

ELECTRONIC RESONANT FREQUENCY TUNING OF A MARINE ENERGY HARVESTER

Tzern T. Toh^{1*}, Paul D. Mitcheson¹, Loic Dussud², Steven W. Wright¹ and Andrew S. Holmes¹

¹Department of Electrical & Electronic Engineering, Imperial College London, SW7 2AZ, UK

²IFREMER, Brest, France

*Presenting Author: tzern.toh@imperial.ac.uk

Abstract: Recently we have reported a new technique for electronic tuning of inertial energy harvesters. An H-bridge power electronic interface is used to apply a variable complex load impedance to the transducer, allowing control over both the transfer of real power to a battery and the mechanical resonant frequency of the system. In this paper we demonstrate the application of this method to two types of resonant inertial harvester designed for marine applications. The first is a pendulum-based device in which the restoring force is provided by gravity, and the second is a rotational device with a torsion spring. Electronic tuning is demonstrated for both devices on a shaker table, and preliminary data is presented from a field trial of the pendulum harvester in a small unmanned surface vehicle (USV).

Keywords: marine energy harvesting; rotational harvester; pendulum harvester; electronic tuning

INTRODUCTION

Inertial energy harvesters generally achieve maximum power density when excited at resonance with the electrical damping, D_e , being at least as strong as the parasitic mechanical damping, D_p [1]. In many applications, the excitation frequency is variable, in which case the harvester needs to be tuneable if maximum power density is to be achieved under all operating conditions. Tuneable energy harvesters have been demonstrated previously in which the stiffness of the resonant mechanical system is directly modified [2, 3]. However, these require an external actuator to adjust the properties of the mechanical system which increases the system complexity, volume and power overhead, making miniaturisation a challenge.

An alternative approach is to shift the resonant frequency by applying suitable reactive electrical loads to the output of the transducer. The principle underlying this method can be understood with the aid of Fig. 1. In this electrical equivalent model the transducer is assumed to be electromagnetic and is represented by a transformer with armature inductance L_a and resistance R_a . On the primary side, which represents the mechanical domain, the resistor, inductor and capacitor correspond to the harvester's parasitic mechanical damping, spring constant and mass (or moment of inertia in the case of a rotational device). The current source represents an excitation source of frequency ω and amplitude Y_0 .

When a resistive load is applied at the transducer output, it will impose electrical damping via the transducer and real power will be transferred to it from the harvester. However, if a reactive load is connected it will exchange reactive power with the mechanical system and this will modify the resonant frequency. For example, adding shunt inductance will increase the resonant frequency, while shunt capacitance will decrease it. Tuning of an energy harvester by this method was first demonstrated in [4] using discrete

reactive components. The limitation of this method is that continuously variable tuning is not possible because the components have fixed values.

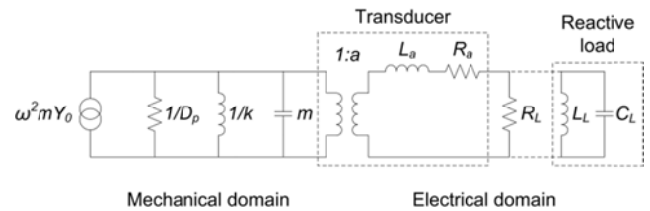


Fig. 1: Electrical equivalent model of energy harvester with generalised lumped element load.

Our approach, shown in Fig. 2, is similar to that in [4] but with the important distinction that we use a power electronic interface (H-bridge circuit) to apply a variable complex load impedance to the transducer output, allowing continuous tuning without any direct modification of the mechanical system [5]. At the same time, this interface rectifies the transducer output and transfers real power into a battery. With the appropriate MOSFET drive signals, this circuit can mimic an inductor, a capacitor, a resistor or a combination of these to form a generalised load.

