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Optimization Design of a Piezoelectric Actuator with Orthogonal Theory

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Abstract **-** In this paper, an optimization design method with orthogonal theory for piezoelectric actuator is presented, and it focuses on getting the maximum output displacement of piezoelectric actuator by optimizing four factors: the length, width, thickness of PZT-5 and the thickness of elastic layer. Based on Finite element analysis as well as Range analysis and Variance analysis of orthogonal test results, the degree of influence of these factors to the maximum output displacement are analysed, and optimization design is done. In addition, a RBF network model of piezoelectric actuator also be researched.

Keywords**:** Optimization Design, Piezoelectric Actuator, Orthogonal Theory, Range, Variance.

1. Introduction

With the development and cross-application of bionics, micro electronic mechanical system and other discipline technologies, the research of flapping micro air vehicle with small size, light, stealth and great operability becomes more and more popular after the end of the 20th century[1-6]. The driving mechanism of flapping micro air vehicle must meets the driving power and high lift requirements while the size is as small as possible. With the advantages of great unit mass output power, small size, good flexibility etc., piezoelectric actuator can be used in the flapping micro air vehicle.

This paper optimizes the size of piezoelectric actuator with orthogonal theory and Finite element analysis, and the method can achieve the optimal size of piezoelectric actuator with fewer experiments and calculations. In addition, a RBF network model of piezoelectric actuator also be researched, thus Finite element analysis can be eliminated to simply to the design process of a piezoelectric actuator.

2. Piezoelectric Actuator's Structure and Operational Principle

In this paper, Piezoelectric material is PZT-5 and elastic layer's material is stainless steel. PZT-5 are pasted with an epoxy resin on both sides of elastic layer. With the DC voltage circuit, piezoelectric actuator's electrical structure as shown in Fig 1.

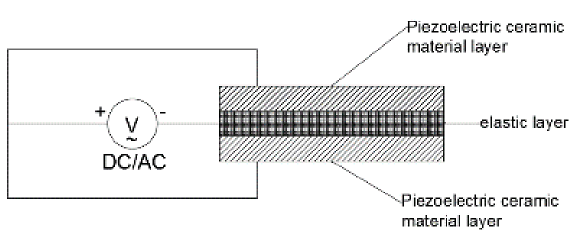


Fig. 1: Piezoelectric actuator's electrical structure.

From the Fig 1, it is clear that the polarization direction of PZT-5 on both sides of elastic layer is the same. It can be known from the inverse piezoelectric effect, while the direction of the voltage and the polarization is the same, PZT-5 will be stretched; on the contrary, PZT-5 will be compressed. When the circuit is closed and voltage is proper, top PZT-5 will stretch while the bottom compress in horizontal direction, thus the piezoelectric actuator will bend down. If the DC voltage is replaced by Alternating voltage, piezoelectric actuator will bend up and down in turn, thus the micro air vehicle can flap up and down accordingly.

3. Finite Element Analysis Method of Piezoelectric Actuator

A piezoelectric actuator is consist of two kinds of materials, its calculation and analysis is difficult, here the finite element method is used. Thickness of piezoelectric ceramics is thin, and it is certain that some slight flaws will appear in polarization process. However, the polarization process is still relatively uniform, and uniform distribution of polarization is a hypotheses for finite element analysis.

By using the method of direct modeling, nodes are created, and the nodes are used to generate the element, thus the finite element model is obtained. This method can generate a large amount of data, but it can get more accurate result and can control the density of the finite element mesh. APDL language is used to define two kinds of materials (piezoelectric ceramic and stainless steel) and their material properties. The grid density of piezoelectric layer and elastic layer are determined respectively, and the coordinates of each node are got from the parameters. After the first node is established, it is copied to produce other nodes, thus a sub-microscopic structure of an actuator can be got. In turn, the sub-microscopic structure is copied to obtain the finite element model of the actuator.

Solid5 elements are used in the process of modeling. Because there is no gap between any neighbouring elements, their boundary nodes are shared in the finite element model. Positive voltage is applied to one electrode, and 0 voltage is applied to the corresponding another electrode. Finally, the finite element calculation is carried out.

