Turn, turn, turn….

Khan, Iqbal, Hinchey, and Masek describe the performance of three different types of Savonius rotor as current-driven turbines for micro-power generation.

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Who should read this paper?

This paper will be of interest to those who are intrigued by the notion of generating power from ocean currents where the flow rate is low (less than 2 knots). Readers may be surprised to find that it is possible to generate a few watts of continuous power from relatively low speed ocean currents. This type of energy is suitable for powering small devices or for charging batteries.

Why is it important?

The nature of this work is to develop a marine current energy conversion system suitable for deployment in low speed currents. To do so, it is important to find a suitable turbine design that is responsive and able to produce a high torque in low speed currents. The result shows that Savonius rotors are viable for deployment as underwater vertical axis turbines in low speed currents. One can use this type of rotor for micro-power applications such as charging batteries or supplying power to ocean monitoring devices. The paper also documents a very simple instrumentation technique to measure the power generated by a turbine in water. Based in part on the results of this work, the authors are investigating the feasibility of a simple Maximum Power Point Tracker-based energy conversion system that can be used for small scale power.

About the authors

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PERFORMANCE OF SAVONIUS ROTOR AS A WATER CURRENT TURBINE

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ABSTRACT

Ocean current energy systems are at an early stage of development with only a small number of prototypes and demonstrations to date. Ocean currents are a potentially significant and currently untapped resource of energy. Energy can be extracted from the ocean currents using submerged turbines that are similar in function to wind turbines but capture energy through a hydrodynamic rather than aerodynamic mechanism. This paper discusses the performance of three different types of Savonius rotors used as water current turbines. This is the first time such rotors have been used as water current turbines. They were tested to determine a suitable water current turbine for a micro seafloor power generation system.

KEY WORDS
Savonius Rotor; power coefficient; tip speed ratio; water current energy devices

INTRODUCTION

Energy conversion from marine currents is quite similar to that of wind energy conversion, but there are also several differences between them. The underwater placement of a marine current energy converter gives some advantages – such as no noise disturbance for the public, low visual exposure, and little use of land space – but also adds some challenges, such as the need for water and salt proof technology, and difficult and costly maintenance. Ocean currents are relatively constant and flow in one direction only, in contrast to the tidal currents closer to shore where the varying gravitational pulls of the sun and moon result in diurnal high tides. Ocean current speeds are generally lower than wind speeds. This is important because the power contained in flowing bodies is proportional to the cube of their velocity. Another important factor is that water is about 835 times denser than air, so for the same area of flow being intercepted the available power in the water current is 835 times more than wind of the same speed. Thus, ocean currents represent a potentially significant, currently untapped, reservoir of energy. The total worldwide power in ocean currents has been estimated to be about 5,000 GW with power densities of up to 15 kW/m^2.

MARINE ENERGY DEVICES

Generally, the two principal forms of marine energy are waves and tides. However, there are other forms, including heat and chemical energy. Ocean swells and waves contain both

Figure 1: A 600 kW marine current generator.

potential and kinetic energy, which can be harnessed with appropriate devices. Tidal streams and tidal bores also contain potential and kinetic energy, arising from the rise and fall of the tides.

Most marine energy conversion devices usually aim to convert potential and/or kinetic energy in waves and tides into electrical energy. To date, there are only a few technologies that have progressed [Khan et al., 2008] as far as the full-scale deployment and testing.

Presently, there are several United Kingdom based companies actively involved in the construction of such devices, supported in their endeavours by numerous financial channels including government and private investors. A well established horizontal axis turbine technology is shown in Figure 1.

Turbines can have either horizontal or vertical axes of rotation. Mechanisms such as posts, cables, or anchors are required to keep the turbines stationary relative to the currents with which they interact. Horizontal axis turbines are the most commercially applied geometry for two primary reasons: the blades of a horizontal axis turbine generate constant, positive torque from the flow during 100% of their rotation; and they operate at higher rotational speeds. A faster rotating rotor is more conducive for electrical power generators, which operate on an order of hundreds if not thousands of revolutions per minute.

In some areas, it would be possible to install water turbines in groups or clusters to create a "marine current facility," similar in design approach to a wind turbine farm. Two possible arrangements are shown in Figures 2(a) and (b).

Figure 2a: Visualization of two possible turbine and anchor technologies.

