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# A vibration powered wireless mote on the Forth Road Bridge

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# A vibration powered wireless mote on the Forth Road Bridge

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**Abstract.** The conventional resonant-approaches to scavenge kinetic energy are typically confined to narrow and single-band frequencies. The vibration energy harvester device reported here combines both direct resonance and parametric resonance in order to enhance the power responsiveness towards more efficient harnessing of real-world ambient vibration. A packaged electromagnetic harvester designed to operate in both of these resonant regimes was tested *in situ* on the Forth Road Bridge. In the field-site, the harvester, with an operational volume of ∼126 $cm^3$, was capable of recovering in excess of 1 mW average raw AC power from the traffic-induced vibrations in the lateral bracing structures underneath the bridge deck. The harvester was integrated off-board with a power conditioning circuit and a wireless mote. Duty-cycled wireless transmissions from the vibration-powered mote was successfully sustained by the recovered ambient energy. This limited duration field test provides the initial validation for realising vibration-powered wireless structural health monitoring systems in real world infrastructure, where the vibration profile is both broadband and intermittent.

## 1. Introduction

Harvesting ambient kinetic energy holds the promise of realising decentralised power generation for the electronic systems at the point of application. Example applications include structural health monitoring of civil infrastructural assets such as bridges, railways and tunnels by using wireless sensor networks (WSN). However, majority of the vibration energy harvesting (VEH) systems reported in the literature are designed for single sinusoidal frequency vibration sources [1], while real vibration environments in these applications tend to be broadband intermittent or of rapidly varying frequency content.

Common frequency broadening techniques in the literature [2] include arraying of multiple harvesters each at a slightly different frequency (at the cost of overall power density), mechanical frequency tuning (actuation power is required), electrical frequency tuning (moderate tuning range) and various other nonlinear vibrational approaches such as Duffing oscillators (moderate broadening) and bi-stable structures (design complexity). At the core, these techniques still involve the direct excitation of a classic linear (or weakly nonlinear) resonator.

The adjustment of the quality factor for a given linear resonator can only maximise either the power peak or the frequency bandwidth. Therefore, a compromise between peak power and operational frequency bandwidth needs to be made while designing for a specific vibration profile. On the other hand, a parametrically excited resonator has been demonstrated as a viable solution to noticeably enhance both the power output as well as the operational bandwidth due to its fundamentally different instability phenomenon [3].

This paper reports a packaged vibration energy harvester designed to operate in both direct resonant and parametric resonant regimes. The harvester prototype, integrated with a power conditioning circuit, has been demonstrated to successfully power a wireless mote on the Forth Road Bridge.

## 2. Method and apparatus

A packaged electromagnetic harvester based on the design of a previously reported auto-parametrically excited vibration energy harvester [4] is shown in figure 1. The package volume was approximately 300 cm$^3$ while the operational volume of the harvester was 126 cm$^3$. The electromagnetic transducer comprised of a coil with a wire resistance of 4 kΩ and two pairs of neodymium iron boron magnets. The experimentally matched load resistance, at which maximum power can be extracted, was in the range of 4 to 5 kΩ for both direct and parametric resonant peaks.

The resonant power amplitudes of the prototype, when driven into both direct and parametric resonance regimes, compare favourably to a commercial electromagnetic VEH counterpart of comparable size (135 cm$^3$) [5] as can be seen in figure 2. The parametric resonant response onsets upon attaining an initiation threshold excitation amplitude ($<$0.2 g$_{rms}$) and then rapidly outperforms its direct counterpart.

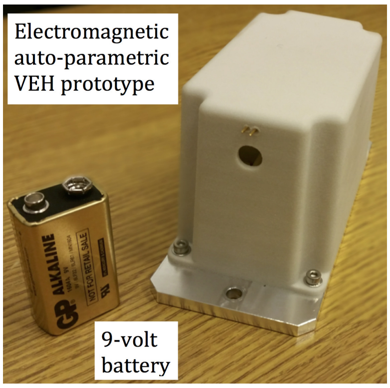


Figure 1: Auto-parametric vibration energy harvester prototype (right) next to a 9 V battery (left).

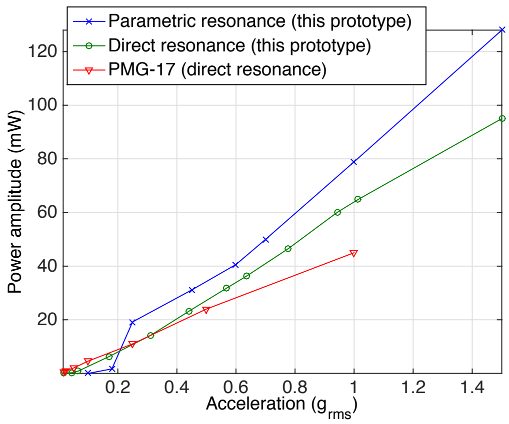


Figure 2: The parametric and direct resonant power output, compared to PMG-17 [5].