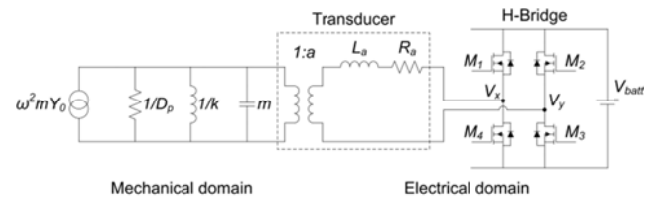


Fig. 2: Electrical equivalent model of energy harvester with power electronic interface.

The new tuning approach has been tested on two types of resonant inertial energy harvester intended for marine applications. The first is a pendulum-based harvester where the restoring force is provided by gravity, and the second is a more conventional rotational device incorporating a torsion spring. Both devices were designed for deployment in the small

unmanned surface vehicle (USV) shown in Fig. 3. The idea is that the rocking of the USV due to wave motion should excite the harvester sufficiently to provide backup power for radio communication in the event of failure of the main batteries.



Fig. 3: Unmanned surface vehicle for water quality monitoring.

In the following sections we briefly describe the two harvester designs and demonstrate electronic tuning of both devices on a shaker table. Experimental results are also presented from a USV deployment of the pendulum harvester on open water.

MARINE ENERGY HARVESTING

Inertial Pendulum Prototype

The pendulum harvester, shown in Fig. 4, consists of three components: an inertial pendulum with its axis of rotation aligned along the bow-stern axis of the USV, a transducer comprising two series-connected direct-current (DC) generators, and a tachogenerator to infer the emf from the transducer. The pendulum is a 120° segment of a hollow dural cylinder having inner and outer radii of 9 cm and 11 cm respectively and a length of 18.4 cm. It is freely suspended from a pivot by ball bearings and its oscillation is coupled to the transducer via a rack and pinion.

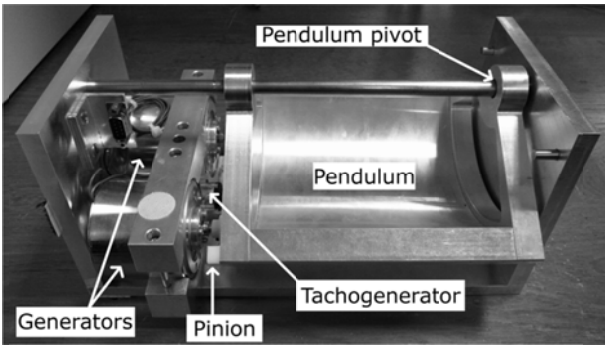


Fig. 4: Prototype inertial pendulum energy harvester.

The dynamics of the device depend on whether the axes of rotation of the USV and the pendulum are coincident. If they are then the pendulum undergoes purely rotational excitation as shown in Fig. 5. The equation of motion in this case is:

$$I(\ddot{\theta}_p + \ddot{\Omega}_h) + D\dot{\theta}_p + mgL \sin(\theta_p + \Omega_h) = 0 \quad (1)$$

where Ω_h is the angular deflection of the host (pendulum enclosure and USV), θ_p is the deflection of the pendulum relative to its enclosure, g is the

gravitational acceleration, m and I are the mass and moment of inertia of the pendulum, and L is the distance from its centre of gravity to the rotation axis.

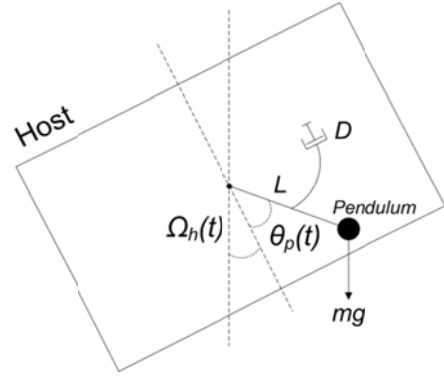


Fig. 5: Mechanical model of inertial pendulum when host and pendulum rotation axes coincide.