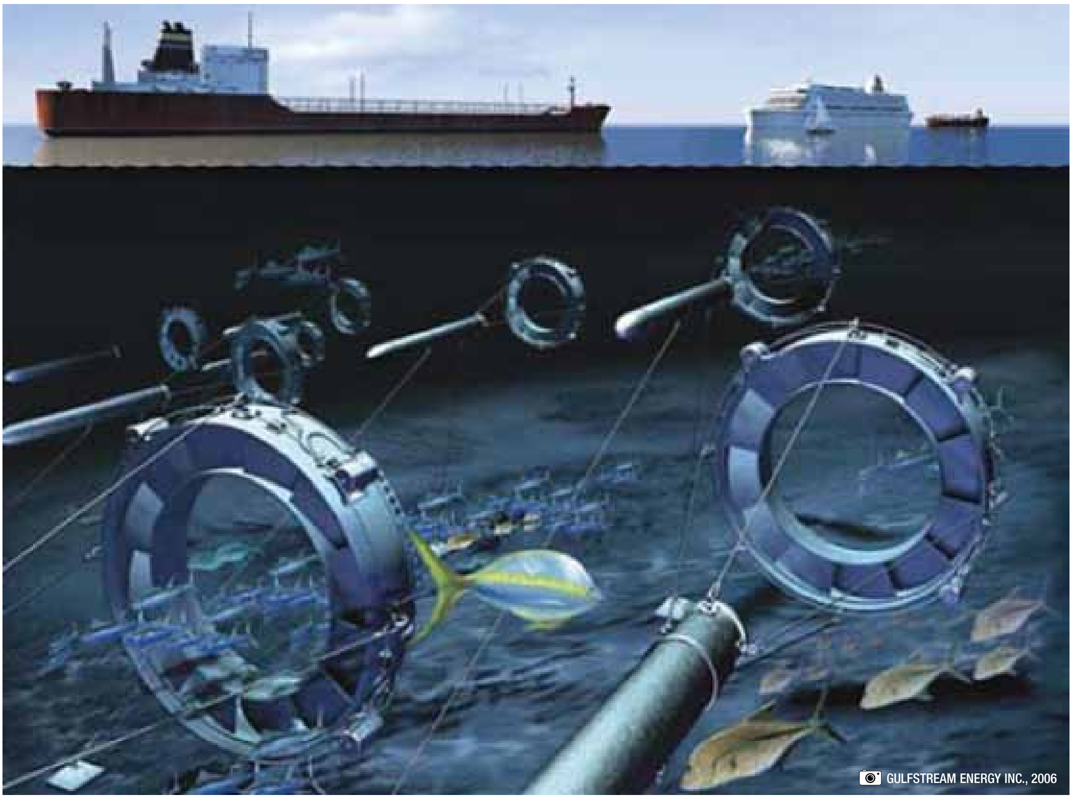


Figure 2b: Visualization of two possible turbine and anchor technologies.

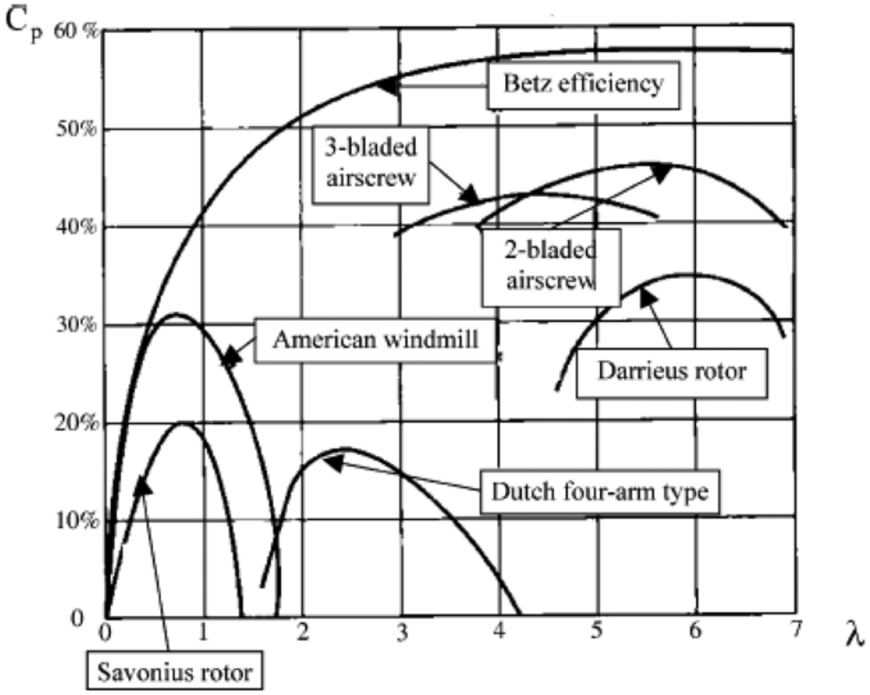


Figure 3: Expected performances of different types of turbines [Menet, 2004].

