Adaptive Vibration Energy Harvesting

Sam Behrens[a], John Ward[a] and Josh Davidson[b]

[a]CSIRO Energy Technology, PO Box 330 Newcastle NSW 2304 Australia
[b]School of Maths, Physics & Information Technology, James Cook University, Townsville QLD 4811 Australia

ABSTRACT

By scavenging energy from their local environment, portable electronic devices such as mobile phones, radios and wireless sensors can achieve greater run-times with potentially lower weight. Vibration energy harvesting is one such approach where energy from parasitic vibrations can be converted into electrical energy, through the use of piezoelectric and electromagnetic transducers. Parasitic vibrations come from a range of sources such as wind, seismic forces and traffic.

Existing approaches to vibration energy harvesting typically utilise a rectifier circuit, which is tuned to the resonant frequency of the harvesting structure and the dominant frequency of vibration. We have developed a novel approach to vibration energy harvesting, including adaption to non-periodic vibrations so as to extract the maximum amount of vibration energy available. Experimental results of an experimental apparatus using off-the-shelf transducer (i.e. speaker coil) show mechanical vibration to electrical energy conversion efficiencies of $27 - 34\%$. However, simulations of a more electro-mechanical efficient and lightly damped transducer show conversion efficiencies in excess of 80%.

Keywords: vibration, energy harvesting, energy scavenging, adaptive control, machine learning

1. INTRODUCTION

Over the past decade there has been a steady decline in volume and weight of portable electronic devices. A major obstacle limiting the miniaturisation of these devices further is the need for energy storage i.e. batteries. In many cases energy storage contributes to more than half the actual volume and weight of the device.

Energy storage devices for portable electronic devices are sometimes unfeasible as they may be deployed in an environment where changing or/and re-charging is not possible (for example medical implants).

However, there are several techniques for harvesting energy at the site of the portable electronic device. These include photovoltaics, thermoelectrics and vibration energy harvesting. Each method has its own advantages and disadvantages such as sufficient sunlight, temperature gradients or vibration. However, vibrations tend to be more ubiquitous and can be utilised more readily in inaccessible environments.[1]

A problem with present vibration energy harvesting techniques for portable electronic device is that vibration sources are often assumed to be sinusoidal in nature.[2,3] However, in most situations, vibrations tend to occur in bursts i.e. quasi-periodic. Secondly, these techniques have to overcome diode voltage drops due to the conditioning circuit before vibration energy can be harvested.[2,3] Another problem to overcome is the change in operating and environmental conditions, such as temperature, which may effect the harvesting performance.[2–4]

In an attempt to overcome some of these problems, Fleming *et. al.*[4] implemented a highly reactive shunt impedance to control vibrations and, hence, could not harvest any real/useful vibration energy.

Since volume, weight and energy are critical parameters for portable electronic devices, it is also critical to harvest vibration energy as efficiently as possible. Some studies[5,6] have attempted to look at conversion efficiencies (i.e. harvesting efficiencies), however, most have focused on the conditioning circuit efficiency.[2,3]

In this paper, we will present a novel adaptive vibration energy harvesting technique that attempts to address some of these problems.

Send correspondence to Sam Behrens, E-mail: Sam.Behrens@csiro.au, Telephone: +61 2 4960 6133.

2. PROPOSED CONCEPT

The vibrational systems that we are dealing with typically receive energy not power in discrete bursts,[1–3] so we can loosely consider our problem to be "*How do we extract the maximum energy out of a burst of energy, before the next burst comes along?*"

In order to promote a better understanding of our work, consider the following simplified example. This system is not a vibration system (so we don't have to deal with the effects of reactive power), however most of the behaviour/features are analogous to the vibration systems that we are dealing with.

2.1. Example: Capacitor Discharge

Consider the circuit in Figure 1, where the capacitor C has an initial charge V_o and we try to determine a load characteristic so that the maximum energy possible is absorbed by the load in time T_p. Example parameter values could be $V_o = 10V$, $C = 20mF$, $R_s = 1k\Omega$ and $T_p = 60s$. Note that these parameters give an initial condition of 1 Joule energy stored in the capacitor C.

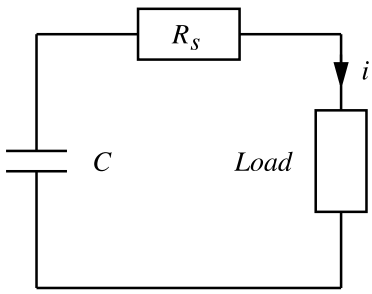

Figure 1. Capacitor discharge example.

2.1.1. Traditional Maximum Power Transfer

The traditional maximum power transfer problem implicitly assumes that the source (the capacitor in this case) has infinite available power, though it is restricted by the source impedance R_s.

