Resonant frequency tuning of an industrial vibration energy harvester

T T Toh, S W Wright and P D Mitcheson
Department of Electrical and Electronic Engineering, Imperial College London, UK
E-mail: tzern.toh@imperial.ac.uk

Abstract. This paper presents preliminary results of tuning the resonant frequency of two industrial vibration energy harvesters. The VEH-450 from Ferro Solutions and the PMG17-50 from Perpetuum were tested using discrete reactive electrical loads. The former could be tuned to +0.5 Hz and -2 Hz from its natural resonant frequency of 50.5 Hz at 0.1 g. The latter, however, has a broadband output power spectrum that spans ±10 Hz and its output voltage saturates at 7 Vrms, thereby rendering it un-tunable using the method presented here. A comparison of output power between a tuned VEH-450 and an un-tuned PMG17-50, normalised by harvester weight, shows that the former outperforms the latter only at a tuned frequency of 49.8 Hz. A discussion of a resonant frequency tuning circuit that can be fitted to an existing harvester without making modifications to the harvester is presented.

1. Introduction
Energy harvesting from industrial machinery typically requires a resonant device that is tuned to the dominant frequency. However, the host structure usually exhibits a vibration spectrum that is often broadband and/or time-varying. This broad frequency range represents an often untapped energy source that could increase the output power density of the harvesting system if the harvester was broadband capable and if there is no built-in rectifier [1]. Recently, considerable attention has been devoted to using mechanical [2] and electronic [3] methods of tuning a resonant harvester. These approaches have only been demonstrated on proof-of-concept harvester designs. This work, however, demonstrates resonant frequency tuning on a vibration harvester that was specifically manufactured for industrial applications. The system presented here will be suitable for retrofitting to a range of electromechanical energy harvesters, as long as direct access can be made to the coil terminals.

2. Industrial vibration energy harvesters
In this work, a VEH-450 from Ferro Solutions and a PMG17-50 from Perpetuum were chosen because they both provide access to the transducer coil terminals, which is necessary for resonant frequency tuning. Figure 1 shows a photograph of the VEH-450 and the PMG17-50 vibration energy harvesters and their physical dimensions are listed in table 1.

When excited with large accelerations, the output voltage of the PMG17-50 device was observed to clip as it approached a peak-to-peak value of 19.8 V. This suggests that Zener diodes are connected across the device terminals as a protection measure. To verify this, a
1 kHz signal was applied across the harvester terminals and as the peak-to-peak amplitude of the signal was varied, the transducer current and voltage were measured.

Figure 1. Photograph of a VEH-450 (left) and a PMG17-50 (right) energy harvester.

Table 1. Dimensions and electrical characteristics of the VEH-450 and the PMG17-50.

| Parameter   | Base diameter | Height | Weight | Resonant frequency | Coil inductance | Coil resistance |
|-------------|---------------|--------|--------|--------------------|-----------------|-----------------|
| VEH-450     | 60 mm         | 68 mm  | 430 g  | 50.5 Hz            | ≈ 0.4 H         | 2.2 kΩ          |
| PMG17-50    | 55 mm         | 55 mm  | 655 g  | 50 Hz              | ≈ 3.9 H         | 3.8 kΩ          |

Figure 2(a) shows the output voltage waveform of the PMG17-50 at a source excitation frequency of 47 Hz and at 50 Hz whereby the waveform is clipped. Figure 2(b) shows that the measured transducer current is proportional to the voltage up to about 7 V\text{rms}. Beyond that, the current increases at a higher rate than the voltage, which suggests that the Zener voltage has been reached. Adding a load resistor in parallel to the transducer will dampen its response and lower its output voltage.

Figure 2. PMG17-50: (a) transducer output voltage waveform at 47 Hz and at the resonant frequency of 50 Hz whereby the waveform is clipped and (b) measured I-V performance.
3. Resonant frequency tuning
In order to compare the output power levels of the VEH-450 and PMG17-50, they were both subjected to the same excitation of 0.1\(g\) at a range of frequencies and connected to an optimal load resistor to quantitatively analyse their power generation capabilities. The optimal resistive load for both harvesters is chosen based on the maximum power point at resonance at 0.1\(g\). This is approximately 28 k\(\Omega\) and 7 k\(\Omega\) for the VEH-450 and PMG17-50 respectively. The PMG17-50, as shown in figure 2, has a Zener diode connected across its terminals and the 7 k\(\Omega\) load is sufficient to prevent the output voltage from clipping.

3.1. Discrete components
Both harvesters were mounted on a vibration platform and an accelerometer provides closed-loop feedback to a vibration controller. Discrete capacitors of several values and a single inductor were connected in parallel with the output terminals of the harvesters, in addition to the aforementioned optimal load resistances.

In order to make a fair comparison, the output power would have to be normalised. For a given excitation frequency and amplitude, the maximum output power of a resonant vibration harvester is proportional to the weight and displacement limit of the proof mass [4]. Since neither of these are easily measurable, the output power was normalised to the harvester weight, which is listed in table 1.

Figure 3(a) shows a plot of the output power normalised to the device mass against frequency for the two harvesters, for various reactive tuning component values at a fixed acceleration of 0.1\(g\). Figure 3(b) shows the measured susceptance of each reactive tuning component plotted against their tuned resonant frequency for the VEH-450 harvester.