4. Orthogonal Optimization Design

Basing on four factors(the length ,width and thickness of PZT-5 and the thickness of elastic layer), the paper optimizes the output displacement of piezoelectric actuator using orthogonal theory. In the paper, A, B, C, and D correspond to the length ,width and thickness of PZT-5 and the thickness of elastic layer, respectively. The factors and levels of these experiments are shown in Table 1.

Table 1: Factor and level table.

Level	Factor			
	A	B	C	D
	l (mm)	w (mm)	h (um)	h_0 (um)
1	$l^{(1)}$	$w^{(1)}$	$h^{(1)}$	$h_0^{(1)}$
2	$l^{(2)}$	$w^{(2)}$	$h^{(2)}$	$h_0^{(2)}$
3	$l^{(3)}$	$w^{(3)}$	$h^{(3)}$	$h_0^{(3)}$
4	$l^{(4)}$	$w^{(4)}$	$h^{(4)}$	$h_0^{(4)}$

An orthogonal table $L_{16}(4^5)$ (five factors that each factor have four levels) is chosed to design table header, and the blank column which is the fifth column can be regarded as the random error. The range analysis result of the blank column can reflect whether there exists interaction between these factors. According to above, we can make orthogonal design scheme easily.

5. Orthogonal Optimization Analysis

According to the design requirements, the original range of the four factors have been confirmed. Then each of them has been chosen four levels just as follows, $l=14、16、18、20$, $w=1.8、2.4、3.0、3.6$, $h=80、100、120、140$, $h_0=40、60、80、100$, the proper voltage E=+100V. Combining with the characteristics of PZT-5, the models are modeled and the corresponding optimization analysis are completed. The results of the first group's model is as follows in Fig 2.

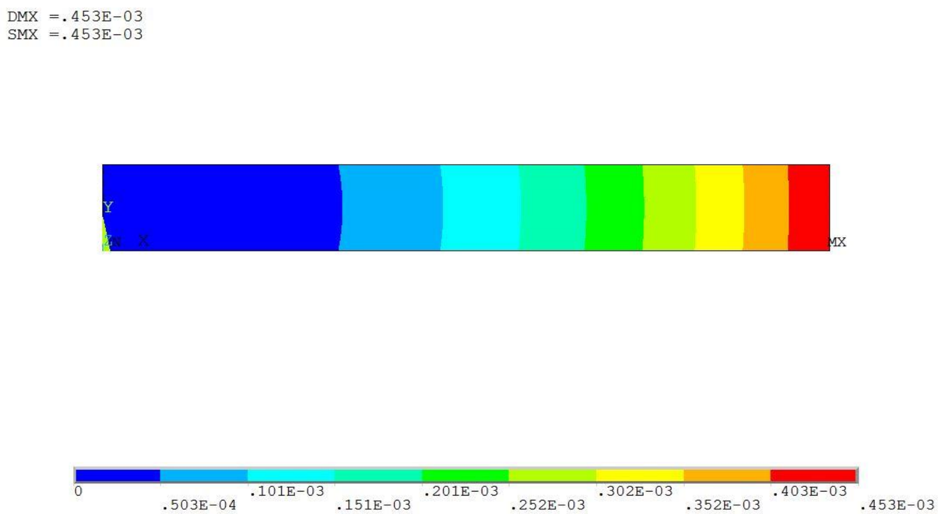


Fig. 2: the output displacement of the first group's model.

The results of all groups are as shown in Table 2.

Table 2: Output displacement of all groups' model.