The solution to the maximum power transfer problem is to set the load impedance R_L equal to the complex conjugate of the source impedance. For this simplified example, this just means that $R_L = R_s$ and for the parameters given, 47.5% of the energy in the capacitor will be absorbed by the load in time T_p. Note this is a special case of the generlised load resistance compared to the next case.

2.1.2. Optimal Impedance for Maximum Energy Transfer

In this case, we explicitly try to find the optimal load impedance (R_L) to maximise the energy absorbed by the load in time T_p. The energy absorbed by the load is given by

$$E_L = \frac{1}{2}CV_o^2 \left(\frac{R_L}{R_s + R_L}\right)\left(1 - e^{\frac{-2T_p}{(R_s+R_L)C}}\right), \tag{1}$$

which when maximised for the parameters of our example system results in 58.5% of the energy in the capacitor being absorbed by the load in time T_p.

2.1.3. Optimal Load Characteristic for Maximum Energy Transfer

The previous two solutions utilised a linear load impedance. In general it is true that for the damping/control problem that a linear control system produces the optimal result for a linear system. However, this is not true for the example system in the form that we have posed this problem.

Rather than restricting the load to a static impedance, we can more generally describe it by a voltage/current relationship. In this generalised version of the problem, we note that the energy absorbed by the load is given by

$$E_L = V_o \int_0^{T_p} i(\tau)\, d\tau - \frac{1}{2C}\left(\int_0^{T_p} i(\tau)\, d\tau\right)^2 - R_s \int_0^{T_p} i^2(\tau)\, d\tau. \tag{2}$$

This can be interpreted as a statement that the energy absorbed by the load is equal to the energy lost by the capacitor (first two terms) minus the energy consumed by the source impedance (last term).

It is reasonably easy to prove that for this simplified example that the optimal solution is given by a time varying load impedance with instantaneous impedance given by the equation

$$R_L(t) = \frac{T_p - t}{C} + R_s \qquad t\epsilon\left[0, T_p\right]. \tag{3}$$

A plot of this time varying impedance is given in Figure 2. When the optimal time-varying impedance is applied to the example system parameters, 60% of the energy is transferred to the load.

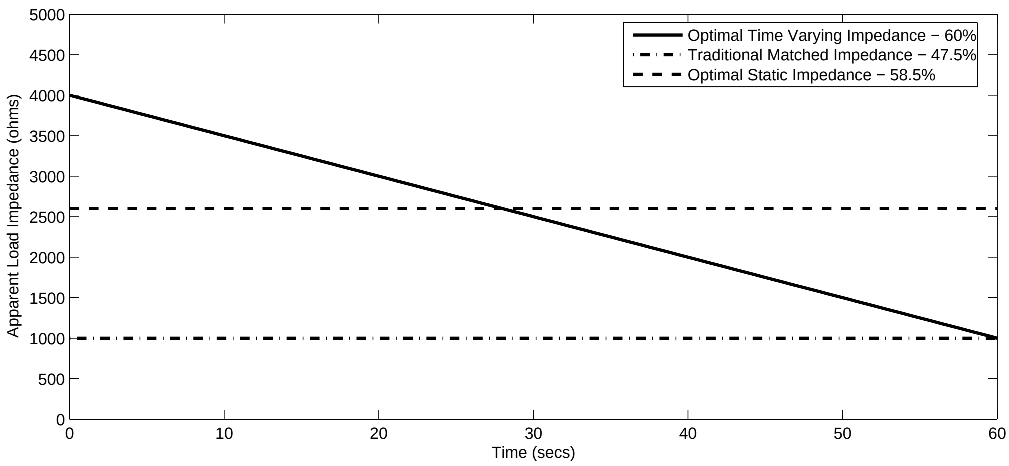

Figure 2. Load impedance *vs* time for the three solutions to example capacitor discharge problem.

2.1.4. Key Points from this Example

1. The tradition maximum power transfer solution which uses matched impedances is optimal for the problem it solves. However, when the excitation is energy constrained, this solution does not provide the best efficiency. This focus on energy rather than power differentiates our work from the previous work.

2. Vibration damping research considers removing the vibration energy from a structure as quickly as possible. In our work we explicitly seek to remove the highest proportion of the available energy to the load not to damp the oscillations. For this simplified example, this is the difference between seeking to discharge C as fast as possible compared with trying to capture the maximum energy from C.

3. The traditional maximum power transfer solution only requires knowledge of the system structure, not of the excitation. It is only with explicit knowledge of the system excitation that the optimal energy transfer can occur. In the simplified example, this knowledge is embodied in the parameters V_o and T_p. In this way our work differs significantly from the previous work.

4. Even when the system excitation is considered, the previous work deals with the question of selecting *the* "optimal impedance" to maximise the energy transfer. Even for this simplified example system we see that the optimal impedance is actually a time varying function rather than a static relationship. As such, anyone looking at this problem from the perspective of identifying *the* optimal impedance is immediately constrained to suboptimal results.

We now show how this approach can be used to maximise energy harvesting efficiency from a vibration mechanical system.