![Figure 3(a)](image)
![Figure 3(b)](image)

Figure 3. Measured results from the VEH-450 and the PMG17-50 harvesters excited at 0.1\(g\): (a) output power against frequency for different reactive components in parallel with an optimum load resistance and (b) susceptance against the tuned resonant frequency for the VEH-450 harvester.

For the VEH-450, its resonant frequency was distinctly shifted from 50.5 Hz with an output power at the tuned lower frequencies that is more than in the un-tuned case. With the inductor, the output power was lower than in its equivalent capacitive case because of the significant losses in the off-the-shelf inductor.

As can be seen, the PMG17-50 is inherently broadband and this was corroborated with the data sheet specifications. The PMG17-50 data presented in figure 3(a) is with a 50 nF tuning capacitor and the performance was similar to the case with just a 7 k\(\Omega\) load resistor. The VEH-450 outperforms the PMG17-50 on two occasions: firstly, at their respective un-tuned resonant frequencies and secondly, when the VEH-450 was tuned to 49.8 Hz. Apart from those instances, the PMG17-50 generates higher output power at frequencies away from the un-tuned cases.
3.2. Synthesised components

In the previous section, resonant frequency tuning was demonstrated using fixed-valued reactive components for one specific frequency in each case. In a practical implementation, where the excitation frequency varies [1], the use of discrete components is inconvenient. Alternatively, synthesised and adaptable reactive loads have been shown to present an optimal tuning impedance under varying excitation conditions [3, 5, 6]. For each resonant frequency, an inductor could be replaced by a synthesised negative capacitor and vice-versa if the tuning was synthesised electronically [3]. Following on from [3, 5], which used an H-bridge to synthesise an optimum impedance, an improved implementation that will be suitable for retrofitting to an existing harvester is presented here.

A characteristic feature of impedance synthesis is that it requires, as inputs, measures of the transducer current and voltage. The former can easily be achieved using Hall-effect current sensors but, until now the latter would have required a separate winding on the transducer. This is because it is not possible to directly measure the source voltage, \(E_g\) in figure 4, when a current is flowing because of the voltage drop across the transducer’s internal impedance [3].

The requirement of a separate winding would, in most cases, require intrusive modifications to the harvester and the host structure. In addition, this will reduce the energy density of the harvesting system because some of the space through which the magnetic flux passes will be occupied by the sense winding. Consequently, that space is not available for the transducer coil. Voltage sensing, in this case, will be achieved by a differential amplifier, removing the need for a separate sense winding.

Figure 4 shows the block diagram of the proposed system. The electromagnetic transducer is modelled by an AC voltage source, an inductance \(L_c\) and a resistance \(R_c\). This is connected across the four MOSFET H-bridge with a battery connected across the other two terminals. By controlling the conduction of the relevant MOSFETs, power can flow from the transducer to recharge the battery, or to provide reactive power from the battery to the transducer.

![Figure 4. Schematic of an adaptive tuning circuit topology.](image)

The controller calculates the desired current \(I_d\) based on the transducer voltage \(V_{out}\) and the values of an RLC synthesised load using (1).

\[
I_d = \frac{V_{out}}{R} + C \frac{dV_{out}}{dt} + \frac{1}{L} \int_0^t V_{out} \, dt
\]  

(1)

The controller adjusts the conduction of the MOSFETs by applying appropriate pulse-width modulated (PWM) signals to each gate. This controls the flow of power between the transducer
and the battery. A PID-controller closes the control loop to maintain the optimum load across the transducer thereby maximising the power transferred, using the methods described in [1].

4. **Harvester characteristics at typical PWM frequencies**

The transducer is connected across the H-bridge and therefore its properties at typical PWM frequencies must be considered because it is now being used as part of a switching circuit. Figure 5 shows that the VEH-450 behaves very much like an inductor in series with a resistor throughout the 20 kHz range. Contrastingly, the PMG17-50 coil is capacitive at frequencies above 6.5 kHz and only has significant inductance at 2 kHz, suggesting an upper limit on the converter switching frequency for the PMG17-50 of approximately 2 kHz.

![Figure 5. Impedance and phase variations of the VEH-450 and PMG17-50](image)

5. **Conclusion**

The VEH-450 harvester was shown to be tunable using discrete reactive components. However, the PMG17-50 is intrinsically broadband and on its own, when compared to the reactively-tuned VEH-450, is capable of generating higher output power levels over a broader range of frequencies. If volume and weight are unimportant, the PMG17-50 will be a better choice. Nevertheless, the PMG17-50 is about 50% heavier but it occupies 32% less volume compared to the VEH-450. The tuning methods described here have potential in expanding the applicability and output power density of resonant vibration harvesters operating under broadband excitations. It also has the desirable feature of sensor-less operation and more importantly, the ability to be retrofitted onto existing harvesters and host structures.

**Acknowledgments**

The authors would like to thank ABB Switzerland AG for their support.

**References**

[1] Bowden J et al. 2012 ASME IDETC/CIE (Chicago, Illinois, US) pp 1263–1268
[2] Wu H et al. 2013 J. Intell. Mater. Syst. Struct. 24(3) 357–368
[3] Mitcheson P D et al. 2011 IEEE Trans. Circuits Syst. II 58(12) 792–796
[4] Mitcheson P D et al. 2007 Journal of Micromechanics and Microengineering 17(9) S211
[5] Kaphengst N F et al. 2012 PowerMEMS (Atlanta, GA, US) pp 420–423
[6] Luo C et al. 2009 International Journal of Electronics 96 1249–1264