Assuming small deflections, Eq (1) can be linearised and a Laplace domain transfer function obtained as:

$$\frac{\tilde{\theta}_p(s)}{\tilde{\Omega}_h(s)} = \frac{-s^2 I - mgL}{s^2 I + sD + mgL} \quad (2)$$

With a harmonic excitation of amplitude Ω_0 and frequency ω , the average power extracted by the damper will then be:

$$P_{out} = \frac{1}{2} D \overline{\dot{\theta}_p^2} = \frac{D \Omega_0^2 \omega^2}{2} \left| \frac{\omega^2 I - mgL}{-\omega^2 I + j\omega D + mgL} \right|^2 \quad (3)$$

An interesting feature of Eq (3) is that the harvester output power goes to zero when $\omega = \sqrt{mgL/I}$, i.e. when the driving frequency is equal to the natural oscillation frequency of the pendulum. Under these conditions the pendulum swings in unison with the driving excitation, and no power is developed in the damper. This anti-resonant behaviour is confirmed by the simulation results shown in Fig. 6 and Fig. 7. This means that the pendulum harvester should be driven off resonance when operated in this purely rotational mode. For this harvester, it is still necessary to control the resonant frequency in order to keep it away from the operating frequency as the input motion changes.

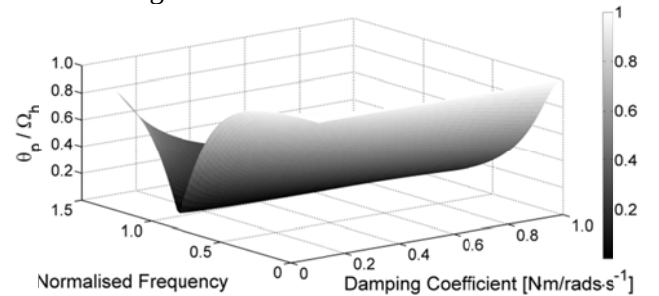


Fig. 6: Simulated anti-resonant behaviour of the pendulum harvester with purely rotational excitation.

If the pendulum and USV rotation axes are different, the pendulum pivot will undergo oscillatory motion along a circular arc, providing a second

excitation source in addition to the rotational excitation. The dynamics in this case are much more complex, with the response of the pendulum generally being chaotic.

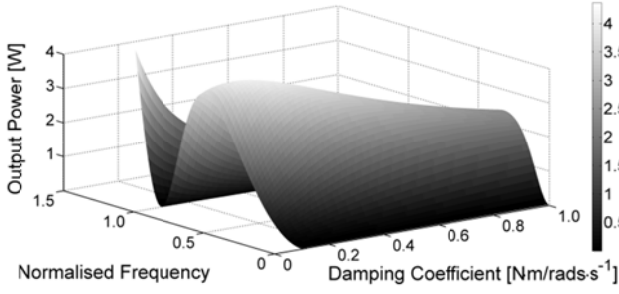


Fig. 7: Simulated output power from the pendulum harvester with purely rotational excitation.

Inertial Cylindrical Disk Prototype

The inertial cylindrical disk harvester, shown in Fig. 8, was designed to overcome the displacement limit experienced by the inertial pendulum device. In this case the cylindrical mass is able to rotate about its axis on ball bearings, and a torsion spring is used to apply a linear restoring torque. The spring allows up to $\pm 360^\circ$ rotation of the cylinder. As in the pendulum harvester, a rack and pinion couples the disk's rotation to two DC generators (transducer) and a tachogenerator. In terms of dynamics, the disk harvester is the rotational equivalent of a classic linear vibration harvester and it therefore shows normal resonant harvester behaviour, unlike the pendulum.

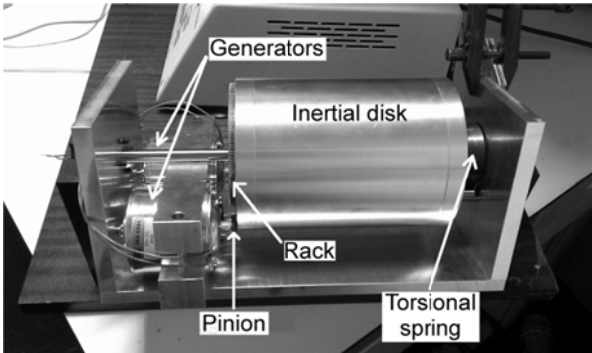


Fig. 8: Prototype inertial cylindrical disk energy harvester.