3. VIBRATION ENERGY HARVESTING SYSTEM

Figure 3 illustrates a typical vibration energy harvesting system. Figure 3 also illustrates schematically the experimental setup that we have for testing the proposed concept, which will be explained in greater detail in Section 4. It allows us to apply force disturbances f_d to a damped resonant system. The system uses an electromagnetic transducer as shown in Figure 4.

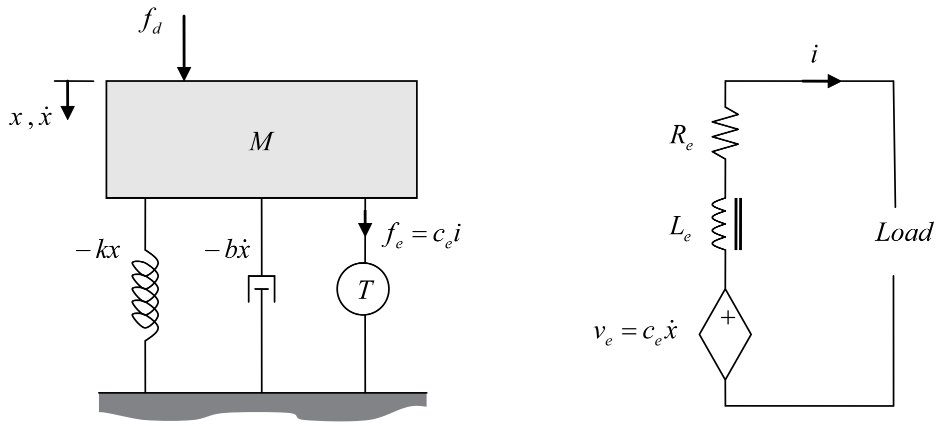

Figure 3. Schematic of the vibrating mass problem.

The transducer is modelled electrically as an inductance L_e, resistance R_e and dependant voltage source ν_e all in series. The voltage of the dependant source is proportional to the velocity $\dot{x}$ of the mass M i.e. $\nu_e = c_e\dot{x}$. Mechanically the transducer is modelled as a force f_e input whose value is proportional to the current i flowing in the transducer i.e. $f_e = c_e i$.

The system is therefore able to be described mathematically by the simultaneous differential equations:

$$\begin{array}{c} f_d - c_e i = M\ddot{x} + b\dot{x} + kx \\ V_{Load} = c_e\dot{x} - iR_e - L_e\frac{di}{dt} \end{array} \tag{4}$$

Note that we have not included the dynamics of the load in the model. We will use this degree of freedom to determine the load characteristics that give the maximum transfer of energy from the mass system to the load.

This can be expressed as an optimisation problem of the form:

$$\max_{i(t)} \int_0^\infty i.V_{Load}dt, \tag{5}$$

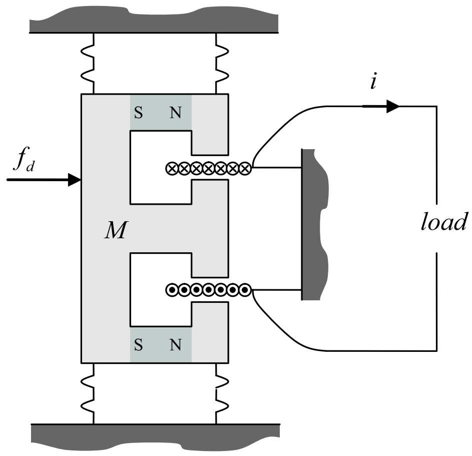

Figure 4. Electromechanical transducer for vibration harvesting.

where V_{Load} is per the above equations. For the purposes of testing, we have initially used step force inputs for f_d. This is convenient since if the system is initially at rest, then a step of magnitude $k\sqrt{2/k}$ results in 1 Joule of work being done by f_d once the system has again reached equilibrium. A step force input is a simplified yet not unrealistic approximation to the excitation that a "real" system of this type may encounter.

As we saw in the capacitor discharge example, Section 2.1, in order to obtain the maximum energy transfer from the system, the characteristics of the excitation need to be included in the optimisation. Figure 5 shows one architecture that provides this functionality.

In Figure 5, the mechanical structure and electromagnetic transducer are as described above. The conversion device is the 'harvesting rectifier', which is a switching device capable of emulating the behaviour of an arbitrary impedance $z(t)$ but rather than dissipating energy, it transfers it to the energy storage or load. More information on the 'harvesting rectifier' can be found in Behrens.[7]

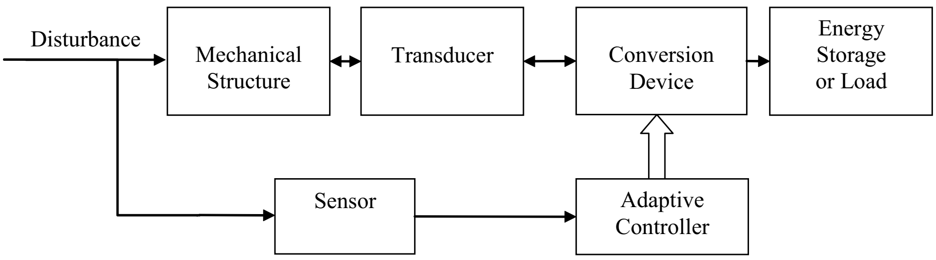

Figure 5. Block diagram of system showing main components.

