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Cymbal Structural Optimization for Improving Piezoelectric Harvesting Efficiency with Taguchi's Orthogonal Experiment

Guangqing Shang[1], Wei Ning[2], Chunhua Sun[1*]

[1]Department of Mechanic and Electronic Engineering, Suzhou Vocational University, Suzhou, China
[2]College of Mechanical Engineering, Shanxi University of Technology, Hanzhong, China
Email: [*]chh_sunny@163.com

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Abstract

To improve piezoelectric harvesting efficiency of Cymbal, optimization design of Cymbal parameters was studied with the method of Taguchi's orthogonal experiment. The effective factors of piezoelectric harvesting property were firstly analyzed. The orthogonal experiment schedule was then designed. The finite element model of Cymbal was built via ASPL tool in ANSYS software and static analysis was done. The experimental results were gotten with developed program. The optimization level of each factor was gained. Under the synthetical optimization level of each design factor, the piezoelectric analysis was tested and the open voltage of 236.476 V was revealed with improving 35.73% than the maximum voltage of 174.228 V in the orthogonal experiment. The average voltage of 229.98 V was measured with the manufactured optimized Cymbal structure design. The relative error was 2.54% between simulation and measured data. It indicated that the optimization design schedule was reasonable. Cymbal harvester with the optimized parameters could scavenge larger voltage.

Keywords

Energy Harvest, Piezoelectric Effects, Cymbal Harvester, Taguchi's Orthogonal Experiment

1. Introduction

The special structural design of piezoelectric Cymbal harvester makes it possess some special characteristics,

[*]Corresponding author.

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such as the ease of fabrication and the ability to tailor performance. The comprehensive piezoelectric effects of d_{33} and d_{31} are easily excited for Cymbal harvester under the axial external force [1]. Besides being used as the actuator and sensor, the piezoelectric Cymbal harvester has recently been focused to be an energy transducer. The harvesting energy properties of Cymbal have been researched via the theoretical analysis method, the finite element method and experiment [2]-[8]. The harvesting energy basic rule and effective factors of Cymbal have been mastered. So basic foundation for applying piezoelectric Cymbal harvester has laid. However, structural optimization and synthetic effect of various factors and the dominance degree of each factor have not been given a clean answer. In this study, the Taguchi experimental design is adopted for studying the synthetic effect of various factors on the output electrical characteristic of piezoelectric Cymbal harvester. The dominance degree of each factor is analyzed according to the result of Taguchi experiment. A optimized structure of Cymbal is determined.

2. Effective Factors of Cymbal Harvester

Figure 1 shows the structure of piezoelectric ceramics Cymbal harvester. The factors of a Cymbal harvester on the piezoelectric harvesting characteristics deal with two kinds: physical and geometrical ones. The physical factors include the materials of endcap, piezoelectric ceramic and binder, while the geometrical factors involve the endcap diameter D, endcap thickness t_1, PZT thickness t_2, cavity depth h, the dimple diameter d_1 and the cavity diameter d_2. In this paper, the above five geometric factors except D are mainly discussed.

Aluminum is used as the endcap material, PZT-5A is to be piezoelectric ceramics. The diameter of the endcap D is the same as that of the PZT piezoelectric ceramics disk and equal to 29 mm. Based on Taguchi's orthogonal experiment design, the piezoelectric harvesting characteristic of Cymbal harvester is discussed to find out the above five optimized structural parameters.

3. The Taguchi's Orthogonal Experiment Design

The open voltage generated by Cymbal harvester is used as optimization objective, the five above-discussed geometric parameters as factors. The aim of the orthogonal experiment is to optimize the geometric parameters of a Cymbal harvester and to obtain the highest voltage. Meanwhile, an alternative aim is to find out the dominance degrees and the optimal values of these factors.

According to Taguchi parameter design methodology, a $L_{16}\left(4^5\right)$ standard orthogonal array with five factors in four levels each in 16 runs is employed [9]. The $L_{16}\left(4^5\right)$ considering the five above-discussed parameters are shown in **Table 1**. Each row of the orthogonal array represents a specified set of factor levels to be tested.

4. The Finite Element Analysis

As shown in **Table 1**, 16 experiments need to run for obtaining the open voltage according to the orthogonal experiment design. For saving time, manpower, material and financial resources, the finite element method is adopted. The technologies of APDL parametric modeling and command stream are used to develop the application program for Cymbal piezoelectric analysis based on two development platform of ANSYS 12.0. The developed primary menu, dialogue of inputting parameters and the finite element model are shown in **Figures 2-4**, respectively.