RESONANT FREQUENCY TUNING

As mentioned in the introduction, changing the current drawn from the transducer will alter the mechanical resonant frequency of the system. In order to do so, the bridge circuit must be able to compensate the measured armature current, I_a , by synthesising reactive components, *i.e.* capacitor and inductor, using an H-bridge circuit, shown in Fig. 9. This effectively allows the load (H-bridge interface) to sequentially store and release power to the mechanical system by introducing a derivative and integral term to induce a phase shift in I_a from the generated emf, V_{emf} , according to Eq.(4):

$$I_{ref} = \frac{V_{emf}}{R_a} + C \frac{dV_{emf}}{dt} + \frac{1}{L} \int V_{emf} dt \quad (4)$$

where I_{ref} is the instantaneous demand current to be drawn from the transducer.

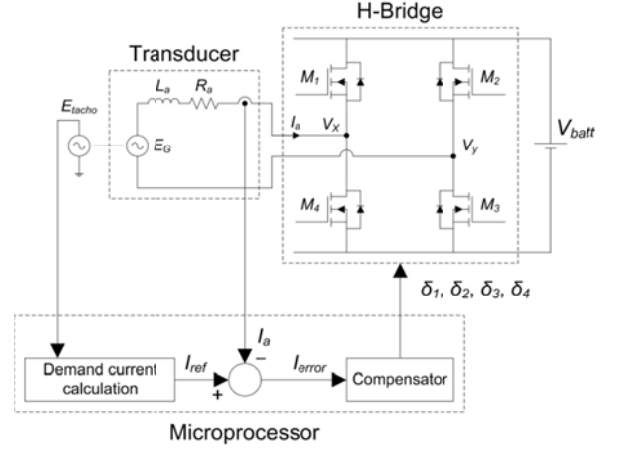


Fig. 9: Schematic of the prototype marine energy harvesting system.

Eq. (4) was realised by using a microprocessor which implements a closed-loop PID controller to match I_a to I_{ref} and the error between the two currents will determine the duty cycle of the switches. The digitised implementation of I_{ref} allows both positive and negative values of the reactive components to be realised, which cannot be done when discrete components are used.

The H-bridge circuit interfaces to the generator output terminals, as shown in Fig. 9 and consists of four semiconductor switches (typically MOSFETs) which can be made to operate like two separate dual-polarity boost or buck switch mode converters. The armature inductance performs the role of the inductor of both switch mode converters. Boost converter operation allows the circuit to extract real power from the mechanical system into the electrical system and is thus the most fundamental mode of operation. Contrastingly, under buck operation, power is transferred from the electrical system to the mechanical system and this is required for reactive power to circulate.

When the mechanical system is operating at resonance, only boost operation is required. However, when the harvester is excited away from resonance, a combination of boost and buck operation is required to allow optimal power generation and resonant frequency tuning respectively.

EXPERIMENTAL RESULTS

Laboratory Tests

Verification of the resonant frequency tuning circuit was performed on a laboratory rocking table at different excitation frequencies at fixed amplitude. This mimics the conditions when the system is placed in the USV. For both the pendulum and cylindrical devices, their mechanical resonant frequencies were observed to change when positive and negative capacitances were synthesised by the H-bridge circuit.

In Fig. 10, adding a positive and negative capacitance caused the untuned resonant frequency

(1.17 Hz) to decrease and increase respectively. A change of between -20% to +5% was achieved and beyond this range, the H-bridge current saturates because of the armature resistance in the generators, restricting the magnitude of the reactive current in the bridge.