Turbine spacing would be determined based on wake interactions and maintenance needs.

Turbines are usually rated by a performance curve, which gives power coefficient (Cp) as a function of tip speed ratio (λ). It is known that for any turbine the power coefficient is always less than the theoretical value 0.593. This is known as the Betz limit. Expected performance curves of different turbines are shown in Figure 3.

SAVONIUS ROTOR

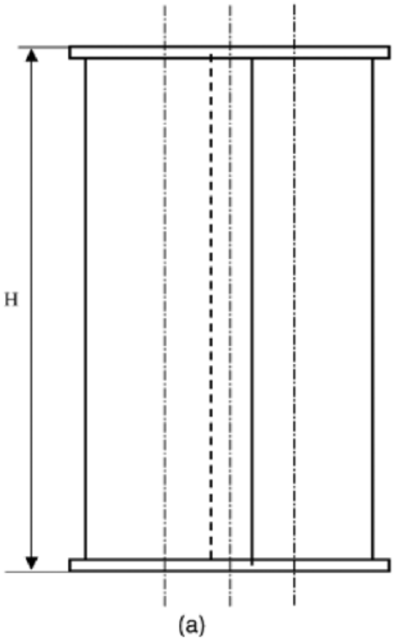
The concept of the Savonius rotor was based on the principle developed by Flettner [Modi and Roth, 1985]. Savonius used a rotor that was formed by cutting the Flettner cylinder into two halves along the central plane and then moving the two semi cylindrical surfaces sideways along the cutting plane so that the cross-section resembled the letter 'S' [Savonius, 1931].

There are two ways a Savonius turbine can extract power from a flow. In Figure 4, imagine the flow is moving upwards from below. Such a flow would produce a wake load top of left bucket and stagnation pressure load below right bucket. There would also be impulse load where a sheet of water moves first along left bucket and then along right bucket. One can imagine the turbine absorbs momentum when it hits the left bucket and expels momentum where it leaves the right bucket. So there is a drag mechanism and a momentum mechanism. A Savonius rotor cannot exceed the speed of the water and operates at a lower RPM range than would a horizontal axis turbine.

The power coefficient Cp of a turbine is:

$$Cp = P/ [2 A\rho V^3]$$

where P is the output power (W)
ρ is the density of water (kg/m^3)
A is the swept area of rotor (m^2)
V is the speed of water (m/s)



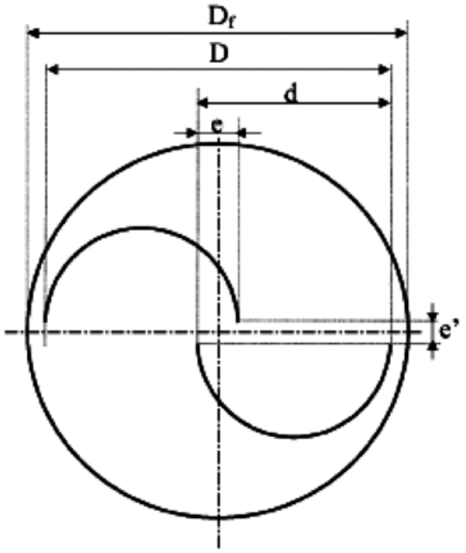


Figure 4: Typical stationary Savonius rotor with round edge.

The tip peripheral velocity of the rotor U = ωr (ω is the angular velocity of rotor and r is the radius of the rotor). The velocity coefficient of the turbine is defined as:

$$\lambda = \frac{U}{V}$$

The aspect ratio α is the height of the rotor divided by its diameter. This is a very important parameter for the performance of a Savonius rotor:

$$\alpha = \frac{H}{D}$$

Generally the value of α is taken higher to improve the efficiency. Values more than 1.0 seem to improve [Menet, 2004] the power coefficient for a conventional Savonius rotor.

It is known that end plates also lead to better hydrodynamic performances [Menet, 2004]. The influence of the diameter Df of these end plates relatively to the diameter D of the rotor has been experimentally studied. The higher value [Menet, 2004] of the power coefficient is obtained for a value of Df around 10% more than D, whatever the velocity coefficient. The overlap ratio β is given by the following equation:

$$\beta = \frac{e}{d}$$

where e is the overlap between two buckets and d is the diameter of each bucket as shown in Figure 4. Ushiyama and Nagai [1988] reported an increase in the starting or static torque as the overlap ratio increases from 0 to 0.2 and a decrease as the overlap ratio increased from 0.3 to 0.5. Fujisawa [1992] observed a monotonic increase in the static torque with an increase in the overlap ratio from 0 to 0.5.