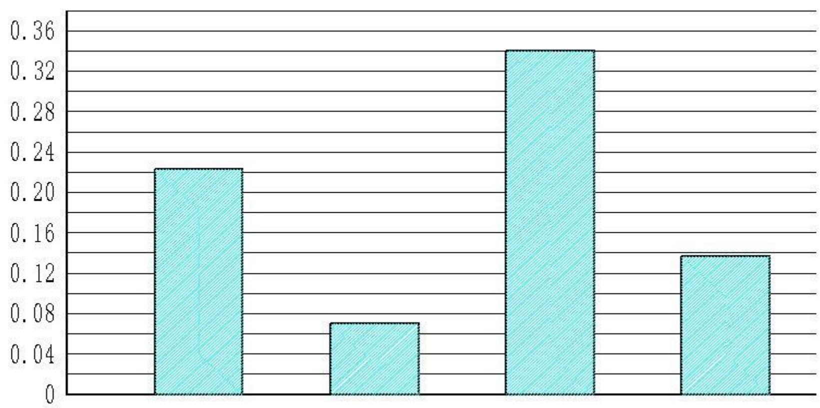
Factor and column / Scheme	A	B	C	D	Random	Displacement
	1	2	3	4	5	
1	1	1	1	1	1	0.453
2	1	2	2	2	2	0.279
3	1	3	3	3	3	0.198
4	1	4	4	4	4	0.138
5	2	1	2	3	4	0.326
6	2	2	1	4	3	0.411
7	2	3	4	1	2	0.216
8	2	4	3	2	1	0.270
9	3	1	3	4	2	0.281
10	3	2	4	3	1	0.236
11	3	3	1	2	4	0.671
12	3	4	2	1	3	0.106
13	4	1	4	2	3	0.309
14	4	2	3	1	4	0.442
15	4	3	2	4	1	0.466
16	4	4	1	3	2	0.735
K_1	0.2670	0.3423	0.5675	0.3563	0.3833	
K_2	0.3057	0.3420	0.2943	0.3778	0.3299	
K_3	0.3235	0.3878	0.2978	0.2560	0.3163	
K_4	0.4880	0.3123	0.2248	0.2443	0.3548	
R	0.2210	0.0755	0.3428	0.1335	0.0670	

6. Range Analysis

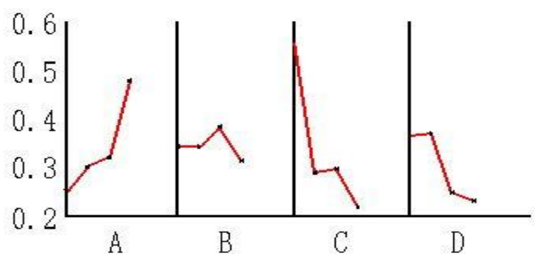
The letter R in Table 2 means the D-value between the maximum and minimum value of the same factor's K_j. It is called the range. It is the basis to divide the degree of influence and significance of factors to the aim. The bigger the R value is, the higher the degree of influence and significance of this factor is. Thus, the key factor can be ensured. K_j is the mean value of one factor at the j level.

Table 2 shows that the sequence of the value between the random column's D-value and each factor's D-value in order of magnitude is the thickness of PZT-5(factor C) , the length of PZT-5(factor A), the thickness of elastic layer(factor D), the width of PZT-5(factor B). Thus, the degree of influence and significance of these factors to the output displacement of piezoelectric actuator in order of magnitude is C, A, D, B. The value between the random column's D-value and the factor B's D-value is so small that the influence of it to the output displacement of piezoelectric actuator can be ignored.

The influence trend of each factor to the aim is as shown in Fig 3.



(a)D-value of each factor



(b) Influence trend of each factor

Fig. 3: Influence trend of each factor to the aim.

The result of the 16th group is the biggest of all results, so the preliminary selection factor level combination is A4, B4, C1, D3. According to Figure 4-(b), decreasing the magnitude of factor D can increase the output displacement of piezo- electric actuator.

7. Variance Analysis

Range analysis can't provide a certain standard to measure the significance of one factor, and it also can't distinguish the error's influence from the change of the experiment environmental conditions' to the aim. But Variance analysis can reduce these defects. Thus it is necessary to do variance analysis.

In this paper, the F-value of one factor is compared with the corresponding value of the F-Distribution Table, according to its α to degree the significance. According to Table 2, the variance square sum (SS), variance (MS), degree of freedom (DF) and F-value[6] are as shown in Table 3.

