Effect of Variation of Wave Height and Ocean depth on the Performance of Savonius Rotors Utilizing the Orbital Motion of Ocean Waves in Shallow Waters

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Abstract: Ocean wave energy conversion technology is renewable and has distinct advantages over its peers. This paper presents an experimental study on the performance of Savonius rotors for the utilization of orbital motion of the fluid particles in ocean waves in shallow waters. A five vaned rotor is considered in this work and the performance is studied for different wave heights and wave time periods for a constant water depth. These input parameters are further non-dimensionalised as orbit overlap ratio and relative water depth. The output performance parameters selected for the studies were rotor speed and shaft power. These parameters are further non-dimensionalised as frequency ratio and efficiency. From the experimental results it was found that the frequency factor increases with an increase in orbit overlap ratio and an increase in ocean depth. The efficiency was found to decrease with increase in overlap ratio but increases with increase in ocean depth. Finally, from the experimental design and *ANOVA* using Design Expert 8.1 software, it was found that the load is the major parameter that influences the rotor output performance.

Keywords: Ocean wave, Orbital, Renewable energy, Savonius rotor.

1. Introduction

The current scenario of demand for new and renewable energy is fast changing and ocean wave energy is just one of many such sources. Oceans have tremendous energy potential in the form of tides and waves and although tidal energy has been harnessed for a long time across the globe, due to its intermittent nature of energy availability and the need for a large site area it is less attractive compared to ocean waves. Ocean waves are produced due to drag created by winds blowing over its surface. It is continuous in nature and has high energy density compared to wind energy. Wave energy is available in the form of kinetic and potential energies. As many as 1000 patents are reported in the quest for an efficient ocean wave energy conversion (OWEC) device. A review of the popular wave energy conversion technologies is reported by Drew *et al.* [1]. The present study is based on the US patent: Application number DE102004060275A1 or PCT/EP2005/013507. This patent proposes the utilization of the orbital motion of the fluid particles in the ocean waves. Figure 1 illustrates the concept of energy utilization. The shape of the orbits depends on the distance from the shore [2]. Water particles move in circular orbits in deep water, however, in shallow water the motion becomes elliptical. This circular or elliptical motion is called the orbital motion of ocean waves. Savonius rotors have been extensively used for harnessing low wind speeds [3] as they are simple semicircular geometries that rotate on the differential drag created by moving fluid. Very little literature [4-5, 7] is available on OWEC devices which use Savonius rotors for ocean waves. The available literature lack detailed study and proper experimental modeling. No work is reported on the output shaft power variation with change in input parameters. Also, the output performance variation, including the output rotational speed, with different Relative water depths, wave heights and other geometric parameters has not been studied. The experimental parameters themselves have to be non-dimensionalised properly so as to give a meaningful significance. Furthermore, studies [6] have shown that near shore sites also offer good wave energy potential in comparison to the deep ocean. Work on the rotor performance in shallow waters is not available in the literature. Rotor performance study in shallow water is advantageous as the transmission losses can be reduced due to its nearness to the shore.

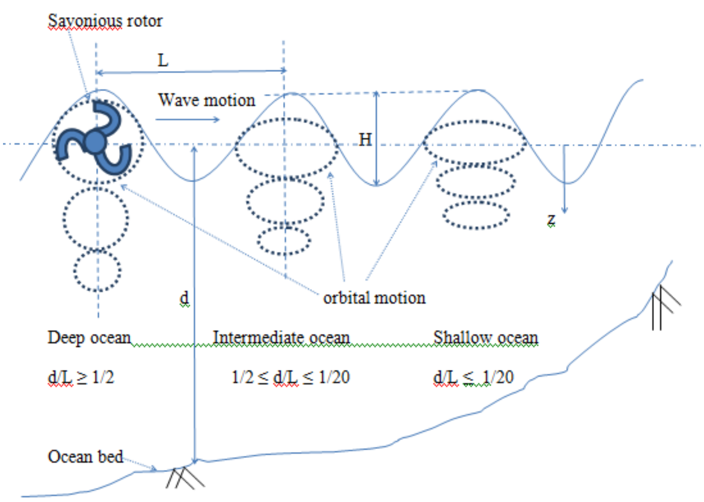

Figure 1. The schematic diagram of Savonius rotor utilizing the orbital motion.