PROTOTYPES DESCRIPTION

In this research, single, two, and three stage Savonius rotors were studied. Many researchers worked to improve the torque characteristics of Savonius rotor [Hayashi, 2005]. For example, a Savonius rotor with twisted rotor blade [Grinspan et al., 2003] was proposed. Although the twisted rotor has very good starting characteristics, it has been avoided here due to complexity of blade shape and manufacturing difficulty. Each of the rotors tested was 0.40 m high by 0.22 m wide.

First Prototype

Figure 5 shows our single stage Savonius rotor. As a wind turbine, this design has trouble starting at low wind speeds and when the buckets are not aligned properly [Hayashi, 2005].

Second Prototype

Our double stage Savonius rotor is shown in Figure 6 where the upper and the lower paddles pairs are set at 90° to each other. As a wind turbine, this design has lower torque variation than the single stage design [Menet, 2004].

Third Prototype

Our three stage Savonius rotor is shown in Figure 7. Each of its stages is phase shifted 60° relative to each other. This design should have the lowest torque variation [Hayashi, 2005].

EXPERIMENTAL SETUP

Experiments were carried out in the wave tank at Memorial University of Newfoundland (MUN). The wave tank is 54 m x 5 m x 3 m. It is equipped with a towing carriage with a

Figure 5: Single Stage Savonius Rotor.

Figure 6: Double Stage Savonius Rotor.

Figure 7: Three Stage Savonius Rotor.

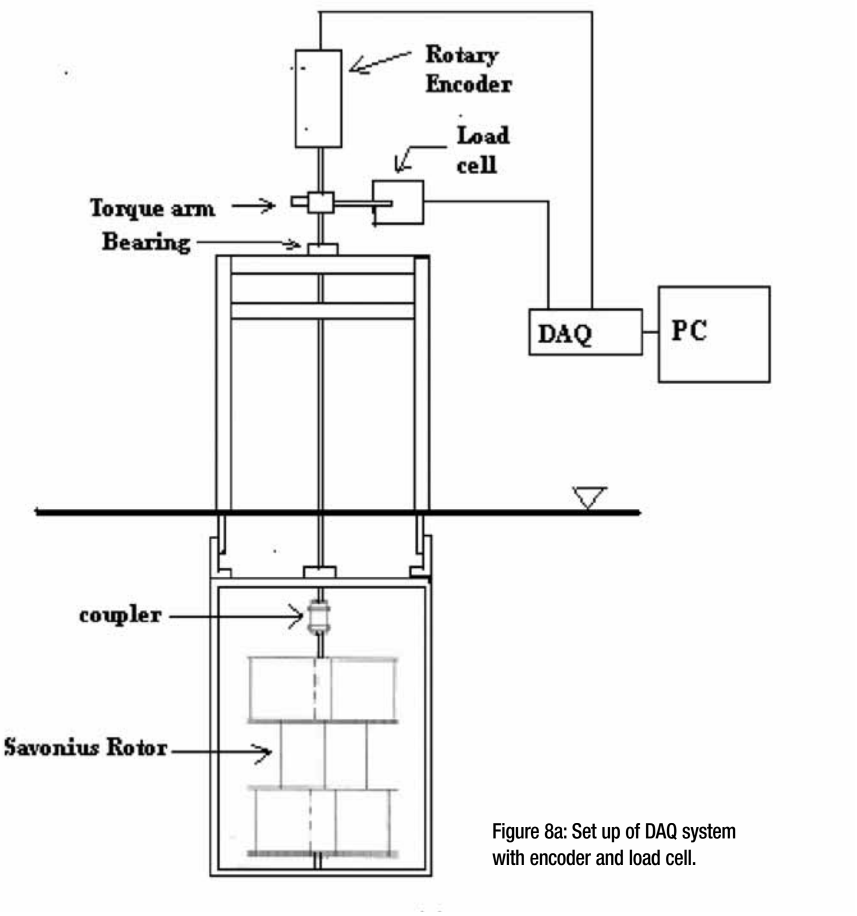


Figure 8a: Set up of DAQ system with encoder and load cell.

maximum speed of 5 m/s and a wave maker capable of producing waves up to 0.5 m in height. The motion of the carriage simulates a current. The rotors were mounted in a box frame that was open on all sides. The dimensions of the box were 35 cm x 35 cm x 50 cm. The frame was made from aluminum in order to avoid rusting. Bearings were used to support each rotor top and bottom.

