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Vibration energy harvesting based monitoring of an operational bridge undergoing forced vibration and train passage

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ABSTRACT

The application of energy harvesting technology for monitoring civil infrastructure is a bourgeoning topic of interest. The ability of kinetic energy harvesters to scavenge ambient vibration energy can be useful for large civil infrastructure under operational conditions, particularly for bridge structures. The experimental integration of such harvesters with full scale structures and the subsequent use of the harvested energy directly for the purposes of structural health monitoring shows promise. This paper presents the first experimental deployment of piezoelectric vibration energy harvesting devices for monitoring a full-scale bridge undergoing forced dynamic vibrations under operational conditions using energy harvesting signatures against time. The calibration of the harvesters is presented, along with details of the host bridge structure and the dynamic assessment procedures. The measured responses of the harvesters from the tests are presented and the use the harvesters for the purposes of structural health monitoring (SHM) is investigated using empirical mode decomposition analysis, following a bespoke data cleaning approach. Finally, the use of sequential Karhunen Loeve transforms to detect train passages during the dynamic assessment is presented. This study is expected to further develop interest in energy-harvesting based monitoring of large infrastructure for both research and commercial purposes.

1. Introduction

Vibration based structural health monitoring (SHM) of built infrastructure is a topic of significant interest in recent times as the dynamic responses of a structure provide unique insights into its condition and health [1]. With advances in monitoring technology and analysis techniques, there have been many investigations into approaches for the provision of long-term monitoring of civil infrastructure using smart sensing solutions, particularly using wireless sensing solutions

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[2]. As part of such solutions, the use of vibration based energy harvesting techniques to scavenge electrical energy from the dynamic response of a structure under operational conditions has been shown to have the potential to form the basis of such sensing networks [3,4].

The integration of vibration energy harvesting technology with civil infrastructure is at its infancy [5]. The use of piezoelectric energy harvesting coupled with bridge structures has received attention in this regard, whereby the forced vibration response of a bridge due to vehicular traffic is utilised [6,7]. The amount of energy which can harvested from train-bridge using piezoelectric energy harvesters has also been investigated for an international train fleet [8], as has the application of an energy harvester with train tracks [9]. The use of harvested energy for the purposes of SHM of built infrastructure is promising [10] and the power generated from bridge-vehicle interactions using piezoelectric energy harvesting has been investigated for damage detection in the bridge structure [11]. Such studies have remained mainly theoretical and the potential of using energy harvested from the dynamic responses of built infrastructure for SHM is yet realized. Full-scale implementations and demonstrations of such concepts can address this gap in a robust manner.

Full-scale dynamic assessments of bridges allow for estimating relevant parameters such as mode-shapes, stiffness and damping ratios [12–14]. The use of vehicle induced vibrations as a source of excitation for the bridge structure to determine its dynamic responses has been used extensively, both for highway and train bridges [15–17]. Conducting such assessments is beneficial as the structure is under operational conditions and does not require bridge closure during testing. Issues do arise, however, due to the presence of traffic on the bridge, as the vehicle mass acts as an additional mass on the bridge structure, which can result in variations in the response of the bridge and in the measured natural frequency [18]. The use of ambient vibrations can resolve such issues [19]. Nevertheless, the use of external excitation devices imparting loadings of known magnitude and frequency, while introducing minimal interference to the bridge, is usually the most reliable way to determine relevant parameters of the bridge [20]. Previous shakers utilised for such dynamic testing of bridge infrastructure include vertical excitation using a dropped weight [21], an eccentric mass shaker [22] and a hydraulic shaker [23].

Unlike full-scale dynamic testing of bridges, experimental investigations into the application of energy harvesting technology with full scale bridge structures is a nascent field. The integration of energy harvesting technology with highway bridges have been studied, using both piezoelectric [24] and electromagnetic harvesting devices [25,26]. For train bridge infrastructure, piezoelectric sensors have been implemented for the purposes of weigh-in-motion (WIM) [27]. Aside from this WIM application and determining the power output potential from bridge structures, no full-scale study has investigated how experimentally scavenged electrical energy from bridge structures can be utilised in its own right for monitoring or estimation of system parameters. Such applications can include SHM of a bridge structure using natural frequency, mode shape and curvature/strain mode shape based analysis techniques using dynamical measurements [28]. More recently, the use of wavelet transforms has been utilised successfully for SHM of bridge structures including using numerical models [29], the response of a scaled experimental model bridge subjected to a moving load [30] and the free vibrations following train passages during full-scale dynamical testing [18]. Applications resulting from the use of such techniques on the electrical signal outputs from energy harvesters from civil infrastructure has not yet been achieved.

This paper investigates the deployment of piezoelectric energy harvesting devices for a bridge structure undergoing forced dynamic excitation in its operational conditions and demonstrates how analyses can be carried out on the harvested energy signature to assess important properties related to the bridge. Piezoelectric energy harvesting devices, in the form of cantilever harvesters, were created and calibrated under swept sine loading conditions within a laboratory environment. The harvesting devices were deployed for full scale bridge vibration testing using an external shaker with varying magnitude of swept-sinusoidal excitation. The response of the energy harvesters when coupled with the bridge undergoing controlled forced vibrations is presented and compared against the response of an accelerometer at the harvester locations in this paper. A bespoke data-cleaning for the energy harvesting signature against time, in conjunction empirical mode decomposition (EMD) analysis is observed to be useful for system identification. Additionally, sequential Karhunen Loeve transform is utilised here to determine relevant events on the bridge, like train passage. This paper provides full-scale validation of a piezoelectric energy harvesting devices for monitoring built infrastructure. The paper also attempts to provide guidance around re-creating similar experiments in future for research of commercial applications along with what the expected harvesting signatures and results can be from such tests.

2. Piezoelectric energy harvesting devices for full scale deployment

2.1. Cantilever piezoelectric energy harvesting device

A cantilever piezoelectric harvester device was developed for the purpose of bridge monitoring. The device uses multiple linear cantilevers tuned to different frequencies, thereby resulting in a wide range of frequencies available for effective energy harvesting. This approach addresses issues associated with the narrow bandwidths for optimal energy harvesting for linear piezoelectric energy harvesting devices [31] and allows for effective harvesting over a wider range of frequencies within which the modes of the bridge are estimated to be. Fig. 1 illustrates the general outline of a piezoelectric energy harvesting cantilever, with the device parameters identified, including the length (L), width (w) and the added tip mass (m) along with a photo of such a harvester.