlinear energy sinks, *Journal of Sound and Vibration* (2017), http://dx.doi.org/10.1016/j.jsv.2016.12.043