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Optimisation of a Piezoelectric System for Energy Harvesting from Traffic Vibrations

Guoliang Ye, Jize Yan, Zi Jing Wong, Kenichi Soga and Ashwin Seshia
Department of Engineering, University of Cambridge, Cambridge, United Kingdom.

***Abstract*—Piezoelectric systems are viewed as a promising approach to energy harvesting from environmental vibrations. The energy harvested from real vibration sources is usually difficult to estimate analytically. Therefore, it is hard to optimise the associated energy harvesting system. This work investigates the optimisation of a piezoelectric cantilever system using a genetic algorithm based approach with numerical simulations. The genetic algorithm globally considers the effects of each parameter to produce an optimal frequency response to scavenge more energy from the real vibrations while the conventional sinusoidal based method can only optimise the resistive load for a given resonant frequency. Experimental acceleration data from the vibrations of a vehicle-excited manhole cover demonstrates that the optimised harvester automatically selects the right frequency and also synchronously optimises the damper and the resistive load. This method shows great potential for optimizing the energy harvesting systems with real vibration data.**

***Index Terms*—Energy Harvesting, Genetic Algorithm, Optimisation, Piezoelectric System, Traffic Vibration.**

I. Introduction

Wireless sensor systems have been used widely in recent years for monitoring built environments. The conventional method of powering the system is to use a battery. However, batteries need to be repeatedly replaced due to their limited life cycle and in the context of a wireless sensor network this may result in substantial maintenance overhead. Recent research has been focused on self-powered sensors using renewable energy from the environment [1]. Wind and solar energy are popular for ambient power generation, but they may be not available in some cases, for example the flow and pressure sensors mounted inside a dark manhole. This paper investigates harvesting vibrations of a manhole cover from vehicular motion to generate power.

A review on the energy harvesting from vibration sources for microsystems can be found at [2]. Energy harvesting from environmental vibrations usually uses piezoelectric cantilever systems which can be modelled as a spring-mass-damper system. The system works in a resonant mode assuming a sinusoidally excited vibration. Thus the optimization of the system parameters to harvest maximum energy can be analytically derived [3], [4]. However, real vibration sources (e.g vibration of a manhole cover) usually have a broad bandwidth with multiple frequency peaks, which results in difficulties in generating an optimal system-level design.

This paper describes the optimal design of a piezoelectric energy harvester using genetic algorithm (GA) based approach using real vibration data. The genetic algorithm allows a numerical evaluation of the output power, instead of restricting in an analytical solution which is difficult to derive from broadband vibrations. This paper also describes the experiment of acquiring acceleration data from a manhole cover and demonstrates that the harvested power is improved by comparing to the conventional system designed by assuming a purely sinusoidal excitation.

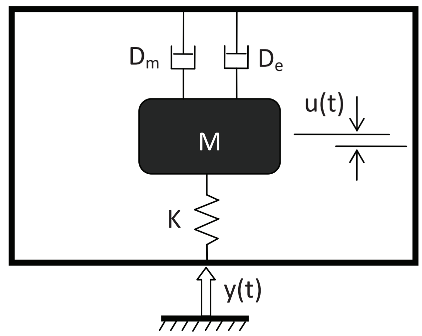


Fig. 1. Modelling a piezoelectric energy harvester.

II. Method

A. Piezoelectric Energy Harvester

The piezoelectric energy harvester is considered as a cantilever structure with a purely resistive load. Figure 1 shows a generic system and it can be modelled by the following ordinary differential equations [5]–[7].

$$\begin{aligned} &M\,\ddot{u}(t) + D\,\dot{u}(t) + Ku(t) + Av(t) = -M\,\ddot{y}(t) \\ &v(t) = RA\,\dot{u}(t) - RC\,\dot{v}(t) \end{aligned} \tag{1}$$

The symbol $'.'$ denotes differentiation. The parameters and variables are denoted as follow. M is the proof mass; K is the spring (cantilever) stiffness; D_m is the mechanical damper (or equally D in equation 1) and D_e is the electrically induced damper expressed in equation 2; A is the piezoelectric coefficient; C is the capacitance of the piezoelectric material and R is the resistive load. t is time; $u(t)$ is the displacement of the mass; $y(t)$ is the external excitation displacement and $v(t)$ is the outgoing voltage.

