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# Energy harvesting from high-rise buildings by a piezoelectric harvester device

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ABSTRACT

A novel piezoelectric technology of harvesting energy from high-rise buildings is developed. While being used to harness vibration energy of a building, the technology is also helpful to dissipate vibration of the building by the designed piezoelectric harvester as a tuned mass damper. The piezoelectric harvester device is made of two groups of series piezoelectric generators connected by a shared shaft. The shaft is driven by a linking rod hinged on a proof mass on the tip of a cantilever fixed on the roof of the building. The influences of some practical considerations, such as the mass ratio of the proof mass to the main structure, the ratios of the length and flexural rigidity of the cantilever to those of the main structure, on the root mean square (RMS) of the generated electric power and the energy harvesting efficiency of the piezoelectric harvester device are discussed. The research provides a new method for an efficient and practical energy harvesting from high-rise buildings by piezoelectric harvesters.


## 1. Introduction

High-rise buildings are very susceptible to dynamic loadings of winds and earthquakes. The induced vibration may bring damage to buildings or cause discomfort to the human occupants. In order to mitigate the vibration, different approaches have been proposed, among which TMDs (tuned mass dampers) are most preferable and popular and have been successfully used in many high-rise buildings to reduce the wind-induced vibration [1]. Due to the complexity of earthquake excitations, no standard and unified designs of TMD structures have yet been realized [2–4]. The widely used designs of a TMD structure normally adopt liquid dampers to absorb vibration energy for civil structures. However, the dissipated damping of liquid dampers is often affected by variations of the environment temperature. In addition, such liquid dampers for TMD structures are inefficient when buildings are subjected to environmental loadings with multi-directions [2,5]. Therefore, in order to enhance structural reliability [6], devices of multiple viscous dampers with complicated structures have to be employed. However, these devices are costly in general. Hence, researchers developed friction dampers in TMD structures instead [7–9], and the invariable friction TMD was first developed due to its simple structure and low cost. Further studies showed that the damping efficiency of the invariable friction TMD is usually affected by the level of excitations [10], and hence, a variable friction damper was developed [11,12]. A piezoelectric variable friction damper [13] is a representative sample of the variable friction dampers. Research findings showed that the variable friction TMD devices can work more effectively than their invariable counterparts under variable external excitations. It is noted that the present variable dampers have not been widely used in real engineering structures due to their low outputs of friction forces. In addition, the high demand of continued power supplies limits their applications [11].

All TMD structures mentioned above are to dissipate the vibration energy with dampers. The existing dampers are usually with complicated structures and high costs and cannot achieve efficient dissipation and harvesting of the vibration energy under complicated environmental conditions. Actually, instead of dissipating the vibration energy into wasted heat, converting the vibration energy into electricity by a transducer is a better practical way of harnessing energy from high-rise buildings while reducing vibrations under various excitations.

Various transducers have been investigated for vibration energy harvesting, including piezoelectric materials [14,15], linear and

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rotational electromagnetic motors [16], electrostatic generators [17], and dielectric generators [18]. Among these transducers, the piezoelectric materials and electromagnetic machines have more potential for large-scale vibration energy harvesting owing to their high efficiency.

A piezoelectric material is a type of smart materials that is able to transfer energy from a mechanical motion into an electrical voltage output. Many research works have been conducted on applications of piezoelectric materials for energy conversion from ambient environmental vibrations [19–22]. Xie et al. [23] introduced an optimal design of a piezoelectric coupled cantilever structure with a proof mass to achieve a higher efficient energy harvesting from high-rise buildings. A ring piezoelectric energy harvester excited by magnetic forces was developed and a power up to 5274.8 W can be realized for a practical design of the harvester with a radius around 0.5 m [24]. The above researches show that applications of piezoelectric harvesters can generate up to thousands of watts of electric power by absorbing ambient vibration energy. Electromagnetic machine is a device that converts mechanical energy into electric energy when a permanent magnet is moved relative to a conductor. Tang and Zuo [25,26] proposed regenerative TMD to harvest vibration energy through electromagnetic machine, where simultaneous energy harvesting and vibration control have been demonstrated on a three-storey building prototype. Ni et al. [27] estimated the power potential that can be harvested in typical buildings exerted by wind excitation. It is shown that more than 85 kW of power is available for harvesting from a 76-storey building with a regenerative TMD in high wind events of 13.5 m/s at a standard height of 10 m. However, the above researches all modeled the building with TMD as a simple two degree-of-freedom (DOF) and usually the TMD just can mitigate the structure vibration of the first mode. For buildings under wind excitations, it is efficient to just conduct structural control of their first mode by TMD. However for building subjected to other excitations such as earthquake motion, only control of the first mode is ineffective because a seismic wave includes a large numbers of high frequency components.