2. Experimental Setup and Non-dimensional Parameters

The experimental setup was fabricated in-house and the influencing parameters were non-dimensionalised to give better physical meaning to the experimental outcomes.

2.1 Experimental Setup Description

The specification of the wave flume facility used for the study is shown in Table 1. The schematic diagram of the experimental setup is shown in the Figure 2. The structure is mounted on the wave flume and the rotor is fixed on the structure at the required depth with the help of fine and rough adjustments. The rotor is marked with a red strip on the shaft for counting the number of rotations. A wooden brake drum is fitted on the rotor shaft to mechanically load the shaft with the help of a plastic wire run on frictionless pulleys as shown in Figure 2. The vanes are fabricated using *PVC* sheets with dimensions 480 mm width × 65 mm height. The profile of the vanes for the rotor is shown in Figure 3.

Table 1. Wave flume Specification.

Total Length	50 m
Channel length	41.50 m
Width	0.71 m
Depth	1.10 m
Wave height	0.08 to 0.24 m
Wave period	1 sec to 3 sec
Wave generator	Bottom hinge flap type
Motor	Inverter driven (7.5Hp, 11Kw, 0-1450rpm, 0-50Hz)

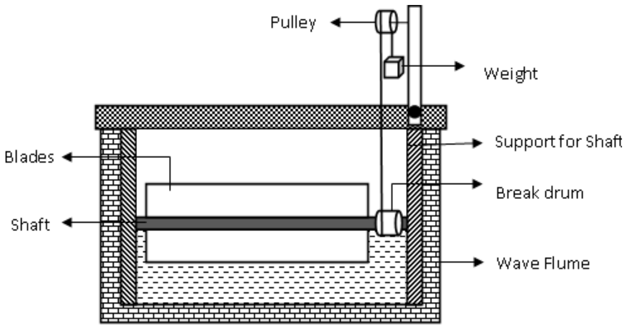

Figure 2. Schematic diagram of the experimental setup.

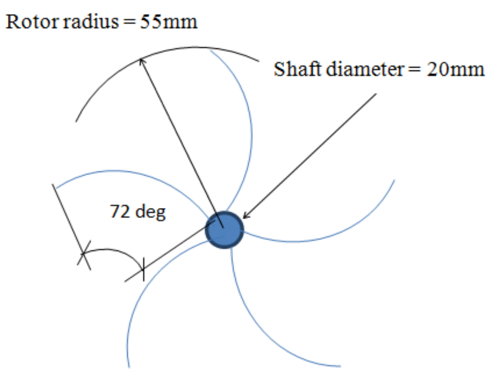

Figure 3. Geometric profile of the Savonius rotor vane.

2.2 Non-dimensional Parameters

Non-dimensionalisation of the experimental parameters is another important outcome of this research and is not reported in any of the literature cited in the references. For studying the performance of Savonius rotors to utilize the orbital motion of the ocean waves, one can think of the following influential parameters: rotor location from normal sea water level (*z*), ocean depth (*d*), rotor speed (*N*), rotor diameter (*D*), rotor width (*L*), wave height (*H*), wavelength (*L*), wave frequency (*f*), shaft power of the rotor (*P*), fluid density (*ρ*), depth of water in the ocean (*d*). Further, reducing the parameters through a non-dimensional approach yields the following non-dimensional quantities:

Non-dimensional expression	Non-dimensional Parameter
z/H	Submergence ratio (μ)
H/D	Orbit overlap ratio (Φ)
d/L	Relative water depth (ε)
N/f	Frequency ratio (χ)
$SP/(\rho g H^2/8T)$	Efficiency (ψ)