The electrically induced damper shown in figure 1 can be expressed by:

$$D_e = A^2R - ARC\frac{\dot{v}\,(t)}{\dot{u}\,(t)} \tag{2}$$

If the external excitation $y(t)$ is purely sinusoidal at the natural frequency of the system, equation 1 can be solved analytically and hence the output power of the system is expressed by [4],

$$p = \frac{RM^2A^2\omega^4}{2\left[\left(A^2R + D\right)^2 + \left(RCD\omega\right)^2\right]}y^2 \tag{3}$$

where $\omega = \sqrt{K/M}$ is the natural frequency of the system. If the system is weakly electromechanically coupled ($A^2R \ll D$ in equation 3), the maximum power of the system can be attained from the optimal R expressed by,

$$R_{opt} = \frac{1}{C\omega} \tag{4}$$

In the context of real vibration sources, it is difficult to select an optimal natural frequency of the piezoelectric energy harvester system as real vibrations usually have a broad bandwidth with multiple frequency peaks.

B. Genetic Algorithm Optimisation

Due to the difficulty of deriving an analytic solution to the output power of a piezoeletric energy harvester with real broadband vibrations, this paper utilises numerical optimisation methods in which the evaluation of output power can be computed numerically. The simplest approach is to simply populate the parameter space and calculate all possible values of all of parameters, also termed as enumeration. However this technique is very inefficient, especially in high dimensionality. An advanced method is to estimate the local gradient of a previously selected point, and then select a new point in the direction of the steepest positive gradient (for maximisation) or largest negative gradient (for minimisation). This is called the gradient-based method and is widely used in engineering. However the gradient-based methods are susceptible to trapping in local minima. This paper selects a genetic algorithm which is a stochastic method including random elements to avoid the drawbacks of local gradient search. However, global optimisation is not always guaranteed.

The genetic algorithm initially starts by selecting a random trial point for each parameter, and then iteratively runs to survive good points which can harvest more energy, and eliminates poor points, until the parameters converge to maximise the harvested energy. The genetic algorithm used in this work follows the procedure described in [8] and the related Matlab toolbox is used. In this work, binary Cartesian coding, a frequently used method, is used to map the discrete space of the parameters to a genetic string (often referred to as chromosomes). Roulette wheel selection is used to reproduce a new population (new trial points), based on a linear ranking of the fitness values.

An evaluation function is devised to measure how well the trial solution performs. Typical acceleration data acquired from a manhole cover will be used to evaluate the trial points. Since the continual output power of the harvester also depends on the number of vehicles passing over the manhole cover, the work here defines a new power metric to evaluate the harvester. It is defined by the harvested energy (Joule) per vehicle, instead of per second. The time of a car passing over a manhole cover is usually less than two seconds, but the vibration of the harvester's mass can last much longer especially in the case of a low frequency piezoelectric system. This means that energy would be stored in the harvester and output to the associated interface circuit even after the vehicle has passed. In this work the output evaluation is simulated for 20 seconds to let the harvester output most of the energy.

Fig. 2. An accelerometer attached to a manhole cover.

III. Results

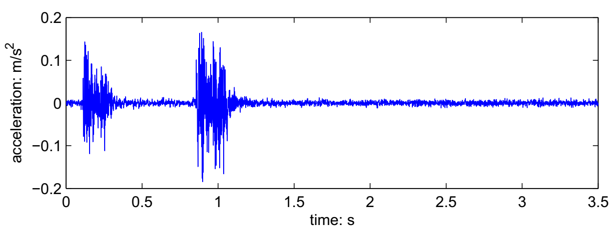
An experiment was carried out using offline acceleration data and the results were compared to a conventional system designed by assuming a purely sinusoidal excitation.

