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Delayed-feedback vibration absorbers to enhance energy harvesting

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ABSTRACT

Recovering energy from ambient vibrations has recently been a popular research topic. This article is conceived as a concept study that explores new directions to enhance the performance of such energy harvesting devices from base excitation. The main idea revolves around the introduction of *delayed feedback sensitization* (or *tuning*) of an active vibration absorber setup. To clarify the concept, the Delayed Resonator theory is reviewed and its suitability for energy harvesting purposes is studied. It is recognized that an actively tuned and purely resonant absorber is infeasible for such applications. The focus is then shifted to alternative tuning schemes that deviate from resonance conditions. Also called Delayed Feedback Vibration Absorbers, these devices may indeed provide significant enhancements in energy harvesting capacity. Analytical developments are presented to study energy generation and consumption characteristics. Effects of excitation frequency and absorber damping are investigated. The influences of time-delayed feedback on the stability and the transient performance of the system are also treated. The analysis starts from a stand-alone absorber, emulating seismic mass type harvesters. The work is then extended to vibration control applications, where an absorber/harvester is coupled with a primary structure. The results are demonstrated with numerical simulations on a case study.

1. Introduction

In recent decades, mankind has come to realize that energy resources are limited and current reserves cannot be taken as granted. Concurrently, the negative environmental effects of existing energy generation methods are also becoming a public concern. Modern industrialized economies heavily rely on earth's fossil fuels, which are not only limited but also cause significant pollution and contribute to global warming. As a result; engineers, scientists and politicians are joining efforts to develop more sustainable sources of energy. These efforts are striving on many different fronts. Increasing the efficiency of energy generation methods, improving solar and wind energy generation are some of the prominent countermeasures that are being developed.

A more futuristic take on the energy problem has been the idea of *energy harvesting*. Generally speaking, this concept attempts to take advantage of systems and processes which produce waste energy during their functionalities. The natural temptation is to *harvest* the wasted energy instead of dissipating it. This idea is not new and numerous clever pathways have

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already been developed as described in the review article [1]. One of the actively studied topics is the harvesting of energy from mechanical vibrations and motion; for instance from automobile suspensions [2,3], from civic structures and buildings [4], from ocean waves [5], and even from human motion [6]. Because the energy levels in most harvesting sources are considerably low, microsystems and wireless electronics are also becoming increasingly popular scientific explorations [7,8]. For more comprehensive reviews on the subject, the reader is directed to the work of Mitcheson et al. [9] and Zou and Tang [10].

Systems that harvest energy from vibrations have been proposed in various forms. The main feature that all applications share is the introduction of some transducers that can convert kinetic energy into electrical energy. They act analogous to mechanical dampers, except that they produce electricity instead of waste heat. In some applications they are even used in lieu of conventional shock absorbers [11]. The most commonly used transducers are either of piezoelectric or electromagnetic type [12–14]. The former is popular in microsystems and small scale applications [15,16] because very few or no moving parts are involved. Electromagnetic devices on the other hand, are more suitable in large scale systems [10]. In both cases, it is also possible to use the transducer as an actuator; a feature which has been utilized in some studies [17].

This article proposes a new concept to enhance the energy harvesting potential from mechanical vibrations using a delayed feedback tuning mechanism. The idea stems from a vibration suppression method known as the *Delayed Resonator* (DR) [18,19]. These devices are capable of absorbing vibrations from a primary structure over a range of frequencies while the center frequency of excitation varies in time. This is achieved by inducing resonance (or near-resonance) in the absorber substructure through the introduction of a delayed feedback force. The main premise is that by inviting resonance, the kinetic energy available for harvesting in this substructure could be significantly increased. This is an interesting proposition which leads to several critical arguments. First of all, the proposed scheme requires a control operation and actuation effort to exert a delayed feedback force. This means that the resulting construct becomes an *active* system which needs a careful assessment for dynamic stability. Secondly, the most natural question is whether the potential increase in harvested energy would be high enough to outweigh the control/actuation energy. Although it appears to be a daring proposition, there are example cases in practice where similar strategies have been implemented with great success. For instance, consider *superchargers* in internal combustion engines. These devices consume a certain percentage of the engine's power. In return, they boost the power production to such levels that the net output is effectively increased [20]. A vital step in this work is then to investigate whether this same principle would hold in a possible DR-harvester combination. In other words, could this construct be more advantageous compared to passive systems where no external energy input is needed? In what follows, we conduct an analytical and numerical analysis of this proposed idea in an attempt to answer these questions. This work is intended as a concept study, to facilitate future research based on the foundations laid out here.

The article is structured as follows. We first present an overview of delayed resonator theory. Then the flow of energy in a DR-harvester combination is investigated. We propose a control scheme that is shown to be feasible in theory and simulations. The main results are first derived on a seismic mass resonator setup, where the absorber is subject to steady harmonic movement as the base excitation. The findings are then extended to cases where the absorber is mounted on a primary structure, as in typical tuned-mass damper applications. The developed concepts are then demonstrated on a case study with the critical evaluations of feasibility.

2. Delayed resonator theory and preliminaries

The Delayed Resonator concept was first introduced in the early 90s by Olgac and Holm-Hansen [18]. It was proposed as a new active absorber tuning method to achieve perfect vibration suppression. The main idea feeds upon the fact that vibration absorption capabilities of passive systems are inherently limited due to damping effects. It is well known that an ideal absorber needs to be *purely* resonant, which is only possible in the absence of damping [21]. The DR concept proposes to resolve this problem, coming from a control theoretic perspective.

A linear time invariant (LTI) dynamical system is said to be *resonant* if the system's rightmost (dominant) eigenvalues are a purely imaginary conjugate pair. The DR achieves this eigenvalue assignment by utilizing a feedback control which has an artificially added delay. Time-delays have been long known to cause closed-loop instabilities in control systems [22]. Consequently, through a proper tuning of the feedback gain and time-delay, it should be possible to impose marginal stability (i.e., resonance).

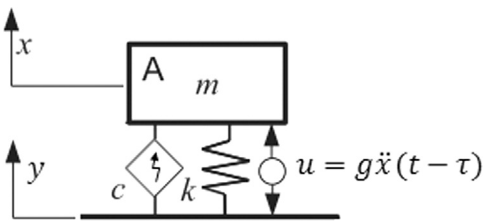

Fig. 1. Energy harvesting from a seismic mass type setup.