In view of the above background on the current development of TMD for high-rise buildings, a novel piezoelectric technology of harvesting energy from high-rise buildings is developed. While being used to harness vibration energy of the building, the technology is also expected to dissipate vibration of the building as a tuned mass damper.

## 2. A piezoelectric harvester device fixed on the roof of a high-rise building subjected to a harmonic base motion

This research is to develop a piezoelectric harvester device fixed on the roof that would absorb the vibration energy of high-rise buildings while generating energy as a power harvester. The generated energy from the piezoelectric slab is deduced from the voltage and the charge generated on the surface of the piezoelectric slab. In the following sub-sections, a theoretical model is developed and introduced to calculate the electric power harvested by the piezoelectric generators and estimate the efficiency of the electric energy harvesting of the piezoelectric harvester device.

### 2.1. Introduction of the analytical model

An analytical model of a piezoelectric harvester device on the roof of a high-rise building is developed and shown in Figs. 1a–c. The piezoelectric harvester device shown in Fig. 1a is made of two groups of series piezoelectric generators connected by a shared shaft. The shaft is driven by a linking rod hinged on a proof mass on the tip of a cantilever fixed on the roof of the building. The generators can transfer large amount of vibration energy of the proof mass into electricity and correspondingly abate the vibration amplitude of the main structure exerted by excitations from earthquake or wind. Fig. 1b is an mechanical model of the piezoelectric harvester device fixed on the roof of a building bearing a base excitation of $w_g(t)$. The main body and the cantilever on the roof of the building are square reinforced concrete tube structures with the Yong's module of $E_1$ and $E_2$, densities of $\rho_1$ and $\rho_2$, wall thicknesses of $h_1$ and $h_2$, side lengths of $a_1$ and $a_2$, and heights of $L_1$ and $L_2$, respectively. The proof mass, with a radius of $r$ and a mass of $M$, is exerted an equivalent excitation force of $F_B(t)$ from linking rods driving the shafts of generators. The function of $F_B(t)$ invariably weakens the motion of the proof mass and evokes distributed vibrating displacement of $\delta_B(x,t)$ shown in Fig. 1c which always attenuates the displacement of $w(x,t)$ from the base excitation.

### 2.2. Development of the theoretical model

Considering the fact that a seismic motion consists of different components of signals with variable amplitudes and frequencies, the vibration-abating efficiency of the piezoelectric harvester device can be studied by setting an excitation of a sinusoidal wave as a simple representative of the seismic motion. Therefore, the base excitation at the bottom of the high-rise building is set to be, $w_g(t) = Y\sin\omega' t$, where $Y$ is the amplitude of the base displacement; $\omega'$ is the angular frequency of the base excitation. The distributing inertia force on the building is therefore written as, $F_g(x,t) = -m(x)Y\omega'^2\sin\omega' t$ and $F_B(x,t) = m(x)\ddot{\delta}_B(x,t)$, where $m(x)$ is the mass per length of the building at the position $x$ ($0 \le x \le vL$).

The governing differential equations of the building, subjected to a base excitation, with a piezoelectric harvester device on the roof shown in Fig. 1b are expressed below:

$$E(x)I(x)\frac{\partial^4 w(x,t)}{\partial x^4} + Mg\frac{\partial^2 w(x,t)}{\partial x^2} + m(x)\frac{\partial^2 w(x,t)}{\partial t^2} = F_g(x,t) + F_B(x,t), \tag{1}$$

where $\delta_B(x,t)$ is the distributing displacement function of the building caused by the excitation $F_B(t)$, and its equation under first mode can be assumed as below [28]:

$$\delta_B(x,t) = \begin{cases} F_B(t)\left(\dfrac{x^2}{6E_1I_1}(3L_1 - x) + \dfrac{L_2x^2}{2E_2I_2}\right) & 0 \le x \le L_1 \\ F_B(t)\left(\dfrac{L_1^3}{3E_1I_1} + \dfrac{L_2L_1^2}{2E_1I_1} + \dfrac{(x-L_1)^2}{6E_2I_2}(3(L-L_1) - (x-L_1))\right) & L_1 \le x \le L \end{cases}, \tag{2}$$