The key intelligence in the system is in the adaptive controller. We have developed a reinforcement learning algorithm to provide this functionality. Over time this algorithm builds up a map between features of the energy input (disturbance) and the appropriate impedance required to maximise energy capture.

Assuming Table 1 parameters, Figure 6 shows the resulting current and voltage waveforms where we have a force step at times $t = 0$ and $t = 0.4$ seconds. Note that although the mechanical system is the same throughout, both the phase and magnitude of the current waveform change with respect to the voltage waveform when the second step occurs. The reason for this change is that during the first step, the system is configured to extract as much energy as possible before the next step arrives, while for the second step there is more time to absorb the energy, so a more efficient configuration is appropriate.

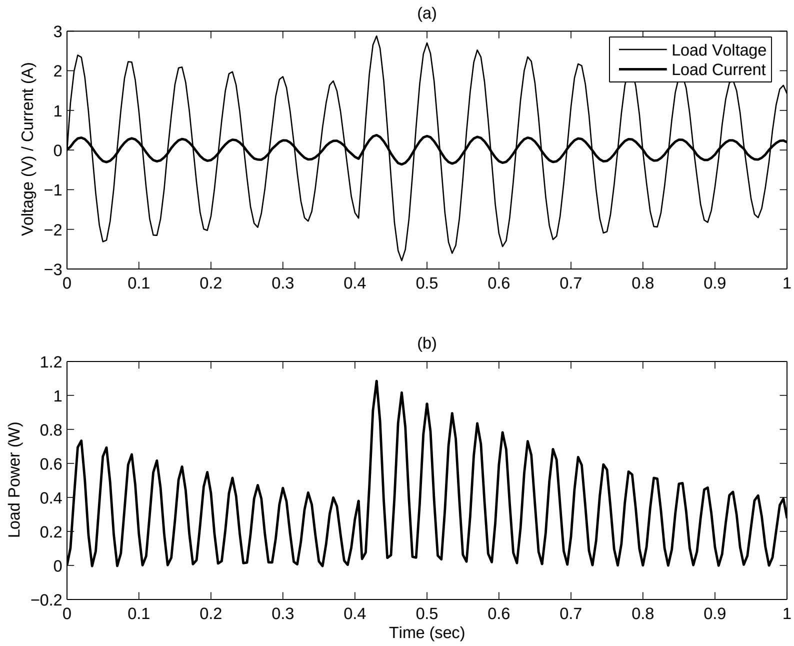

Figure 6. Optimal load voltage and current (a) and power (b) for the vibration energy harvesting system.

This system also serves to highlight an unusual characteristic of the input energy characterisation that we use - namely that we need to produce an estimate of when the next disturbance is likely to occur. A practical example of why this is not unreasonable can be seen by considering the motion of a person walking as the energy input - when walking at a constant speed, the time between steps tends to be fairly constant.

The learning problem for this system was reasonably straightforward as we restricted ourselves to step energy inputs, and the load current was able to be characterised as a phase/magnitude shifted version of the load voltage. We will need to perform more experimentation with more realistic systems to determine how well this works for different structures, transducers and energy disturbances.

A variation on this structure that we are currently working with is shown in Figure 7, where a soft sensor is used to infer characteristics of the energy input disturbance rather than having to measure it directly.

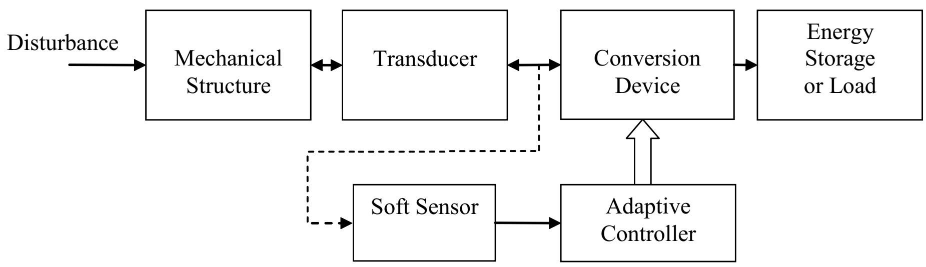

Figure 7. Block diagram of system using a soft sensor rather than direct disturbance measurement.

