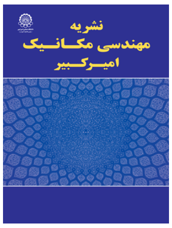

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Energy harnessing from water waves using a piezoelectric energy harvester with and without ore-like tip: an experimental study

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ABSTRACT: In this article, the piezoelectric energy harvester of cantilever type with the ability to be angled relative to the vertical direction, and also with rectangular fins attached to the end of the harvester has been investigated. The purpose of this study is to investigate the effect of design parameters such as the angle of inclination of the energy harvester, its distance from the wave source, the depth of the beam, and the presence or absence of fins at the end of the beam, on the effective output voltage of the energy harvester. Low efficiency is the most important limitation for the advancement of piezoelectric energy harvesters, and for this reason, it is necessary to use methods based on tests and optimization to increase the efficiency of piezoelectric energy harvesters. To carry out the experimental study, experiments have been designed using the central composite design (CCD) and the design parameters have been optimized using the response surface methodology (RSM). Also, the effect of equipping the energy harvester with a fin on the final voltage has been investigated. It was observed that the optimal conditions for both finned and non-finned harvesters occur when the distance ratio of the beam from the wave-maker is minimum and the depth of penetration ratio is maximum.

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1- Introduction

Harvesting energy from water waves is one of the new methods of producing clean energy with the help of piezoelectric materials. In this method, the mechanical energy of water waves is converted into electrical energy. Piezoelectric energy harvesters are made in various configurations, and one of the most common configurations is the uni-morph cantilever configuration [1]. Attempts to improve the efficiency of piezoelectric cantilever energy harvesters have been a common theme in most studies [2]. In this article, a new experimental study is conducted on the design of piezoelectric cantilever harvesters. The energy harvester under study has a uni-morph cantilever structure, and the distance of the harvester from the wave maker, the depth of its penetration in the water, as well as the angle of the harvester concerning the vertical axis, are the main input variables. Also, a rectangular fin is used at the end of the piezoelectric harvester, and all the experiments are performed for both finned and non-finned harvesters, and the effect of the presence of fins at the end of the harvester is investigated. An empirical model is extracted using response surface methodology, based on which the input parameters are optimized to achieve the maximum effective voltage.

2- Materials and Procedures

All experiments were carried out in a water channel with a length of 3.7 meters and, a width and height of 0.6 meters. Two types of cantilever structures, according to Figure 1, were used in the experiments.

The energy harvester is in the form of a cantilever beam connected to a piezoelectric disc (see Figure 1) and placed at a variable distance from the central axis of the wave generator using a fixture that can rotate and adjust the angle relative to the vertical axis.

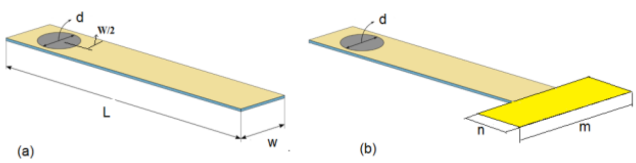

Fig. 1. Schematic picture of finless (part a) and finned cantilever energy harvester (part b)

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Table 1. Input factors in the experimental runs

Test Order	Test number	Length ratio(%)	Depth ratio (%)	Tilt angle (degree)
17	1	60	6	30
15	2	60	6	30
16	3	60	6	30
5	4	40	3	45
14	5	60	12	60
11	6	60	0	30
12	7	60	12	30
6	8	80	3	45
20	9	60	6	30
13	10	60	6	0
19	11	60	6	30
3	12	40	9	15
18	13	60	6	30
2	14	80	3	15
7	15	40	9	45
9	16	20	6	30
4	17	80	9	15
8	18	80	9	45
10	19	100	6	30
1	20	40	3	15

3- Design of Experiments by CCD method

The design variables are the dimensionless ratio of the distance of the cantilever from the wave maker, the dimensionless ratio of the depth of the cantilever in the water, and the angle of the tilted cantilever.

The response surface methodology uses second-order models to develop the response surfaces of the model and optimize the design parameters. The CCD method is one of the best experimental design methods for defining the necessary experiments to fit the second-order models. The number of tests for the CCD method is calculated by the relation ($n = 2^k + 2k + 1$), where k is the number of input factors. On the other hand, to analyze the precision and adequacy of the model, it is necessary to repeat the tests multiple times at a single point in the experiment. In this article, the experiments have been repeated 5 times at the central point of experiments, and due to the presence of 3 input variables and 5 repetitions, the number of experiments is equal to 20.

4- Extracted Empirical Model

Using the RSM, the effective output voltage of the piezoelectric energy harvester was expressed as a second-order mathematical function of the input variables. Equation 1 represents the extracted second-order empirical models for the energy harvesters with the end fin:

Table 2. Results of ANOVA for the empirical models

Statistic quantity	S	R^2	$R^2_{adjusted}$	$R^2_{predicted}$
Without end-tip	0.353553	99.94%	99.89%	99.54%
With end-tip	0.157592	99.98%	99.97%	99.87%

$$V_{rms} = 87.801 - 1.0571L + 0.242H - 0.1098\theta + 0.004307L^2 + 0.069H^2 - 0.005288\theta^2 + 0.0043L \times H + 0.004458L \times \theta + 0.00916H \times \theta \quad (1)$$

The empirical model for the energy harvesters without the end fin is expressed as:

$$V_{rms} = 104.88 - 1.2563L + 0.041H - 0.1583\theta + 0.005000L^2 + 0.0832H^2 - 0.005556\theta^2 + 0.0083L \times H + 0.005L \times \theta + 0.01111H \times \theta \quad (2)$$

where V_{rms} , L, H, and θ are the effective voltage (in mV), length ratio (in percent), depth ratio (in percent), and tilt angle of the cantilever, respectively. An analysis of variance has been applied to check the precision and adequacy of the model, and the summary of the analysis of variance is reported in Table 3 for both types of energy harvesters.