Table 3: the variance analysis table.

Variance	SS	MS	DF	F	Significance
A	0.1141	0.0380	3	10.9388	High
B	0.0116	0.0039	3	1.1165	Very low
C	0.2751	0.0917	3	26.3661	Very High
D	0.0462	0.0154	3	4.4248	low

Table 3 shows the influence degree of these factors for the output displacement of piezoelectric actuator. In order of magnitude is the thickness of PZT-5 (factor C) , the length of PZT-5(factor A), the thickness of elastic layer (factor D), the width of PZT-5(factor B). And the factor B's influence is very small.

Range analysis(qualitative analysis) is consistent with the result of Variance analysis(quantitative analysis). So the preliminary selection factor level combination is A4, B4, C1, D3. To achieve bigger output displacement, the final factor level combination is A4, B3, C1, D2 according to the result of Range analysis and the displacement contour of the actuator is shown in Fig 4.

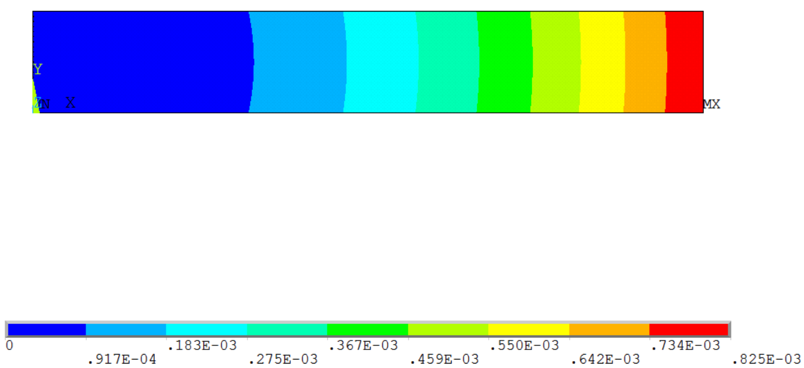


Fig. 4: the displacement contour of the piezoelectric actuator.

8. Network Model of Piezoelectric Actuator

The tip displacement of a piezoelectric actuator varies with such factor as dielectric constant, piezoelectric strain constant, piezoelectric stress constant, elastic modulus, geometry parameters, etc. When the materials of piezoelectric layers and elastic layer are determined, the design of a piezoelectric actuator involves with geometry parameters. To simplify the design process, it is necessary to know the relation between the tip displacement and geometry parameters. Herein we obtain the relationship with artificial neural network method.

Radial basis function (RBF) networks can be used for universal approximation without local minimum, so we use RBF model to describe the relationship between the tip displacement and geometry parameters. Basing on the above influence analysis of each factor, we use 66 sets of data to train network. Function newrb in Matlab is chosen to train the network. After training the RBF network, we got paramters w1, b1, w2,b2. If the input vector is X, the output of the middle layer and output layer can be expressed as follows:

$$\mathrm{Y1} = e^{-(\|w1-X\|b1)^2} \tag{1}$$

$$\mathrm{Y2} = \mathrm{w2Y1} + \mathrm{b2} \tag{2}$$

We use 4 sets of data to validate the RBF model, the result is shown in table 4. It is clear that the maximum error is less than 10%, and the model is effective. If the RBF model should be improved, more training data are needed.

Table 4: validation of the RBF model.

A	B	C	D	result from FEA	result from RBF	error
14	1.8	0.08	0.06	0.401	0.4107	2.4%
18	3.0	0.12	0.10	0.286	0.2750	-3.8%
16	2.4	0.10	0.04	0.398	0.4197	5.5%
20	3.6	0.14	0.08	0.296	0.3076	3.9%

9. Conclusion

This paper bases on four factors (the length, width and thickness of PZT-5 and the thickness of elastic layer) to investigate the output displacement of piezoelectric actuator, and the following work was carried out:

(1) Presents an optimization design method with orthogonal theory for piezoelectric actuator, and completes Range analysis and Variance analysis.

(2) Network model of piezoelectric actuator is created with RBF network.

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