4. EXPERIMENTAL APPARATUS

An experimental apparatus was built to test the proposed technique of vibration energy harvesting at the CSIRO Energy Centre, Newcastle, Australia. A photograph of the apparatus, showing the laser doppler vibrometer (LDV), rigid support, flexible supports, mass and two identical electromagnetic transducers (speakers) is provided in Figure 8. Figure 9 shows a section view of the experimental apparatus and is equivalent to the vibration energy harvesting system as shown in Figure 4. Table 1 list the experimental apparatus parameters.

Figure 8. Photograph of the experiential apparatus.

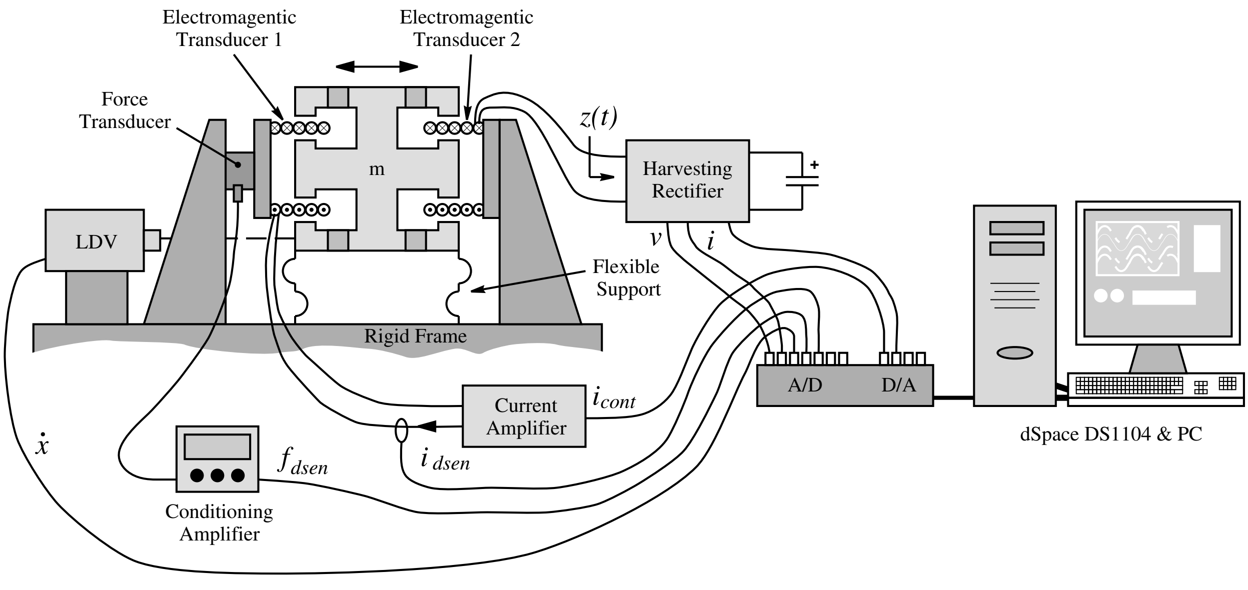

Figure 9. Experimental set up with section view of the apparatus.

In order to measure the experimental apparatus conversion efficiency η, i.e. the energy out E_{out} divided by energy in E_{in}, we need to measure the disturbance force f_d (or f_{dest}), mass velocity $\dot{x}$, and 'harvesting rectifier' current i and voltage v.

A dSpace DS1104 system generated a current control signal i_{cont} and measured the disturbance force F_{dsen}, mass velocity $\dot{x}$ and 'harvesting rectifier' current i and voltage v. By applying a step disturbance current i_{dsen} to the electromagnetic transducer 1, a disturbance force f_{dest} can be estimated i.e. $f_{dest} = c_e i_{dsen}$. A disturbance force f_{dsen} was directly measured using a PCB Piezotronics 218C force transducer through a Nexus 2692 conditioning amplifier, with a high-pass filter of $0.1Hz$. The sensed disturbance force f_{dsen} magnitude could then be compared against f_{dest} as a means of verifying the estimation. Mass velocity $\dot{x}$ of the mechanical system was measured using an Ometron VH-1000-D laser doppler vibrometer (LDV) and was used to determine the experimental apparatus parameters i.e. k and b. The experimental apparatus set up is depicted in Figure 9.

Table 1. Experimental apparatus parameters.

Parameter	**Symbol**	**Value**	**Unit**
Mass	m	11	kg
Damping Coefficient	b	14.3	Ns/m
Spring Coefficient	k	87.1	kN/m
Coil Inductance	L_e	1.9	mH
Coil Resistance	R_e	3.4	Ω
Coupling Coefficient	c_e	8.3	N/A or V/ms^{-1}

5. VERIFICATION

In this section, we will demonstrate results from the adaptive vibration energy harvesting concept via simulation and experimentation.

5.1. Simulation

By applying a step disturbance force $f_d = 8.3N$ (or $E_{in} = {f_d}^2/2k = 0.395mJ$) to the model, the 'harvesting rectifier' learns and adapts such that it maximises the conversion efficiency i.e. maximise E_{out}.