A. Experimental Setup and Data Acquisition

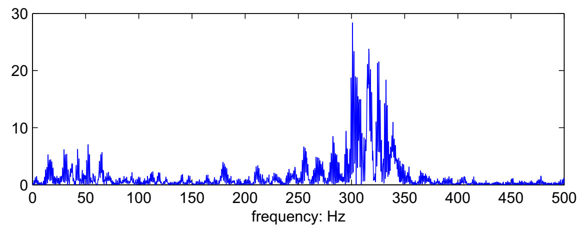
Since the cost function is a numerical solution to equation 1, the external excitation has to be known. The vibration data is captured by an ultracompact accelerometer (model ADXL311, Analog Devices Inc., USA). The accelerometer is packaged as an single monolithic integrated circuit (IC) in the size of 5 mm $\times$ 5 mm $\times$ 2 mm, and attached on a 2 cm $\times$ 2 cm PCB (printed circuit board). Fig. 2 shows that the PCB is attached to a 10 cm $\times$ 10 cm metal plane and then the metal plane is attached to a manhole cover. The accelerometer can measure a dynamic acceleration (e.g. vibration) and its output is an analog voltage proportional to acceleration. The analog voltage is digitalized and logged in the sampling frequency of 1 KHz using an embedded controller (model cRIO-9014, National Instruments, USA). Fig. 3 shows typical acceleration data and associated power spectrum when a car passes over the manhole cover. Note that over 80% of the vehicles passing over the manhole are cars and hence the power spectrum of related recorded vibration data are similar to Fig. 3(b). The spectrum shows that there are two main frequency components widely spaced between 10-80 Hz and 280-330 Hz.

B. Experimental Results

There are 6 parameters in the system. They are M, K, D, A, C and R in equation 1. In practice, K depends on the



(a) manhole cover vibration data (one car).



(b) power spectrum

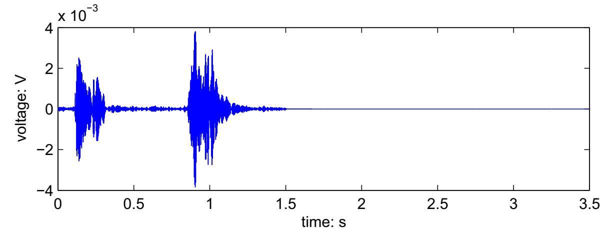
Fig. 3. The vibration data (a) of a car passing over a manhole cover and its power spectrum (b).

material and the dimensions of cantilever. In this work the dimensions of the cantilever are not optimised and $K = 4320$ N/m is assumed. In equation 3, the damper decreases with the output power. However a small damper might not be easy to achieve in practice. Thus a practical damper, 0.042 N/(ms), is selected from [4]. A and C depend on the piezoelectric beam. This work adopts the piezoelectric beam used in [4]. The parameters are $A = 4.7 \times 10^{-4}$ N/V and $C = 1.27 \times 10^{-7}$ F. The remaining parameters M and R are analysed below.

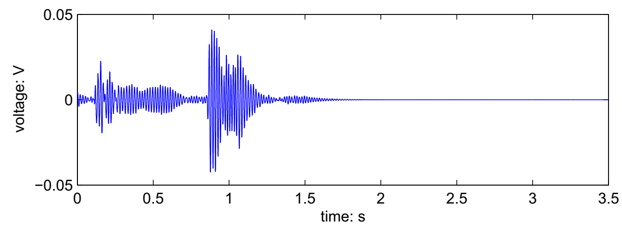
In the conventional optimisation method of assuming a sinusoidal vibration, a resonant frequency of the system F has to be given. Table I shows the results of using different resonant frequencies which are the peaks on the power spectrum shown in Fig. 3(b). M was calculated by $M = K/(2\pi F)^2$. R was optimised by equation 4. Once all parameters in the piezoelectric system are determined, the harvested energy can be evaluated numerically using the recorded acceleration data. The output voltages of different systems are shown in Fig. 4. Since the natural frequency of the system has to be manually selected, it is hard to select the right frequency to maximise the system output. For example, the peak at 304 Hz contains the most energy but the system optimised for that frequency does not harvest much energy. This might be because the damper is relatively large and the small mass is too weak to gather energy from the source in practice. In Table I, the harvested energy increases with the mass and have a maximum at the frequency of 14.4 Hz.