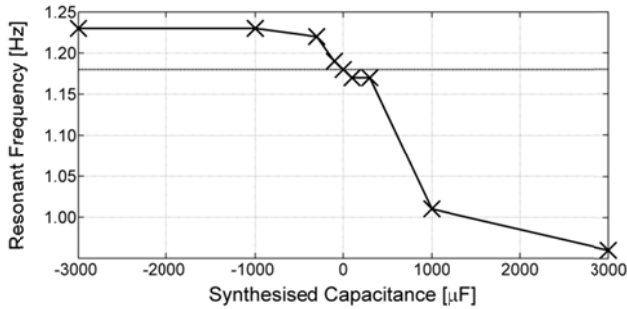


Fig. 10: Observed changes in resonant frequency of the pendulum harvester using different synthesised capacitances and resistive load of 80 Ω.

For the cylindrical harvester, a $\pm 14\%$ change from the untuned mechanical resonant frequency of 0.58 Hz was achieved, as shown in Fig. 11.

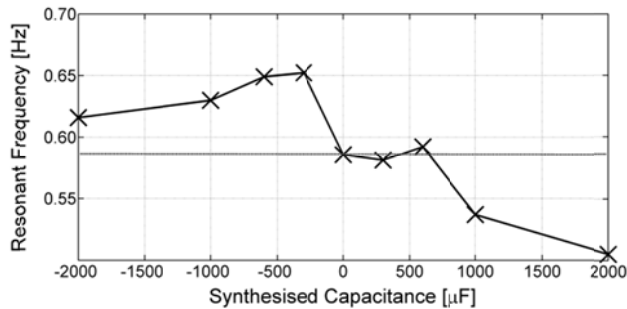


Fig. 11: Observed changes in resonant frequency of the cylindrical harvester using different synthesised capacitances and a load resistance of 100 Ω.

Field Deployment

The inertial pendulum harvester was observed to have generated twice the output power of the cylindrical disk harvester under the same experimental conditions in the laboratory. Therefore, it was chosen to be deployed in the USV along with the H-bridge interface. Fig. 12 shows the energy accumulated in the battery over a 2-hour in-field test which took place in the Bay of Brest, France. The current flowing into and out from the battery is shown in grey whereas the cumulative energy stored in the battery is shown in black.

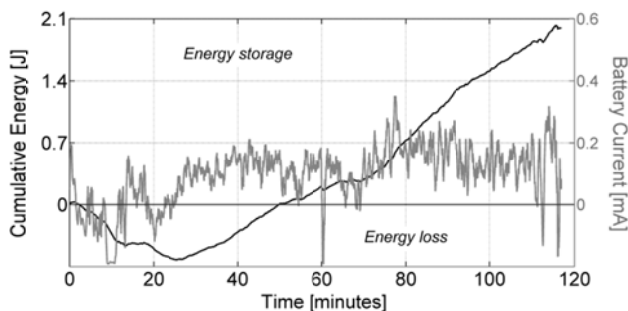


Fig. 12: Energy storage profile during a 2-hour deployment of the marine energy harvesting system.

The circuitry was switched on at time 0 whilst the USV was still on land. After 23 minutes, the USV began manoeuvring around the test site whilst subjected to incoming waves from the open sea. The battery current profile is indicative of the pendulum's oscillation. An increase in battery current will lead to a positive gradient in the cumulative energy profile whereas a decrease in battery current results in a negative gradient. Over a period of 2 hours, the total energy stored in the battery is ~ 2 J, corresponding to an average power generation of 0.3 mW.

CONCLUSIONS

A tuning capability is critical for resonant energy harvesters that are to be deployed in scenarios where the excitation characteristics change during device operation. In this paper we have demonstrated a technique for tuning an inertial harvester and applied the technique to two implementations of a device for harvesting energy in a USV on open water. The power electronic interface is able to control both real and reactive power flows between the battery and the mechanical system allowing changes in both damping and resonant frequency to be made. We have shown that a change in resonant frequency of up to $\pm 20\%$ is achievable. In a deployment of the pendulum harvester on a USV, an average useful power output of 0.3 mW was achieved by storing the energy in a battery. Whilst the application demonstrated here is not miniaturised, this method of frequency tuning is more promising for MEMS implementations than previously reported techniques in the literature.

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