Figure 10 shows the simulated model results for the 'harvesting rectifier' subjected to a step disturbance force with a period of 5 seconds. The conversion efficiency (η) is displayed in plot (a) which reveals that after a number of iterations the system converges to an optimal conversion efficiency of 0.21 i.e. 21%. Plots (b), (c) and (d) in this figure show the disturbance force f_d, the mass velocity $\dot{x}$ and the impedance z respectively, as functions of time. It can be seen that for each period the velocity of the mass decays to zero, and the impedance changes accordingly to the algorithm as to ensure maximum conversion efficiency, as shown in Figure 10 (d).

Figure 11 shows the results from the same simulation run with the period of the step disturbance force f_d set at 2 instead of 5 seconds. Owing to the faster period of the step force, the mass velocity $\dot{x}$ does not completely decay for each period. Also, the impedance needs to updated 'faster' on a time scale, as shown in Figure 11 (d). The efficiency is seen to converge to an optimal value of 0.24 (i.e. 24%), which is slightly higher than for the 5 second case.

The simulation was then repeated, however, this time the step disturbance force was changed intermittently between 2 and 5 seconds. The results from this are displayed in Figure 12.

In this simulation, we see that when the input excitation changes, the reinforcement learning algorithm is able to immediately reconfigure itself to the previously learnt optimal configuration. This is in contrast to adaptive optimisation type approaches where the optimisation has to be recalculated every time there is a change in the system. The reinforcement learning algorithm achieves this by building up a map of previous experiences, which is called upon any time a new operating point is required.

5.2. Experimental

Using the same procedure as described in the previous section, Section 5.1, a $f_d = 8.3N$ step disturbance force was applied to the experimental apparatus for 5 and 2 second periods, and intermittent 2 and 5 second periods. Experimental results for these three scenarios can be seen in Figures 13, 14 and 15 respectively.

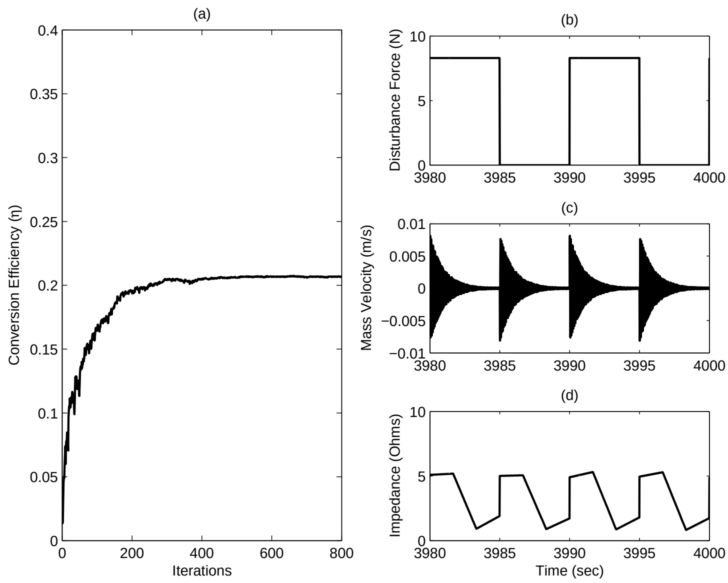

Figure 10. Vibration energy harvesting system – 5 second periods. Conversion efficiency *vs* iterations (a), and disturbance force (b), mass velocity (c) and impedance (d) *vs* time.

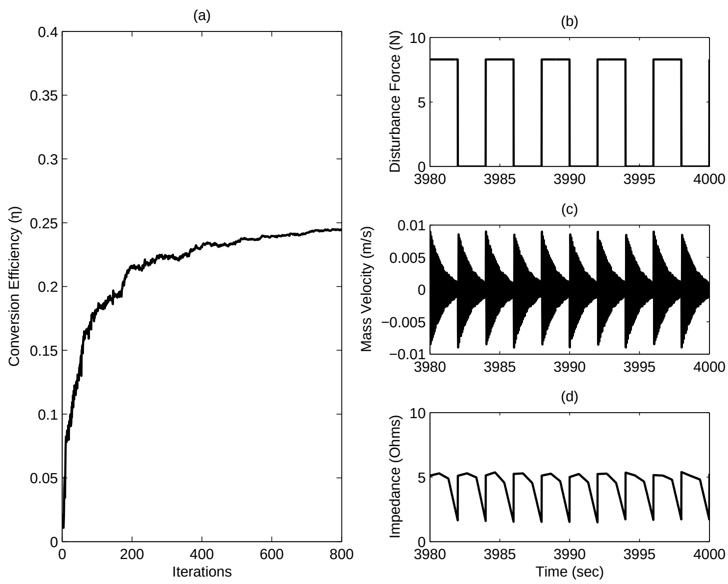

Figure 11. Vibration energy harvesting system – 2 second periods. Conversion efficiency *vs* iterations (a), and disturbance force (b), mass velocity (c) and impedance (d) *vs* time.