The rotor submergence ratio is basically the location of the rotor from still water level (*SWL*) with respect to the wave height. The Orbit overlap ratio can be used to understand the physical significance of the effect of wave height variation for a given rotor diameter. The Relative water depth provides information of the orbital shapes of the ocean waves which change from circular to elliptical as they approach the shore from the deep ocean. The frequency ratio gives information on the relative speeds of ocean wave and rotor. Finally, the efficiency is the ratio of rotor output power for a given wave power approaching the rotor. The performance of the Savonius rotor should depend on all the other non-dimensional parameters listed in the Table 2, however, the present work focuses only on the influence of variations in the orbit overlap ratio and relative water depth. The output performance parameters considered are frequency ratio and efficiency.

Table 2. Experimental Settings**.**

Case No.	μ	Φ	d/L
A	0	1, 1.25 and 1.5	1/9
B	0	1	1/9, 1/10 and 1/11

3. Testing Methodology

Having fixed the non-dimensional parameters, the experiments were carried out for the following cases:

A. Constant ε & μ and varying Φ
B. Constant Φ & μ and varying ε (*shallow waters*)

3.1 Rotor speed measurement

The rotor shaft speed depends on the wave position with respect to the rotor and its blade orientation. Therefore, the number of rotations (*n*) for a given time is first calculated and then averaged over time to obtain the rotor speed (*N*). A red strip is marked on the shaft of the rotor to facilitate counting the number of rotations of the rotor. The number of rotations for a total of 6 waves striking the rotor is noted and the same is expressed in the form of rotational speed i.e., the time taken for '*n*' rotations of the rotor is same as the time for '*m*' waves striking the rotor.

3.2 Shaft Power measurement

The rotor shaft is mechanically loaded with dead weights on a break drum (Figure 2) using a plastic wire hung on frictionless pulleys.

4. Results and Discussions

4.1 Effect of variation of Φ on the rotor performance (Case A)

From Figure 4 it is clear that with an increase in the orbit overlap ratio the frequency ratio increases for all loading conditions. However, this increase is more at zero loading and decreases at higher loads. Also, the frequency ratio decreases almost linearly with increasing load. However, from Figure 5 the efficiency is found to decrease with an increase in the orbit overlap ratio indicating that excess wave heights for a given rotor diameter would result in underutilized wave energy. Further, the efficiency is found to increase initially from zero loading and then flattens out near the maximum load condition indicating the existence of an optimum load condition.

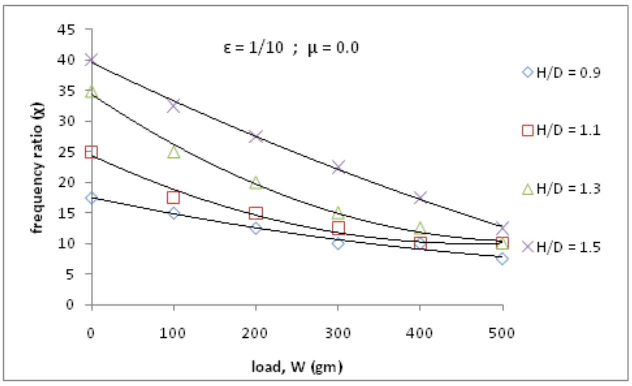

Figure 4. Plot of frequency ratio vs load.