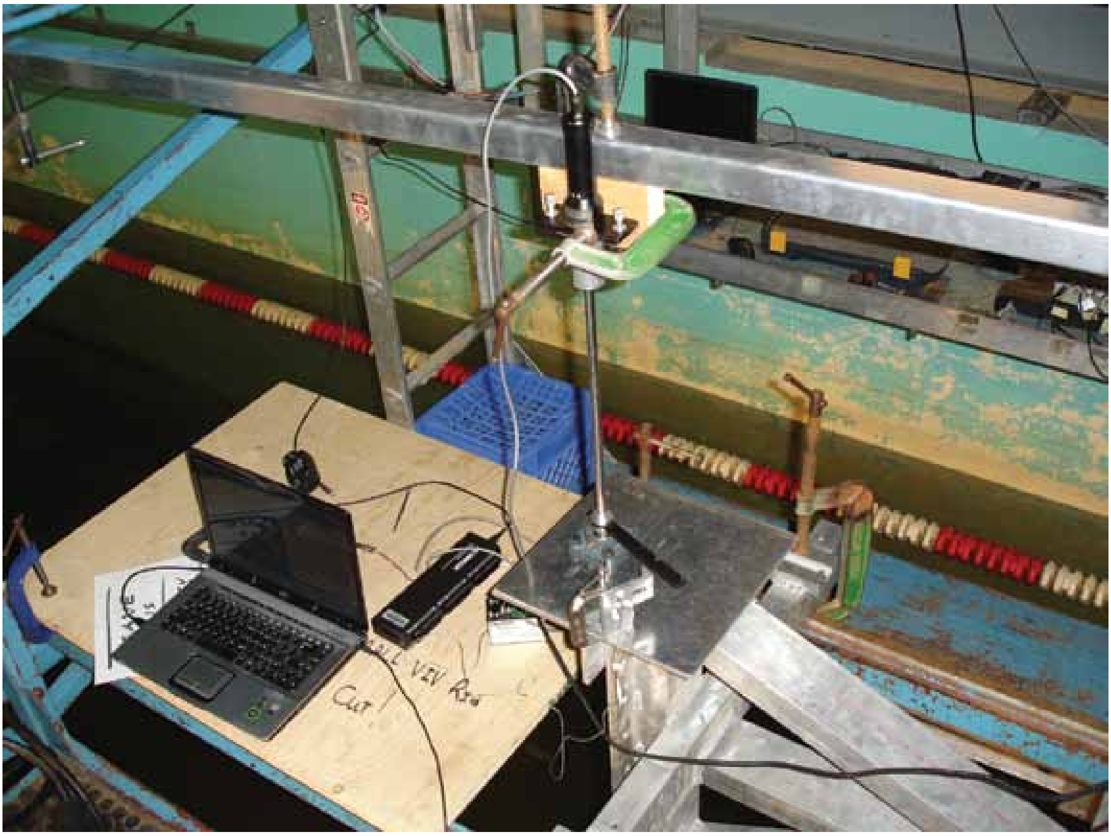
A schematic of the experimental set-up is shown in Figure 8(a). Figures 8(b) and 8(c) show the set-up of the rotor in the wave tank. A prony brake was used to measure the torque produced by each rotor. It used a button load cell (LCKD-5 OMEGA DYNE) to measure brake load. Load times moment arm gave torque. The RPM of each rotor was measured using a tachometer (Lab Volt EMS 8931-00). Sensors were wired into an OMB-DAQ-3000 16 bit 1 MHz data acquisition system. This was interfaced with a laptop using an USB port. The sampling time of the DAQ was 0.02 s.

EXPERIMENTAL RESULTS

MATLAB has been used to analyze the tests' data and plot characteristics of the turbines. All the prototypes were tested individually in the wave tank. In each case, the speed was increased gradually from 0 to 1 m/s. Figure 9 gives the

8b: Set up of the frame and rotor in the wave tank.

8c: Instrumentation to measure torque and RPM of rotor. (below)



power coefficient of the single stage rotor as a function of tip speed ratio. Figure 10 gives the corresponding result for the double stage rotor, while Figure 11 is for the three stage rotor. Working backwards, one finds that for the single stage rotor at water speed of 1 m/s, the peak power was 1.7 W at a rotor speed of 61 rev/min. At a speed of 1 m/s, the double stage gave 2.2 W at 70 rev/min, while the three stages gave 1.8 W at 61 rev/min. These differences are minor.

The torque variation of all three prototypes is shown in Figure 12 for one torque setting and one flow speed. It was expected that the three stage prototype would have the least torque variation, but the data shows that all three prototypes have roughly the same variation and the frequency is the same for all three. Analysis showed that the torque variation was due, not to the details of the rotor geometry, but to a flow induced vibration of the box frame that held the rotors. In any future work, the frame must be stiffened to prevent this vibration. The flow is complicated and requires further investigation using either computational fluid dynamics analysis or flow visualization experiments.