A high value of R^2 and a very small difference between adjusted and predicted R^2 indicates the appropriate accuracy of modeling [3].

Figure (2) shows three-dimensional response surfaces fitted based on relations (1) and (2). Parts a and b of figure (2) are related to the piezoelectric cantilever without the fin, and parts d and e are related to the cantilever with the end fin. As it is evident, the parameters of the distance from the wave-maker and the depth of the cantilever underwater penetration are the most important parameters affecting the output voltage. Reducing the distance from the wave maker and increasing the depth of the depression has increased the effective voltage in the piezoelectric harvester. The effect of the tilt angle is less than the other two parameters, and there is an optimum angle to achieve the highest effective voltage. The effect of all three parameters is non-linear, and all the input parameters interact with each other. Optimization of the design and setting parameters to maximize the effective voltage was done using the response surface methodology for both finned and non-finned modes. It was observed that the optimal conditions for both finned and non-finned harvesters occur when the distance ratio of the beam from the wave-maker is minimum and the depth of penetration ratio is maximum.

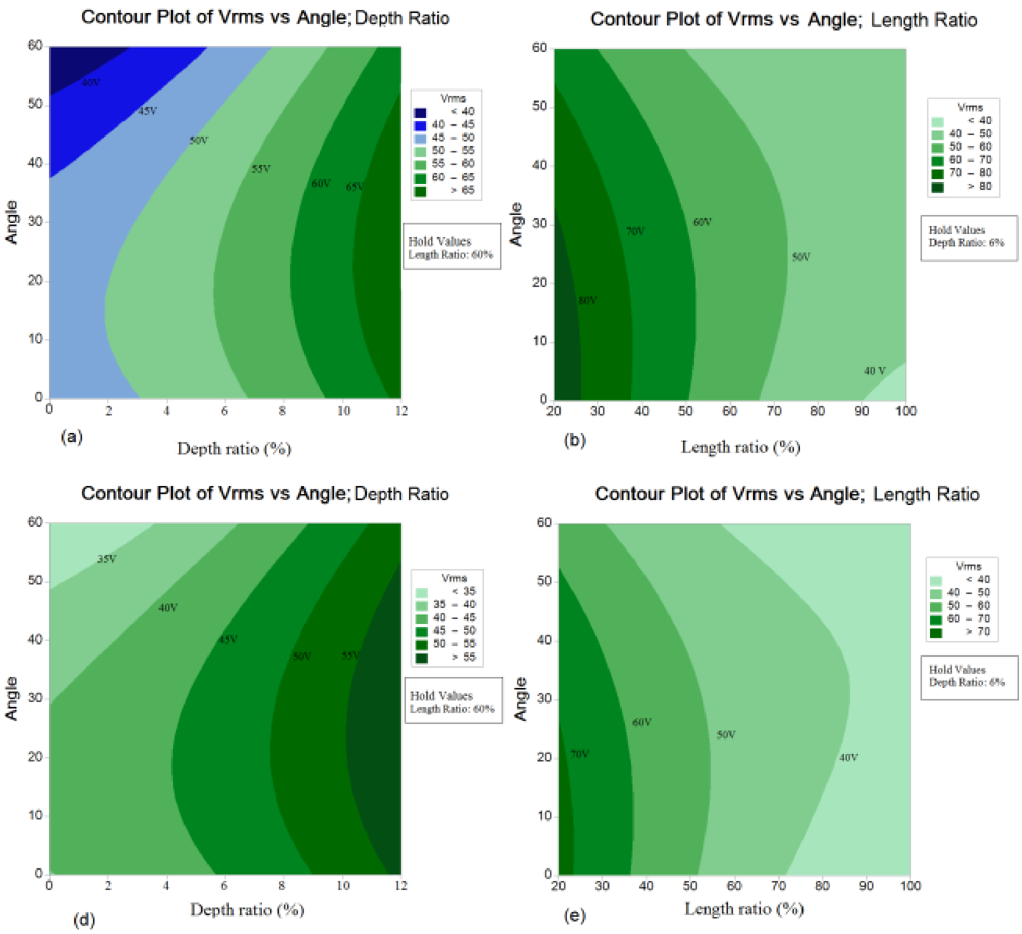

Fig. 2. Contour diagrams of effective voltage changes concerning the design parameters

5- Conclusion

In this article, the central composite method and response surface methodology were used to study the effects of the design and adjustment parameters of the piezoelectric energy harvester from water waves. An analysis of variance showed that all three input variables, including tilt angle, distance ratio, and indentation depth ratio, have a nonlinear effect on the output voltage. On the other hand, all three mentioned parameters interact with each other. The effect of the distance ratio is greater than that of the other two variables on the effective voltage. Using an ore-like end tip did not change the overall behavior of the energy harvester; however, it reduced the harvester's maximum output by 14.5%.

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