The natural frequency is in the vicinity of 13.2 Hz and auto-parametric resonance is observed at approximately twice of this frequency as illustrated in figure 3. It can also be noted that at the same acceleration level in figure 3, the parametric resonant peak is both higher and broader. Table 1 summaries the performance of the reported prototype and commercial harvester. The metrics employed are two of the most widely used in the literature; namely, power density normalised against acceleration squared (N.P.D) [1] and a figure of merit derived from N.P.D normalised against operational bandwidth divided by resonant frequency (F.O.M) [6].

Limited duration *in situ* field-testing of the prototype was carried out at various locations under the deck of the Forth Road Bridge, a suspension bridge in Scotland with a main span of 1006 m and services an average traffic of ∼60 thousand vehicles per day [7]. Lateral bracings were identified as the primary points of interest (figure 4), where abundance of traffic-induced

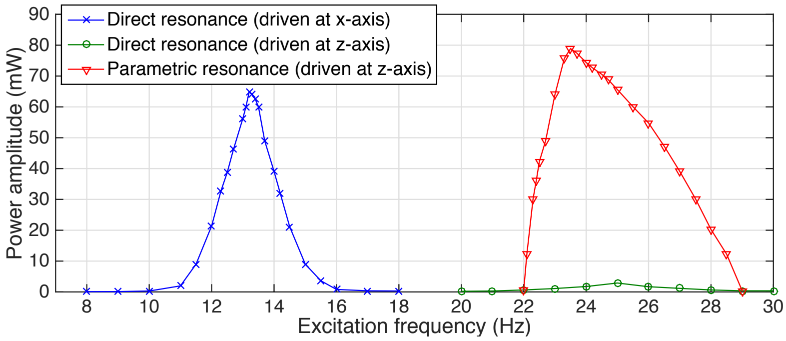


Figure 3: Frequency domain power response when the device is driven at 1 $g_{rms}$.

Table 1: Comparison of the power performance of the auto-parametric prototype when driven into direct resonance and parametric resonance, and a commercial VEH. All are subjected to 1.0 $g_{rms}$ (13.9 $ms^{-2}$) of acceleration at their resonant frequencies. N.P.D denotes normalised power density [1] and F.O.M represents figure of merit [6].

| Device | Power (mW) | Frequency (Hz) | -3dB band (Hz) | Volume ($cm^3$) | N.P.D ($\mu Wcm^{-3}m^{-2}s^4$) | F.O.M |
|---|---|---|---|---|---|---|
| Parametric | 78.9 | 23.5 | 4.5 | 126 | 3.24 | 0.62 |
| Direct | 64.8 | 13.2 | 2.0 | 126 | 2.66 | 0.40 |
| PMG-17 | 45 | 110 | 2.0 | 135 | 1.73 | 0.03 |


(a) Forth road bridge (b) Bracing below deck

Figure 4: A top lateral bracing and cross girder at Forth Road Bridge were used to test VEH-WSN.

vibration is suitable for VEH and stems the motivaton for structural health monitoring of the dynamically stressed structures.

A 6-stage charge pump circuit to amplify the raw AC voltage of the harvester, an off-the-shelf power conditioning circuit (LTC3588-1), a 5 mF storage supercapacitor and an in-house ultra-low power WSN mote (based on Atmel Lightweight Mesh) were integrated with the harvester (figure 5) for the trial test. The mote was programmed a transmission rate of once per minute and consumes 11 $\mu$W average power (measured value). No external sensors were used for this particular trial and the vibration powered mote transmits a preset message to a battery powered mote, in order to demonstrate successful transmission. Figure 6 illustrates the attachment (magnetically) of the harvester kit onto one of the locations on the Forth Road Bridge. An acceleration data logger was also used to record the vibration experienced by the harvester, for follow up lab-based characterisation tests.

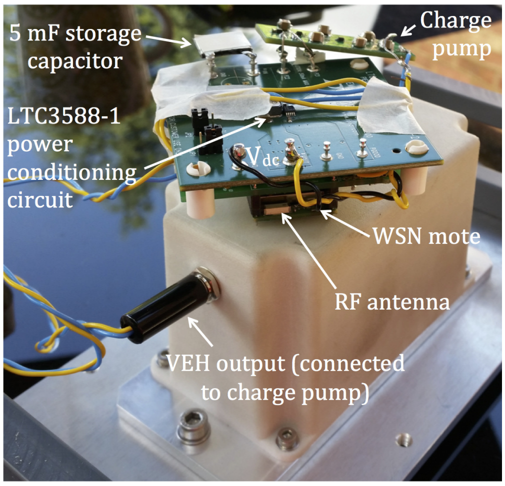


Figure 5: Vibration powered wireless mote system used for the field site trial.


Figure 6: Photograph of the deployment trial testing using the VEH prototype powering a WSN mote. This particular location illustrates testing on the cross girder underneath the deck of the Forth Road Bridge.

## 3. Results

The harvester produced >1 mW average raw AC power when attached to one of the top lateral bracings at a particular orientation. The eventual conditioned power delivered to the load suffered due to the poor efficiency of the current conditioning and power management circuit. Nonetheless, the conditioned power achievable on the bridge was more than sufficient to sustain the power budget of the wireless mote purely from the intermittent traffic induced vibration energy in the site. Table 2 summarises the power values attained at some of the locations. The location-dependency of power output was due to the localised nature of the vibration.

