SCALING LAWS FOR ENERGY HARVESTERS IN A MARINE ENVIRONMENT

L. D.A. Thorner, P. D. Mitcheson, A. S. Holmes, and E. M. Yeatman
Department of Electrical and Electronic Engineering, Imperial College London, UK

Abstract: A survey of energy harvesting methods specific to a marine environment is presented in order to optimally choose and design an energy harvester that will be embedded in an autonomous water quality monitoring platform. Output power formulae are derived as a function of characteristic device length in order to perform a scaling analysis and a comparison of the mechanisms. Limitations of the different harvesting techniques are discussed. It is found that an oscillating pendulum mounted in a floating craft and a hinged device designed to ride over water waves provide good power densities at the energy harvesting scale.

Keywords: ocean wave energy converters, microgenerators, marine energy harvesting

INTRODUCTION

The demand for clear water resources is increasing considerably as the world population grows, and it is therefore likely that maintaining an adequate availability of fresh water will be one of the greatest challenges we will face in the near future. Real time monitoring of water quality is advantageous to facilitate better management and use of fresh water resources. A prerequisite for this monitoring is the deployment of large numbers of autonomous WSNs, which themselves require energy harvesters in order to achieve low or zero maintenance.

In this paper, many different possible energy harvesting techniques specific to a marine environment are presented and discussed. Formulae for the power outputs of the harvesters are derived as functions of the parameters of the energy source and the size of the harvesting device, in order to allow comparisons and to inform the choice of device under particular operating conditions. Limitations of the operating conditions and dimensions of the different devices are briefly discussed.

HARVESTING MECHANISMS

The different energy harvesting mechanisms available for use in a marine environment are summarized in fig. 1. The upper part presents the different environmental energy sources that can be harvested and the lower part the possible implementations for capturing this energy. The sources are divided into non-kinetic and kinetic types, as significantly more configurations of motion harvester have been identified.

Further details on wave energy conversion devices are given in [1], [2], and [3] but an analysis of the scaling of their power and comparison of their power densities has not previously been reported. Marine energy harvesting techniques are difficult to compare because for each technique the output power depends on the specific implementation structure for the relevant mechanism. However, the aim of this analysis is to allow meaningful, yet simple, comparisons to be made between the possible techniques in terms of power output, for different sizes of generator under different environmental conditions.

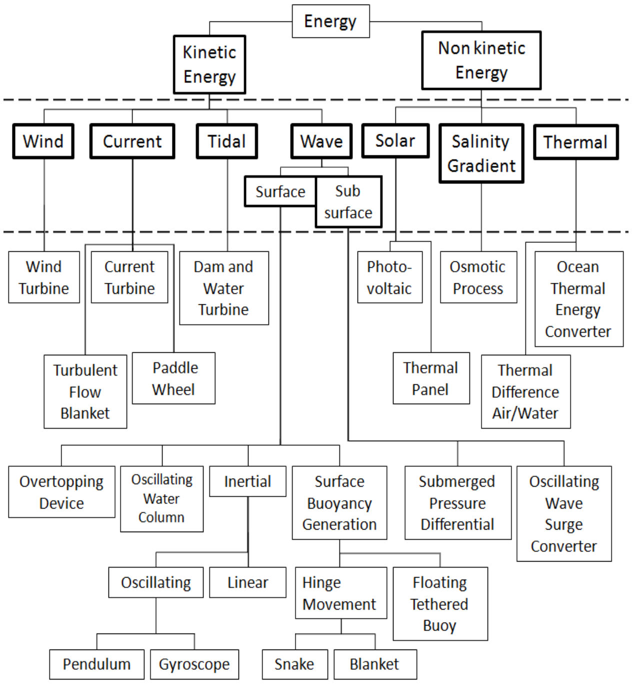


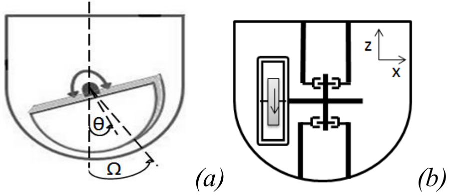
Fig. 1: Classification of harvesting mechanisms.