CONCLUSIONS

Three different types of Savonius rotors were tested as water current energy devices. A double stage rotor had the maximum power coefficient of the three rotors tested. Its peak power was around 5%, while the single and three stage rotors' peaks were both around

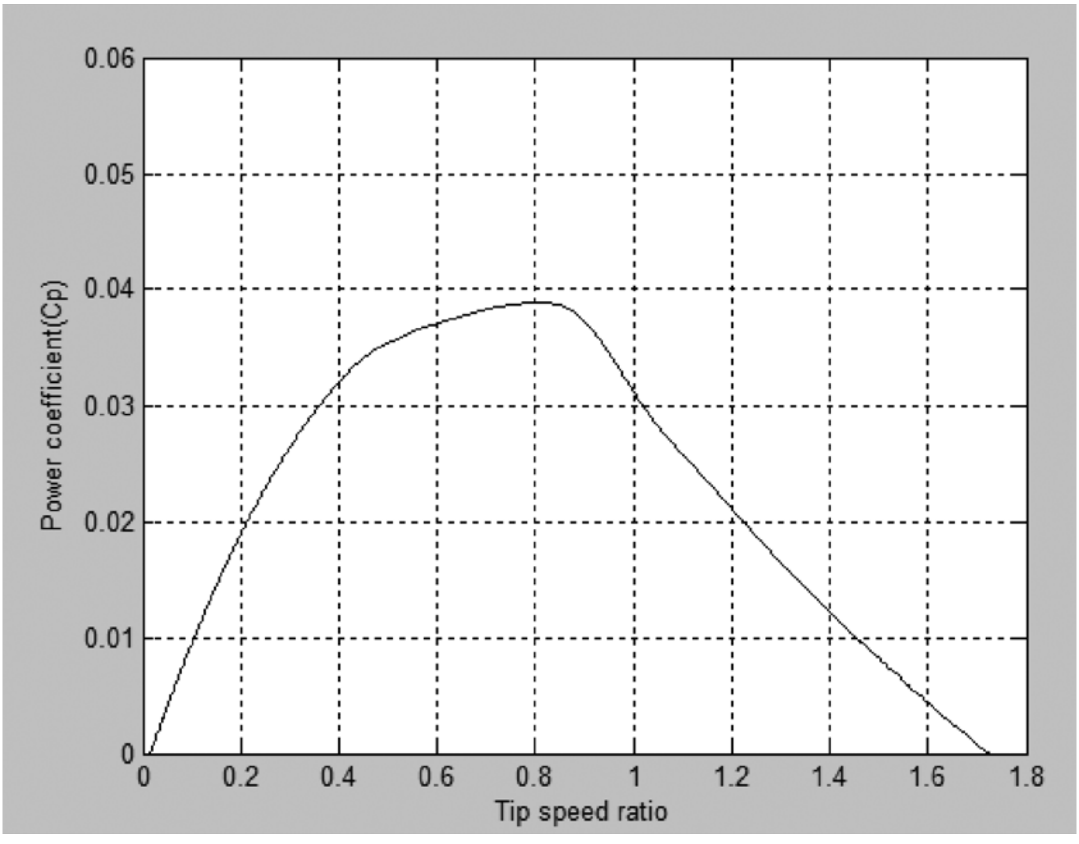


Figure 9: Single stage rotor: power coefficient vs. tip speed ratio.