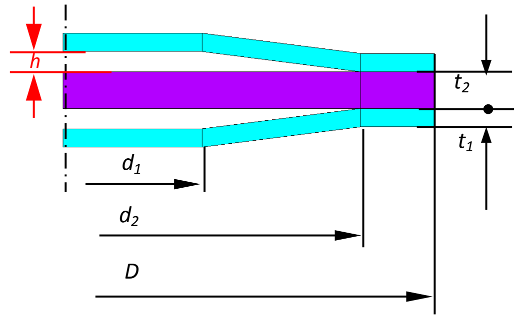

Figure 1. Cymbal structural parameters.

Table 1. Schedule and results of Taguchi's orthogonal experiments.

Run No.	Factors					Results
	1 (t_1/mm)	2 (t_2/mm)	3 (h/mm)	4 (d_1/mm)	5 (d_2/mm)	Open voltage/V
1	1 (0.3)	1 (1)	1 (1.5)	1 (4)	1 (16)	30.652
2	1 (0.3)	2 (2)	2 (1.6)	2 (5)	2 (18)	58.626
3	1 (0.3)	3 (3)	3 (1.8)	3 (6)	3 (20)	91.838
4	1 (0.3)	4 (4)	4 (2.0)	4 (8)	4 (22)	169.639
5	2 (0.4)	1 (1)	2 (1.6)	3 (6)	4 (22)	117.835
6	2 (0.4)	2 (2)	1 (1.5)	4 (8)	3 (20)	174.228
7	2 (0.4)	3 (3)	4 (2.0)	1 (4)	2 (18)	32.557
8	2 (0.4)	4 (4)	3 (1.8)	2 (5)	1 (16)	41.766
9	3 (0.5)	1 (1)	3 (1.8)	4 (8)	2 (18)	94.535
10	3 (0.5)	2 (2)	4 (2.0)	3 (6)	1 (16)	45.925
11	3 (0.5)	3 (3)	1 (1.5)	2 (5)	4 (22)	97.034
12	3 (0.5)	4 (4)	2 (1.6)	1 (4)	3 (20)	50.936
13	4 (0.6)	1 (1)	4 (2.0)	2 (5)	3 (20)	49.544
14	4 (0.6)	2 (2)	3 (1.8)	1 (4)	4 (22)	50.795
15	4 (0.6)	3 (3)	2 (1.6)	4 (8)	1 (16)	87.227
16	4 (0.6)	4 (4)	1 (1.5)	3 (6)	2 (18)	81.143
Sum of level 1: $\sum_{i1}(V)$	350.755	292.566	383.057	164.94	205.57	
Sum of level 2: $\sum_{i2}(V)$	366.386	329.574	314.624	246.97	266.861	
Sum of level 3: $\sum_{i3}(V)$	288.43	308.656	278.934	336.741	366.546	
Sum of level 4: $\sum_{i4}(V)$	268.709	343.484	297.665	525.629	435.303	
Average of level 1: X_{i1} (V)	87.689	73.142	95.764	41.235	51.393	
Average of level 2: X_{i2} (V)	91.597	82.394	78.656	61.743	66.715	
Average of level 3: X_{i3} (V)	72.108	77.164	69.734	84.185	91.637	
Average of level 4: X_{i4} (V)	67.177	85.871	74.416	131.407	108.826	
Range R_i (V)	24.42	12.729	26.03	90.172	57.433	

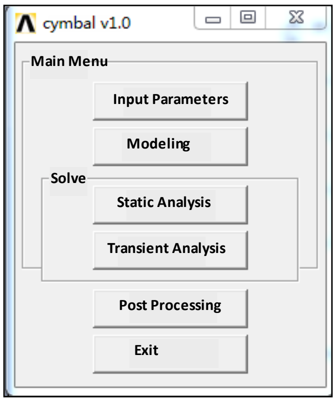

Figure 2. The developed main menu.

