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Multi-resonant electromagnetic shunt in base isolation for vibration damping and energy harvesting

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ABSTRACT

This paper investigates multi-resonant electromagnetic shunts applied to base isolation for dual-function vibration damping and energy harvesting. Two multi-mode shunt circuit configurations, namely parallel and series, are proposed and optimized based on the H_2 criteria. The root-mean-square (RMS) value of the relative displacement between the base and the primary structure is minimized. Practically, this will improve the safety of base-isolated buildings subjected the broad bandwidth ground acceleration. Case studies of a base-isolated building are conducted in both the frequency and time domains to investigate the effectiveness of multi-resonant electromagnetic shunts under recorded earthquake signals. It shows that both multi-mode shunt circuits outperform traditional single mode shunt circuits by suppressing the first and the second vibration modes simultaneously. Moreover, for the same stiffness ratio, the parallel shunt circuit is more effective at harvesting energy and suppressing vibration, and can more robustly handle parameter mistuning than the series shunt circuit. Furthermore, this paper discusses experimental validation of the effectiveness of multi-resonant electromagnetic shunts for vibration damping and energy harvesting on a scaled-down base isolation system.

1. Introduction

Base isolation is one of the most effective techniques for low and middle rise buildings to save lives and reduce property damage from strong earthquakes [1]. The isolation shifts the fundamental frequency of the combined building-isolation system to a lower value, moving it away from the dominant frequency range of earthquakes [2]. In addition, the isolation system can dissipate the vibration energy so that the vibration of the primary structure is reduced [3]. In the past few decades, researchers have investigated various ways to achieve the effects of additional vibration damping in base isolation, e.g. viscoelastic damper [4], magnetorheological fluid damper [5], and piezoelectric friction damper [6]. In addition to civil structures, base isolation has also been successfully used for protecting precision machine and instrumentation [7,8]. By dissipating the energy induced by ambient oscillations, base isolators exhibit excellent features to ensure the safety and functionality of vibration sensitive equipment [9].

Recently, electromagnetic resonant shunts have become a new method for realizing structural vibration damping while simultaneously harvesting energy [10,11]. Behrens et al. [12] proposed the electromagnetic shunt damping technique and validated it with a basic electromagnetic mass spring system. Inoue et al. [13] optimized parameters of a single mode

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electromagnetic shunt circuit by using the fixed point method to achieve the effect of tuned vibration absorbers. Zuo and Cui [14] proposed the series electromagnetic tuned mass damper (TMD) for dual-function vibration control and energy harvesting, which can achieve enhanced effectiveness and robustness without suffering from the large strokes of series TMDs. Tang et al. [15] proposed closed-form H_2 and H_∞ optimal solutions of the electromagnetic resonant circuit for both vibration damping and energy harvesting. Later, Liu et al. [16] presented the exact optimal tuning laws for the energy harvesting series electromagnetic TMD and verified its effectiveness in experiments. Without introducing additional masses, the electromagnetic resonant shunt provides a convenient way to damp the vibration of low and middle rise buildings in which it is not suitable to implement large TMDs. Additionally, the vibrational energy harvested by shunt circuits could be used for providing electrical powers to the structure sensing and control system when regular power supplies are unavailable in extreme earthquake events [17]. However, base-isolated buildings are generally considered multiple degrees of freedom systems [18]. Traditional electromagnetic shunt circuits with a single resonance are not capable of suppressing two separate vibration modes at the same time. Therefore, electromagnetic shunts with multiple resonances are required for the application of base isolation.

Inspired by multi-mode shunt damping in piezoelectric applications [19,20], Cao and Zuo [21] proposed a current-flowing electromagnetic shunt circuit, in which a current-flowing *LC* network is inserted into each circuit branch to approximate an open circuit at the resonant frequency of another branch. However, this seriously complicates the task of implementing the required circuits. Cheng and Oh [22] employed a modified current-flowing multi-mode resonant circuit for electromagnetic shunt damping of cantilever beams. The circuit is concise requiring less circuit components. However, optimal vibration suppression performance is not achieved due to non-optimal electrical parameters. As pointed out in Ref. [23], the foremost difficulty in implementing resonant shunt circuits is the need for large inductance values on the order of tens or hundreds of Henrys. Moreover, negative resistance may be necessary due to the large internal resistance of the electromagnetic transducer. In these cases, synthesized inductors and resistors have to be used which are difficult to tune and sensitive to component characteristics [24]. Thus, it becomes crucial to find a more systematic way to design the multi-resonant electromagnetic shunt circuit and determine the optimal circuit parameters.

In this paper, two simplified multi-mode resonant shunt circuits − parallel and series − are proposed for dual-function vibration damping and energy harvesting for building base isolation. A numerical optimization method for the multi-resonant shunt circuit is employed. H_2 criteria is used to minimize the RMS value of the relative displacement between the base and the primary structure with the goal of improving building safety under random ground accelerations. The optimal electrical parameters for the multi-resonant shunt circuit are determined, providing guidance for designing and implementing the proposed circuits. The effectiveness and robustness of parallel and series shunt circuits are investigated and compared. In addition to simulations, this paper also experimentally validates the effectiveness of multi-resonant electromagnetic shunts for vibration damping and energy harvesting.

This paper is organized as follows. Section 2 presents the modeling and optimization of the base isolation system with the proposed parallel and series multi-mode shunt circuits. Section 3 is the numerical analysis for a case study, in which recorded earthquake signals are applied to a base-isolated structure. The performance of the multi-mode shunt circuit is studied and compared with a single mode shunt circuit. The effectiveness and robustness of parallel and series shunt circuits are also investigated. In Section 4, a scaled-down base isolation system is studied experimentally. Both impact hammer testing and shake table testing are conducted to verify the effectiveness of the dual-functional multi-resonant electromagnetic shunt. Section 5 gives conclusions of the investigation.

2. Modeling and optimization

2.1. Modeling

The concept of the base isolation system with a multi-resonant electromagnetic shunt is to replace the traditional oil damper with an electromagnetic transducer and shunt it with a multi-resonant electrical circuit. The resonances of the electrical circuit can be tuned based on the vibration mitigation performance of the base isolation system. The electromagnetic transducer acts as an effective generator, converting the seismic energy into the electrical energy, which will be harvested and stored by the electrical shunt circuit. In this paper, all the energy regulation and storage packages are modeled as pure external resistive loads [14]. The energy dissipated in resistors is regarded as the harvested electrical energy.

As shown in Fig. 1, the base isolated building structure can be modeled as a two-degree of freedom system, with motion in the horizontal direction only. An electromagnetic transducer with inductance L_0 and internal resistance R_0 is placed between the base and the ground. The electromagnetic transducer is then shunted with multi-resonant shunt circuits. Here we propose two multi-mode shunt circuit configurations: parallel and series. The parallel shunt circuit, as shown in Fig. 1 (a), consists of two RLC circuits in parallel. The proposed series shunt circuit, as shown in Fig. 1(b) is inspired by the concept of multiple series TMDs [25], which are more effective and robust than parallel TMDs. Electrical and mechanical analogies are used to devise this setup [26].