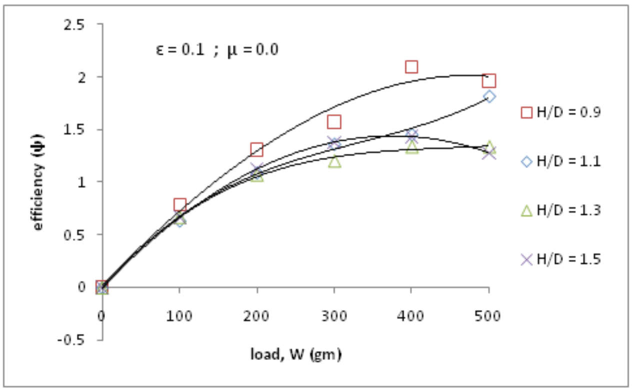

Figure 5. Plot of Efficiency vs. load

4.2 Effect of variation of ε on the rotor performance (Case B)

From Figure 6, it can be seen that with an increase in *d/L*, the frequency factor increases indicating circular motion of fluid particles in the wave are preferred over elliptical motion. From Figure 7, it is can be seen that the efficiency increases with *d/L* indicating an increase in efficiency with increase in distance from the ocean shore. However, for a $d/L > 1/9$ the waves approaching the rotor were too fast and resulted in breaking before reaching the rotor. For a $d/L < 1/11$, the waves approached at a relatively slow rate and the rotor lost some of its momentum before the next trough of the wave arrived.

4.3 Experimental Design and ANOVA

In order to study the combined effect of the input parameters on the output performance parameters, the experimental data was analyzed using Design Expert 8.1 software. A two factorial design approach has been considered with 3 input parameters (*H/D*, *d/L* and W) and two responses (χ, ψ).

The relative effect of each input parameter is shown in Figures 8 and 9 from which it is found that the effect of load, W, is highly influential on both the output parameters. The Main effects model has been considered and the ANOVA resulted in the following expressions for χ and ψ (eqn. 1-2).

$$\chi = -1.007 + 17.71 \times \phi + 69.44 \times \varepsilon - 0.03125 \times W \quad (1)$$

$$\psi = 3.02 - 0.75 \times \phi - 22.22 \times \varepsilon + 0.0037 \times W \quad (2)$$

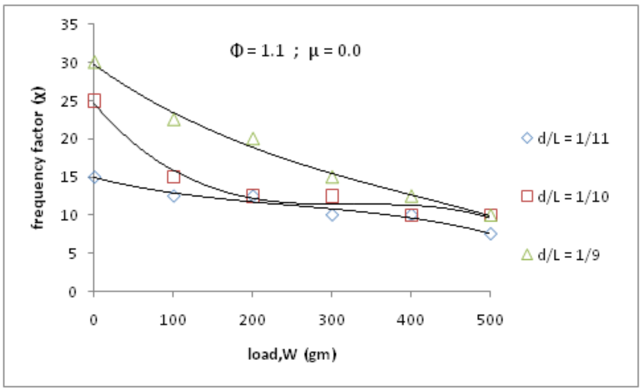

Figure 6. Plot of frequency factor vs load.

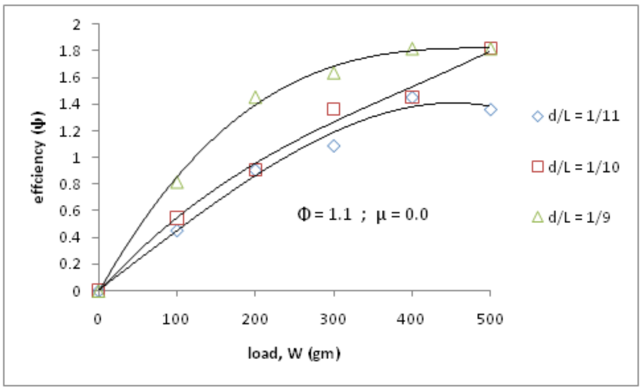

Figure 7. Plot of efficiency vs load.

Term	Stdized Effects	Sum of Squares	% Contribution
Intercept			
A-H/D	-0.45	0.40	5.16
B-d/L	-0.20	0.080	1.02
C-W	1.85	6.85	87.14
AB	0.100	0.020	0.25
AC	-0.45	0.40	5.16
BC	-0.20	0.080	1.02
ABC	0.10	0.020	0.25
Lenth's ME	1.13		
Lenth's SME	2.70		

Figure 8. Relative effect of each parameter on efficiency.

Term	Stdized Effects	Sum of Squares	% Contribution
Intercept			
A-H/D	10.63	225.78	26.98
B-d/L	0.62	0.78	0.093
C-W	-15.63	488.28	58.36
AB	3.13	19.53	2.33
AC	-5.63	63.28	7.56
BC	-3.13	19.53	2.33
ABC	-3.13	19.53	2.33
Lenth's ME	17.64		
Lenth's SME	42.23		

Figure 9. Relative effect of each parameter on frequency ratio.