-	F (Hz)	M (g)	R (KΩ)	Power (μJ/Vehicle)
Sinusoidal based	304	1	4.1	0.00013
Sinusoidal based	60	30	20.8	0.0064
GA based	14.4	525	63.5	1.9
Sinusoidal based	10	1090	125	0.76

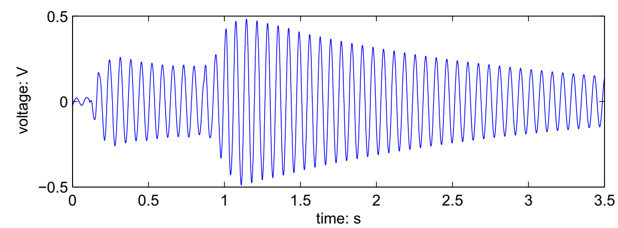
TABLE I
THE OUTPUT POWER OF DIFFERENT SYSTEMS.



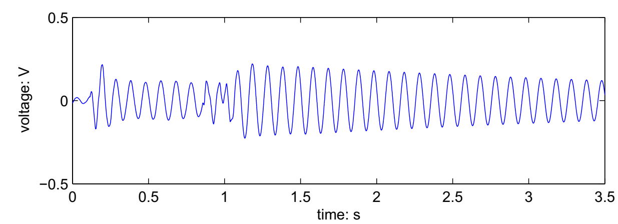
(a) 304 Hz system



(b) 60 Hz system



(c) 14.4 Hz system



(d) 10 Hz system

Fig. 4. Output voltage from different systems.

In GA Optimisation, M, D and R are synchronously optimised to maximise the harvested energy. Fig. 5 shows the maximum harvested energy and corresponding parameters in each generation. The energy increases with generation and converges to 1.9 μJ after the 22nd generation. The mass is optimised to 525 g which gives a natural frequency of 14.4 Hz. The damper is optimised to the smallest possible value. The resistive load is optimised to 63.5 KΩ. The output of the GA optimised system (14.4 Hz) is shown in Table I, and the output voltage over time is shown in Fig. 4(c).

C. Discussion

The sinusoidal based method has to manually select a natural frequency for the system. It seems reasonable to select the frequency with the highest peak in the power spectrum, but the result shows that it is actually not a good choice. Other lower frequency peaks may have less power in the power spectrum, but are associated with a larger mass and hence can

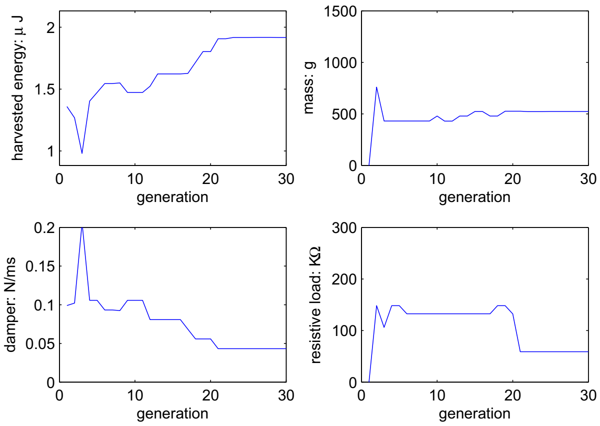


Fig. 5. GA optimsed output power and the corresponding parameters M, D and R. M is optimised in the range from 1 to 2000 g. D is optimised in the range from 0.042 to 0.2 N/(ms). R is optimised in the range from 1 to 300 KΩ.

potentially allow for more energy harvesting from the vibration source. Thus it is difficult to select the right natural frequency to maximise the output power. The genetic algorithm based method globally considers the effects of the mass and the natural frequency for the system, so it automatically selects the right frequency (through the right mass). The optimal damper and resistive load are also automatically selected.

IV. Conclusion

This paper presents a genetic algorithm to optimally design a piezoelectric energy harvester. The genetic algorithm based optimisation approach shows great potential and the possibility for enhanced energy recovery from ambient vibration in practical settings. The maximal output power of the system was evaluated using the data recorded from a vehicle-excited manhole cover. The harvested energy also depends on the specific constraints on the fabrication of the piezoelectric cantilever beam with larger beams allowing for more harvested energy. In addition, other traffic vibrations (for example the train-excited bridge vibration) could be much stronger, which could produce feasible power for practical applications. Research into extending the validity of this optimisation approach is ongoing.

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