The power outputs of the devices have been derived assuming that the energy harvesters occupy a cube of length *L*. The photovoltaic devices are defined in terms of a square area, also length *L*. In each case, the output power is found to be proportional to the characteristic length of the device to the power *n*. Devices with a large *n* achieve better power densities at large sizes, and those with small *n* achieve better power densities at small sizes. Devices with a low value of *n* are thus better suited to MEMS fabrication.

In this work, ρ is the mass density of inertial masses, g is the gravitational constant, f is the average water wave frequency, H is the significant wave height and L is the characteristic length of the harvester.

Inertial Systems

Inertial systems in a marine environment rely on an proof mass whose relative movements are caused by the waves and drive a generator. In this work, waves are considered to provide a sinusoidal excitation force. The waves have different frequencies but it is still possible to design a mass-spring-damper system whose resonant frequency is close to the average wave frequency. Fig. 2a and 2b show, as an example, the mass in a host vessel either similar to a pendulum or a gyroscope respectively. A large scale example of the inertial pendulum harvesting mechanism is the Searev [4] and an example of the gyroscope type is the Gyro-gen [5].



(a) *(b)*

Fig. 2: Inertial types, pendulum (a) and gyroscope (b.)

For the pendulum, θ and Ω represent the absolute angles of the pendulum mass and the host vessel respectively, and both are considered as harmonic, with amplitudes θ_0 and Ω_0. Assuming the damping torque is proportional to the relative velocity, and applying the small angle approximation for the gravitational torque, the equation of motion is, as derived in [6]:

$$I\ddot{\theta} = D(\dot{\Omega} - \dot{\theta}) - mgl\theta \qquad (1).$$

The expression of the output power is then given by:

$$P = D(\dot{\Omega} - \dot{\theta})^2 \qquad (2).$$

At the pendulum natural frequency, the relative velocity is zero, and consequently, there is no output power. At frequencies smaller than the natural frequency, the output power is obtained as:

$$P_{AVE} = \frac{\pi}{3}\rho_{steel} gf\Omega_0^2 L^4 \qquad (3).$$

In the gyroscopic architecture, the mass is initially given a precession movement around the x-axis, with the waves forcing a rotation around the y-axis resulting in a final generating movement around the z-axis, as explained in [6].

For inertial linear mass-spring and damper system described in [7], the average output power for a device of linear motion is:

$$P_{AVE} = \frac{1}{2} Y_0^2 \omega^3 \frac{Z_L}{Y_0} \qquad (4)$$

The following expression is obtained by replacing the appropriate quantities in (4):

$$P_{AVE} = \frac{1}{2} \rho \pi^3 f^3 H L^4 \qquad (5)$$

Surface Buoyancy generation

These systems are composed of either one floating buoy driving a generator with its movements, fig. 3a, or several floating rafts which move relative to one another. In fig. 3b, the mechanism relies on hydraulic rams resisting the wave-induced motion of the device, and pumping a fluid into a hydro electric motor. In fig. 3c, the circulation of compressed air in a double layer of chambers is induced by the waves; a turbine completes the conversion into electricity. The Wave Blanket [9] is an example of this technique. In a miniature energy harvesting device, piezoelectric material could be used as a transducer.

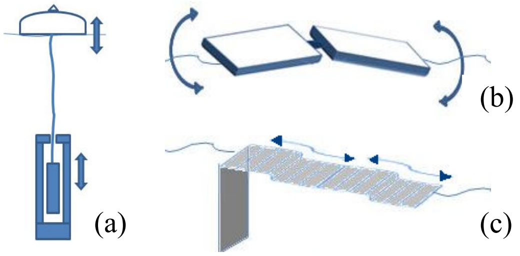


Fig. 3: Surface buoyancy generation, floating tethered buoy (a), Hinge movement snake form (b), Hinge movement blanket form (c).