The contour plots obtained from the Design Expert software are shown in Figures 10 and 11. From these plots it is clear that for a given load, a higher efficiency can be attained even for lower values of *H/D*, if *d/L* is increased further. Also it can be seen that the frequency ratio is poorly dependant on *d/L* and heavily dependant on the *H/D* ratio.

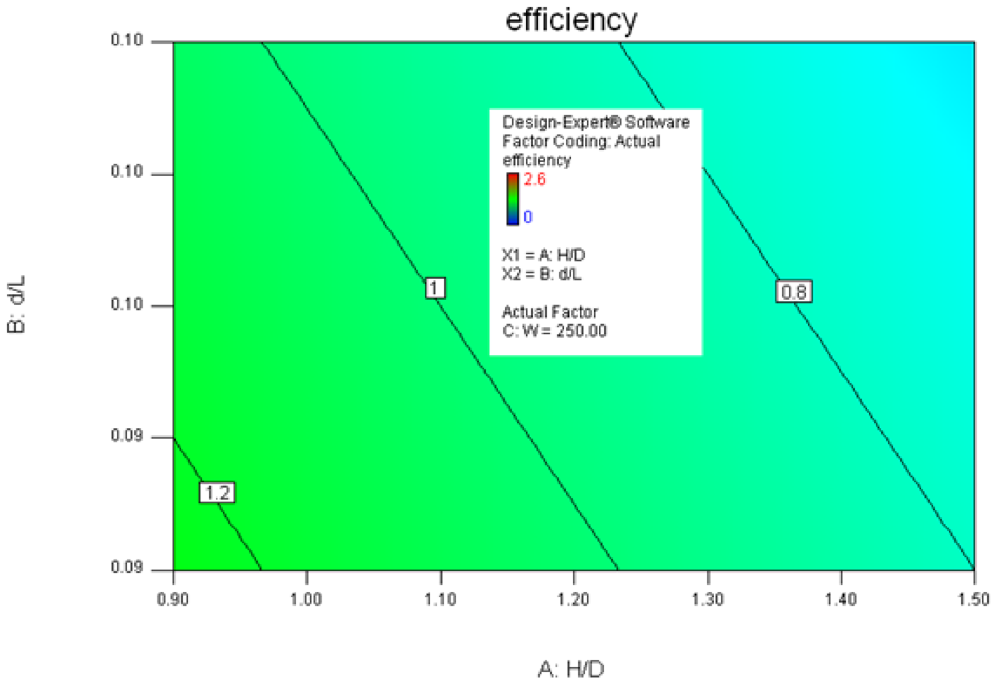

Figure 10. Efficiency variation (contour plot).