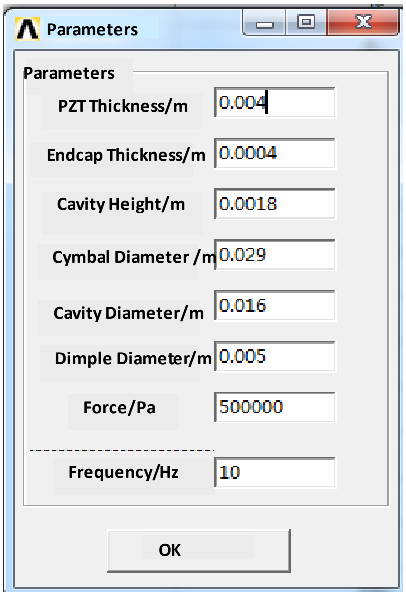

Figure 3. Dialogue of input parameters.

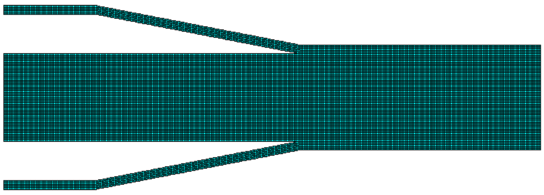

Figure 4. Cymbal finite element model.

Table 1 lists the simulation results calculated by using the developed program. Meanwhile, **Table 1** is also shown the average and range of each level of factors.

5. Analysis of Simulation Results

From the results shown in **Table 1**, it can be seen that the maximum voltage of 174.228 V is obtained under the parametric conditions of No. 6. However, from the average of each factor in four levels, the optimized parameters are: level 2 of factor 1 (endcap thickness of t_1 = 0.4 mm), level 4 of factor 2 (PZT thickness of t_2 = 4 mm), level 1 of factor 3 (cavity depth of h = 1.5 mm), level 4 of factor 4 (dimple diameter of d_1 = 8 mm) and level 4 of factor 5 (cavity diameter of d_2 = 22 mm). Using the above optimized parameters, the open voltage is up to 236.476 V. The optimized result increase 35.73% compared with the maximum value of 174.228 V using the orthogonal experiment in **Table 1**. **Figure 5** shows the potential distribution under the optimized conditions.

According to the range value of R, factors in order of dominance degree from big to small list as follows: dimple diameter d_1, cavity diameter d_2, cavity depth h, endcap thickness t_1 and PZT thickness t_2.

6. Test Measurement

Figure 6 shows the manufactured samples according to the optimized parameters of Cymbal. During measuring, the material test system is used as the loading equipment, Tektronix oscilloscope is adopted to collect electric signal. The test results are shown in **Table 2**. The average of test results is 229.98 V while data processing. Compared to the simulation result of 236.476 V, the absolute error is 2.54%. The error mainly comes from the following: 1) without considering effect of binder during simulation; 2) material difference between simulation and test. It shows that the simulation and test fits well and Taguchi's orthogonal experiment design is available for optimizing Cymbal structure.

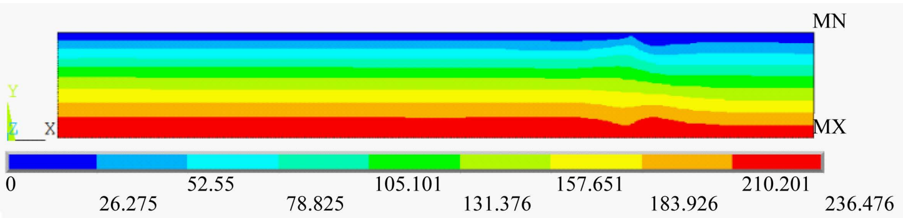

Figure 5. Voltage distribution with optimized parameters.

Figure 6. Cymbal samples with optimized parameters.

Table 2. The measured voltage data.

Sample No.	Open voltage(V)	Sample No.	Open voltage(V)
1	230.5	6	228.8
2	230.1	7	229.4
3	229.6	8	230.2
4	230.4	9	230.4
5	229.8	10	230.6

7. Conclusions

To improve the efficiency of Cymbal harvesting energy, Taguchi's orthogonal experiment design is adopted. The finite element program is developed to simulate the experimental conditions via ANSYS 12.0 two development platforms. Effects of synthetical factors on piezoelectric harvesting efficiency of Cymbal are analyzed. The results show that the dominance degree of each factor lists following: dimple diameter d_1, cavity diameter d_2, cavity depth h, endcap thickness t_1 and PZT thickness t_2. The excited open voltage of Cymbal with the optimized parameters is larger than the maximum of orthogonal experiment. It indicates that the method of the orthogonal experiment design for optimal Cymbal harvester is available and the optimized structure of Cymbal harvester can be used for savaging higher electrical potential.

The future of work will focus on the application of the optimal Cymbal and coupling with the environment.

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