6. DISCUSSIONS

From the results, we can observe both the simulations and experimental apparatus converge to an optimal conversion efficiency of $21 - 34\%$. We also notice the load impedance $z(t)$ for the 'harvesting rectifier' learns and adapts to changing disturbance, and is fast changing.

Additionally, the experiential apparatus conversion efficiency results are slightly larger (i.e. $6 - 10\%$) and

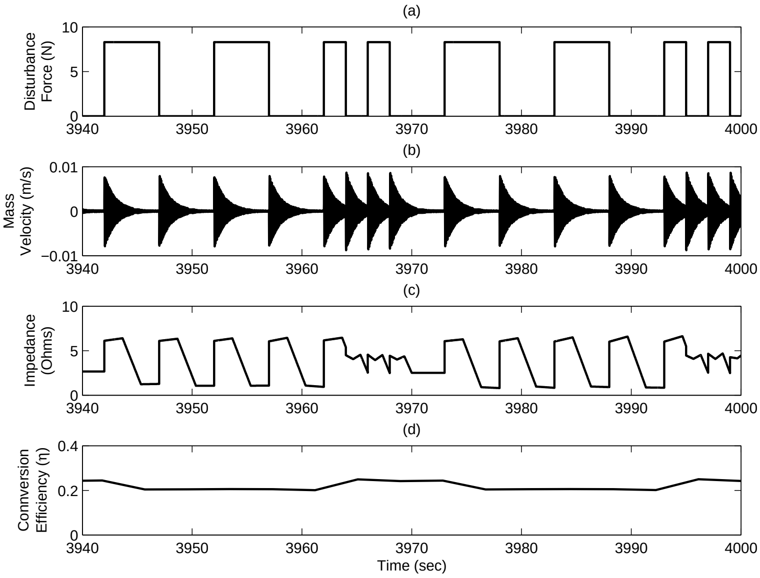

Figure 12. Vibration energy harvesting system – intermittent 2 and 5 second periods. Disturbance force (a), mass velocity (b), impedance (c) and conversion efficiency (d) *vs* time.

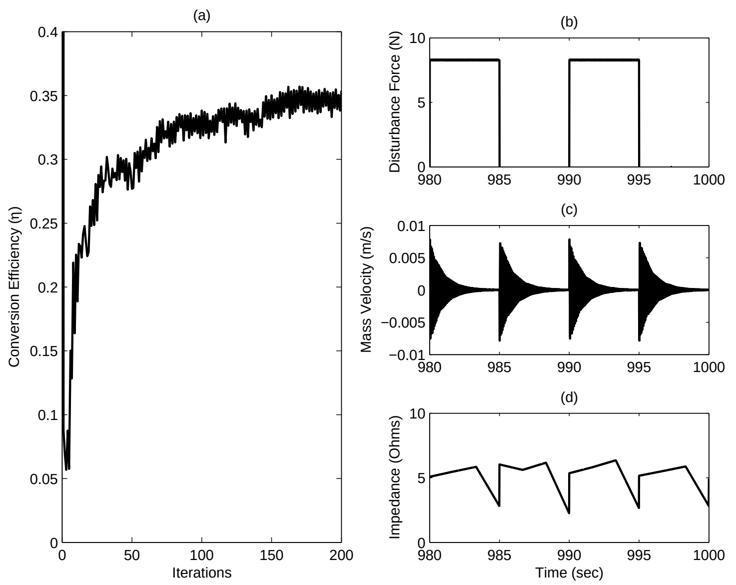

Figure 13. Experimental apparatus – 5 second periods. Conversion efficiency *vs* iterations (a), disturbance force (b), mass velocity (c) and impedance (d) *vs* time.

optimal impedance $z(t)$ is considerably different than the simulations. We believe this is attributed to the non-linearities, additional dynamics and off-sets for the experiential system. This is a positive outcome, as this demonstrates the proposed learning technique can compensate for changing operating and environmental conditions.

We also observe that the vibration energy harvesting system has a *poor* conversion efficiency i.e. $27 - 34\%$.