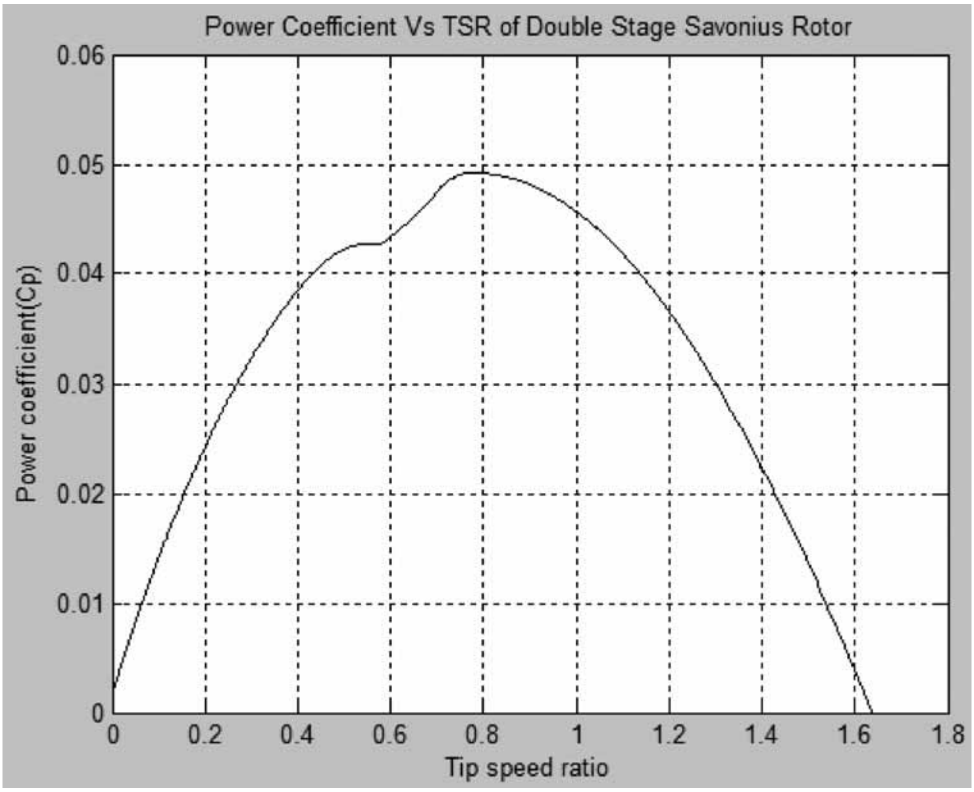


Figure 10: Double stage rotor: power coefficient vs. tip speed ratio.

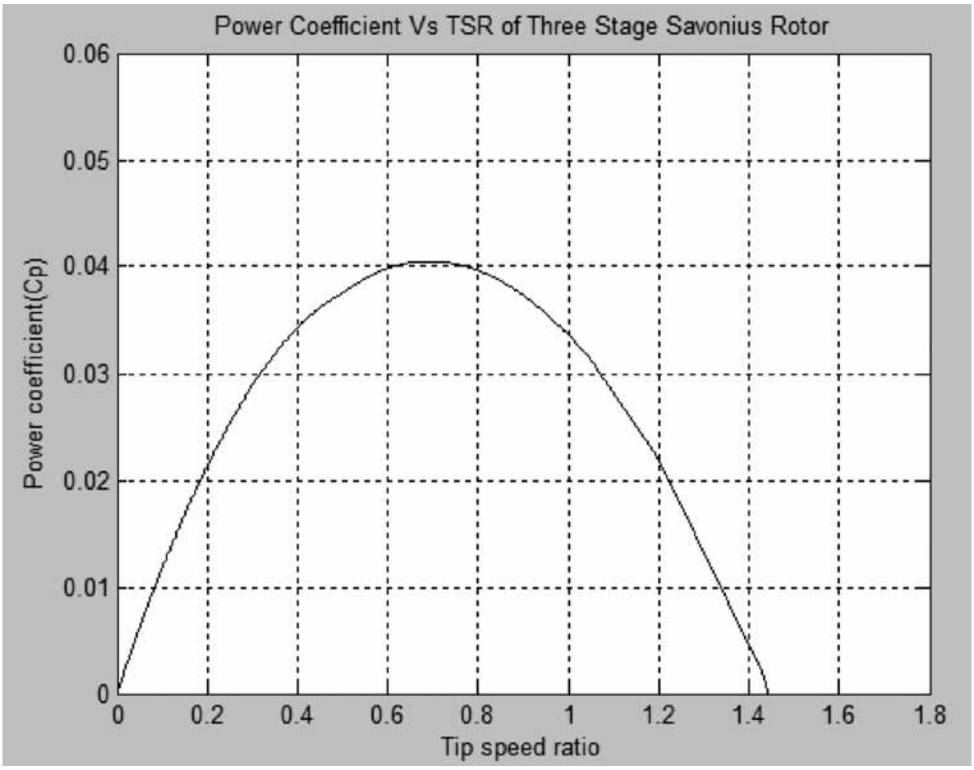


Figure 11: Three stage rotor: power coefficient vs. tip speed ratio.