The floating tethered buoy mechanism is illustrated in [8]. Moreover, supposing the floating buoy is an ideal air-filled sphere and assuming the generator is linear, the work done by the generator over one period is:

$$W = 2(mgH) \qquad (6).$$

The average output power is then

$$P_{AVE} = \frac{8}{3} \pi \rho_{air} gHfL^3 \qquad (7).$$

The Pelamis [1] is a case of hinged buoy providing energy between the different rafts, as shown in fig. 3b. The force applied by the wave on a element the raft is:

$$F = \rho.g.w.h.dL \qquad (8).$$

Where w is the width and h is the height.
Integrating (8), the average output power is then:

$$P_{AVE} = \frac{\pi}{8}\rho g f L^4 \quad (9).$$

Oscillating Water Column

An oscillating water column consists of a hollow structure partially submerged. The waves compress and decompress the trapped air column which is thus forced to cross a Wells turbine. This type of turbine rotates regardless of the direction of the airflow. An example of this mechanism is the Limpet [1].

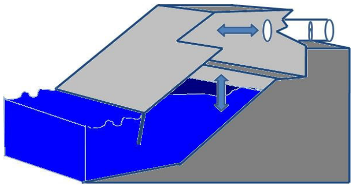


Fig. 4: Oscillating Water Column.

Supposing the air column is trapped in an ideal cubed structure of length L, $y(t)$ is the harmonic amplitude of the wave and $y_C(t)$ is the harmonic level of water in the OWC. The pressure difference is:

$$\Delta p = \rho g(y - y_C) \quad (10).$$

The conservation of volume leads to:

$$vA_T = L^2 \dot{y}_C \quad (11).$$

Where A_T is the area of the turbine. Finally:

$$P_{AVE} = \frac{\pi}{2}\rho g f H^2 L^2 \quad (12).$$

A different output power formula is presented in [3].However the equation stated does not depend directly on wave parameters and this could not be easily compared with the formulae presented in this paper.

Overtopping device

An overtopping device relies on a ramp enabling water to be trapped into a reservoir. The reservoir border is located at a certain height above the average water level. The wave potential energy is thus absorbed and a turbine is activated as water goes back to the average level. A generator is linked to the turbine. In a first approximation, the ramp is not taken into account. The problem is simplified by supposing that only the water in the superior part of the wave can fall into the reservoir. A large scale example of this architecture is the Wave Dragon [1].

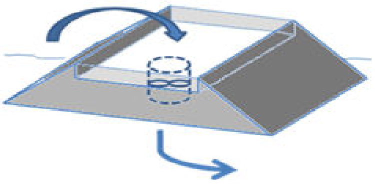


Fig. 5: Overtopping device.

The average output power is consequently given by:

$$P_{AVE} = 0.87\rho g Q_1 h_C \quad (13).$$

Q_1 is a parameter depending on the wave period and wave height, h_C is the height of the reservoir border.

Current Turbine

A current turbine is useful in a river environment. An illustration of this energy harvesting mechanism is discussed in [10]. Furthermore water and air are fluids that differ by the velocity and the viscosity coefficient, as well as the compressibility. The average output power is given in (14). The velocity V and the coefficient C_P are specific to water.

$$P_{AVE} = \frac{\pi}{8} C_P \rho V^3 L^2 \quad (14).$$

Photovoltaic Solar Panel

This energy harvesting mechanism is the most widely used in a marine environment since it has a good power density and also an affordable price. Supposing a cubic buoy covered with photovoltaic solar panels on all its faces but the one beneath, the average output power is then:

$$P_{AVE} = 5\alpha P_S L^2 \quad (15).$$

Where α is the efficiency of the solar panel, P_S the average solar power and L the length of the panel.