Table 2: The estimated average power values generated by the harvester prototype at various locations on the Forth Road Bridge. Typical traffic conditions were assumed for the day of measurement. Net power represents remaining average DC power after accounting for the average power consumption of the wireless mote.

| Location and orientation | Active frequency range (Hz) | Raw AC power ($\mu$W) | Conditioned power ($\mu$W) | Net power ($\mu$W) |
|---|---|---|---|---|
| Cross girder vertical | 10 to 30 | 160 | 32 | +20 |
| Top lateral vertical | 10 to 30 | 800 | 174 | +160 |
| Top lateral horizontal | 7 to 26 | 1050 | 315 | +300 |

The measured vibration data from the field site was used to program a mechanical shaker in the lab in order to experimentally simulate the vibration conditions from the bridge. Reduced-amplitude profile of the measured data was used, coupled with only single axis excitation achievable by the shaker, the simulated bridge vibration produced in the lab was conservative. Figure 7 represents the raw power response and figure 8 demonstrates a transmitting wireless mote powered by the harvester prototype driven with the above-mentioned vibration conditions.

As the voltage across the supercapacitor is charged to 4.0 V, a regulated DC voltage of 2.5 V is supplied to the wireless mote. As can be seen from figure 8, apart from the large initial energy drain required to initialise the wireless network, a steady and continuous rising voltage across the supercapacitor can be seen. Therefore, net power gain was achieved despite the energy drain from wireless transmissions of once per minute (denoted by the red circles).

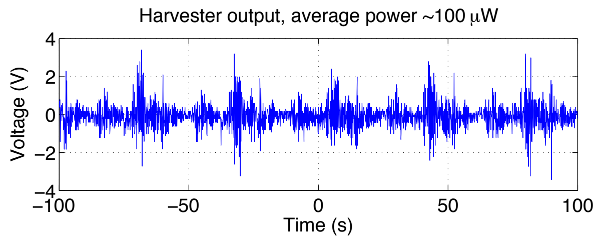


Figure 7: Lab-simulated experimental testing using recorded vibration profile (conservative values) from the Forth Road Bridge.

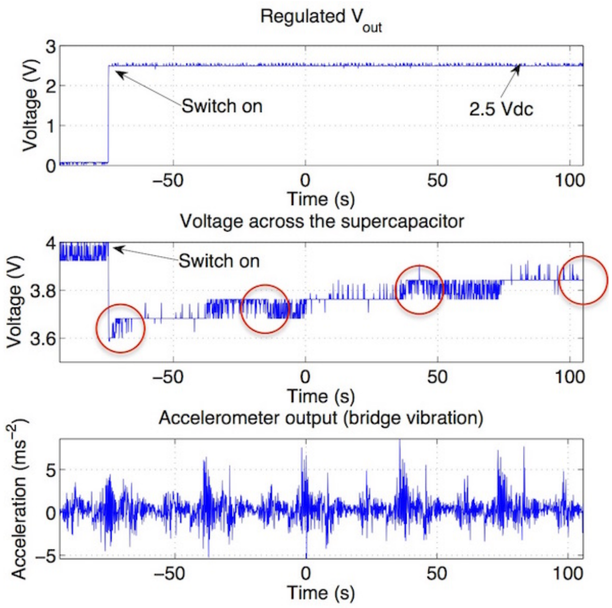


Figure 8: VEH-powered WSN mote using recorded bridge vibration profile driven by a shaker in the lab. Red circles indicate transmission events. Net gain in power can be observed for a transmission rate of once per minute.

## 4. Conclusion and future work

A packaged auto-parametric vibration energy harvester, integrated with power conditioning circuit and a wireless mote, was demonstrated *in situ* on the Forth Road Bridge. Over 1 mW average AC power was generated at certain locations. Despite the poor efficiency of the current power conditioning circuitry, ∼0.3 mW of conditioned DC power delivered to a wireless mote was more than sufficient to successfully sustain wireless transmissions to another battery powered mote (average power consumption of the mote: 11 $\mu$W).

Further work involves enhancing the robustness of the harvester prototype, improving the efficiency of the power conditioning circuitry, further minimising the power requirement of the WSN mote and incorporating sensor systems onto the vibration powered mote in order to realise long term deployment trials at field-sites.

## Acknowledgement

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## References

[1] S Priya and D Inman, 2009, *Energy Harvesting Technologies*, (New York: Springer US)
[2] D. Zhu, M.J. Tudor and S.P. Beeby, 2010, *Meas. Sci. Technol.*, **21**(2)
[3] Y Jia, J Yan, K Soga and A A Seshia, 2014, *Smart Mater. Struct.* **23**
[4] Y Jia and A A Seshia, 2014, *Sens. Actuators A.*, **220**, 69-75
[5] Perpetuum - Products, 2008, PMG-17, URL: `http://perpetuum.com/products.asp`
[6] R Andosca *et al.*, 2012, *Sens. Actuators A.*, **178**, 76-87
[7] Forth Road Bridge, URL: `https://www.forthroadbridge.org/home`