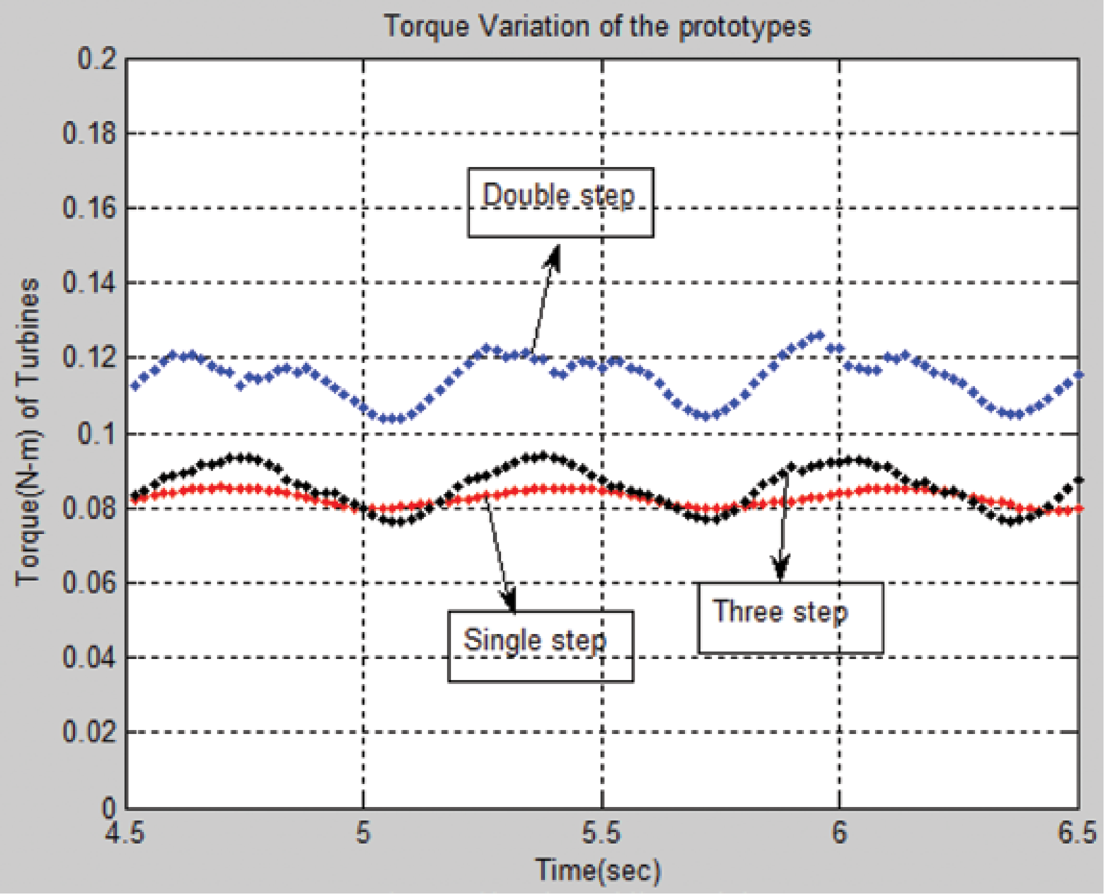


Figure 12: Torque variations of three prototypes at 0.8 m/s water current.

4%. These differences are minor, which suggest that one should pick a rotor based on ease of construction and not on power output.

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REFERENCES

Fujisawa, N. [1992]. On the torque mechanism of Savonius rotors. *Journal of Wind Engineering Industrial Aerodynamics*, Vol 40, Issue 277, pp 92.

Grinspan, A. S., Suresh Kumar, P., Saha, U.K., and Mahanta, P. [2003]. *Performance of Savonius wind turbine rotor with twisted bamboo blades*. (Proceedings of 19th Canadian Congress of Applied Mechanics, Calgary, Alberta, Canada, Vol 2, pp 412-413.)

Hayashi, T. [2005]. Wind tunnel test on a different three phase Savonius rotor. *Japan Society Mechanical Engineers International Journal*, Vol 48, pp 9-16.

Khan, M.J.A., Iqbal, M.T., and Quaicoe, J.E. [2008]. River Current Turbine Technology: Progress, Prospects and Challenges. *Renewable and Sustainable Energy*

Reviews Journal, Vol 12, Issue 8, pp 2177-2193.

Menet, J.L. [2004, September]. A double-step Savonius rotor for local production of electricity: a design study. *Renewable Energy*, Vol 19, pp 1843-1862.

Modi, V.J. and Roth, N.J. [1985, March]. *A prototype design and performance of the Savonius rotor based irrigation system*. (M.A.Sc Thesis, University of British Columbia.)

Savonius, S.J. [1931, May]. The S-Rotor and its applications. *Mechanical Engineering*, Vol 53, No 5, pp 333-338.

Ushiyama, I. and Nagai, H. [1988]. Optimum design configurations and performances of Savonius rotors. *Wind Engineering*, Vol 12, Issue 1, pp 59-75.