COMPARISON AND DISCUSSION

The choice of the most appropriate micro-generator depends on criteria such as the best power density, mobility requirements and miniaturization. If mobility is required, the mechanisms that are fixed such as the OWC, cannot be used. The overtopping device is not reducible below the wave pitch.

Limits of the comparison

The shapes have been approximated by cubes and spheres for the different harvesting mechanisms. Waves are simplified into harmonic oscillations with a constant frequency and height. The losses are not considered in this comparing process. The graphs of fig 6, show the power outputs of several types of harvester as a function of length under different sea conditions.

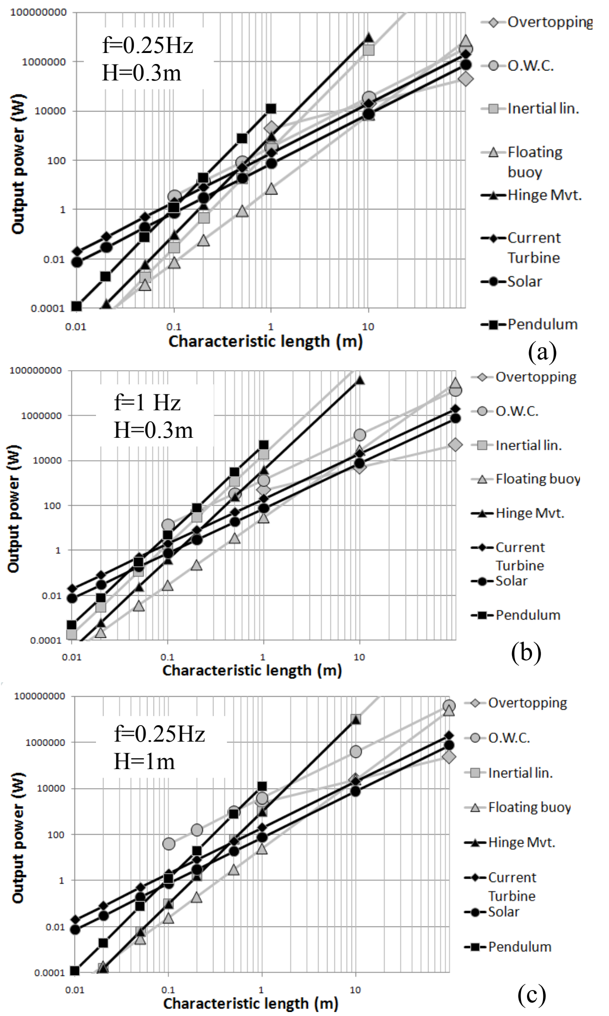


Fig. 6: Comparison graphs: normal conditions (a), smooth state (b) and heavy sea (c).

Interpretation

In the log-log format, the different slopes indicate the power of L in the output power formulas. The photovoltaic cell is independent from the wave parameters and it has a good power density. The surface buoy with a hinge movement and the inertial pendulum mechanism are more influenced by the frequency than by the wave height. The inertial linear type heavily depends on the frequency. A tethered water turbine is a specific option for a river scenario. The oscillating water column and the overtopping mechanism are more sensitive to the wave height than to frequency.

CONCLUSION

Different energy harvesting mechanisms specific to a marine environment have been described and compared. This comparison informs the choice of a microgenerator that will be implemented on a water quality monitoring, autonomous and mobile platform. The PV solar panel is appropriate for a sunny weather usually linked to a normal or smooth state of the sea. The current turbine is specific to the rivers. The inertial oscillating pendulum mechanism and the surface buoy with a hinge movement have a very good power density at a large scale but they also turn out to be good for an energy harvesting scale because design considerations eliminate the other systems.

Both will be retained for the choice in a sea or lake environment and the current turbine will be appropriate for a river environment. The design of a prototype will be chosen according to this study.

ACKNOWLEDGEMENTS

This work was supported by the European Community's Seventh Framework Program under grant agreement n°223975 project MOBESENS.

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