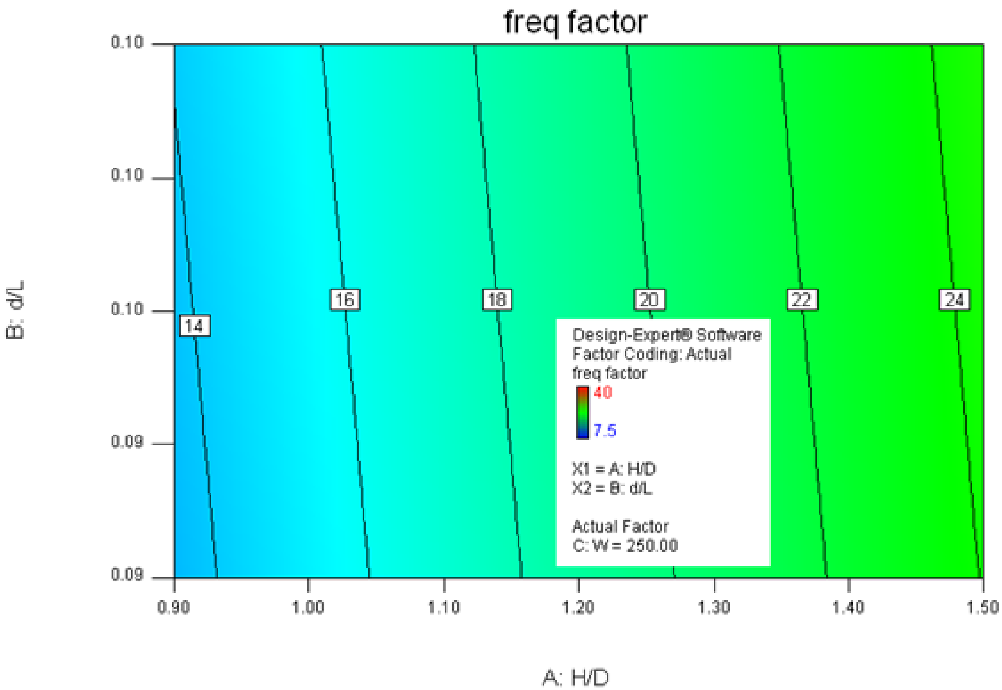

Figure 11. Frequency ratio variation (contour plot).

5. Conclusion

An attempt is made to identify the proper non-dimensional numbers associated with the present method of ocean wave energy conversion technology. From the experimental study carried out it can be concluded that:

i. The wave height and time period both influence the rotor speed and shaft power output.

ii. The frequency factor increases with an increase in *H/D* and *d/L*.

iii. The efficiency decreases with an increase in *H/D* but increases with an increase in *d/L.*

iv. From analysis with Design Expert software it is clear that the variation of load *(W)* is the major parameter that affects the output performance of the rotor.

A single rotor utilizing the orbital motion has been considered in this work. One can study the performance of multiple rotors arranged in series at varying distances from each other. The optimal arrangement can be obtained through optimization by experimental design technique. New methods to increase the differential drag across the rotor can be thought of such as use of a deflector plate. Furthermore, the number of vanes on the rotor can be varied and their relative performance can be studied.

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References

[1] Drew B, Plummer AR, Sahinkaya MN, A review of wave energy converter technology, *Proc. IMechE Part A: J. Power and Energy* 223 (2009) 887-902.
[2] Dean RG, Dalyrmple R, Water wave mechanics for Engineers and Scientists, *Advanced Series on Ocean Engineering* 2 (1991) 368 p.
[3] Kamoji MA, Kedare SB, Prabhu SV, Experimental investigations on single stage modified Savonius rotor, *Applied Energy* 86 (2009) 1064-1073.
[4] Faizal M, Rafiuddin AM, Lee YH, On utilizing the orbital motion of water waves to drive a Savonius rotor, *Renewable Energy* 35/1 (2009)164-169.
[5] Khan MNI, Iqbal MT, Hinchey M, Masek V, Performance of Savonius rotor as a water current turbine, *The Journal of Ocean Technology, Maritime and Port Security* 4/2 (2009) 71-83.
[6] Folley M, Whittaker TJ, Analysis of nearshore wave energy resource, *Renewable Energy* 34 (2009) 1709-1715.
[7] Hindasageri V, Ramesh H, Kattimani SC, Performance of Savonius rotors for utilizing the orbital motion of ocean waves in shallow waters, *J. Sustainable Energy and Environment* 2 (2011) 117-119.

Nomenclature

Symbol	**Description**	**Unit**
ANOVA	Analysis of Variance	
d	Depth of water in the wave flume	m
D	Rotor diameter	m
H	Wave height	m
L	Wavelength	m
m	Number of waves striking the rotor	
N	Rotor speed	Revolutions per minute
n	Number of rotations of the rotor	
f	Wave frequency	Hz
SWL	Still water level	
SP	Shaft power	W
T	Wave time period	Sec
W	Dead weight load	gm
z	Distance from still water level in the wave flume	m
Greek Notations		
μ	Submergence ratio	
Φ	Orbit overlap ratio	
ε	Relative water depth	
χ	Frequency ratio	
ψ	Power coefficient	