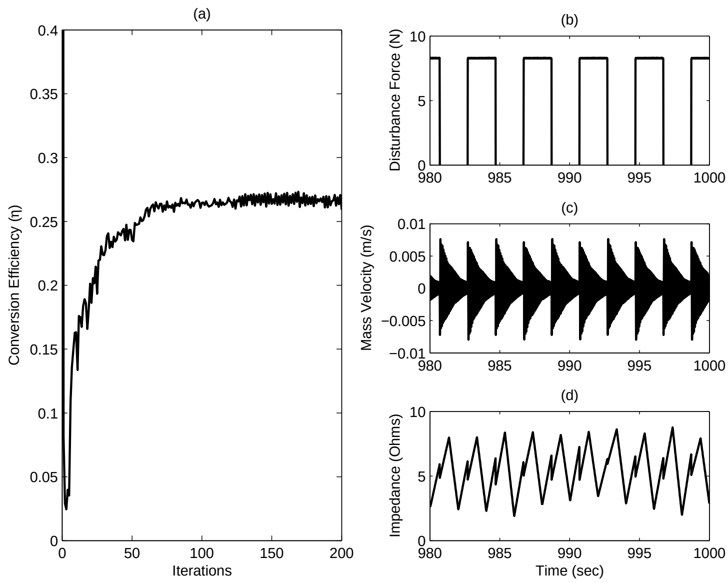

Figure 14. Experimental apparatus – 2 second periods. Conversion efficiency *vs* iterations (a), disturbance force (b), mass velocity (c) and impedance (d) *vs* time.

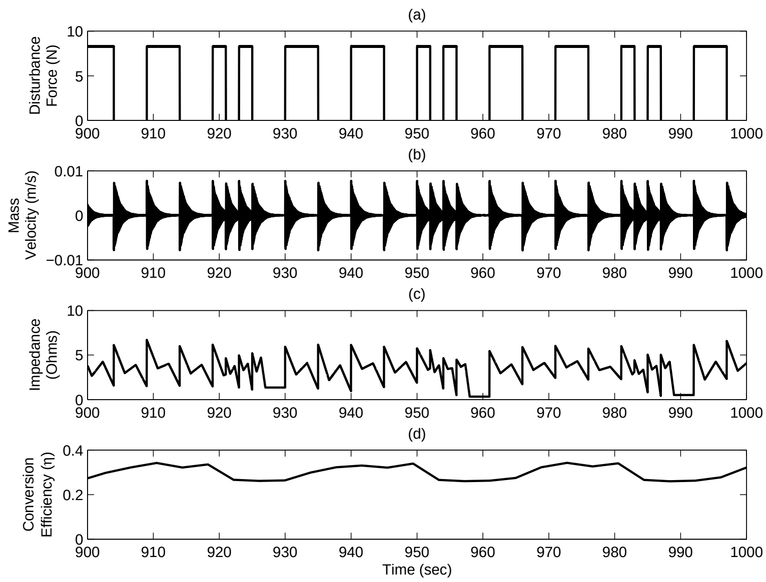

Figure 15. Experimental apparatus – intermittent 2 and 5 second periods. Disturbance force (a), mass velocity (b), impedance (c) and conversion efficiency (d) *vs* time.

This can be attributed to the efficiency of the electromagnetic transducer and relatively large damping of the vibration system. However, if we apply the above concepts to a more efficient electro-mechanical system, such as a QDrive STAR Linear Motor/Alternator 1S362M/A,[8] simulations suggest that energy conversion efficiencies of greater than 80% could be achieved, as shown in Figure 16.

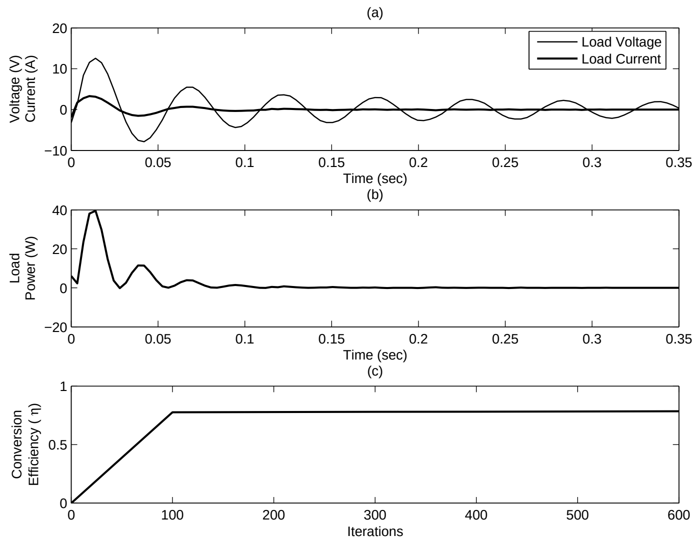

Figure 16. Optimal load voltage and current (a), power (b) *vs* time, and conversion efficiency *vs* iterations (c) for the QDrive Star Alternator/Generator 1S362M/A.

7. CONCLUSION

In this paper we have demonstrated a novel approach to vibration energy harvesting where a reinforced learning algorithm is used to maximise the extracted vibration energy for different disturbance scenarios. The proposed concept was experimentally verified on a simple experimental apparatus. Results from the apparatus demonstrated mechanical vibration to electrical energy conversion efficiencies of $27 - 34\%$. Simulations for a more efficient electro-mechanical system, suggest conversion efficiencies of greater than 80% could be achieved.

Research is continuing at the CSIRO Energy Centre to demonstrate higher conversion efficiencies.

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