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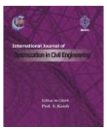

OPTIMIZATION OF PLACEMENT\VOLTAGE OF PIEZOELECTRIC ACTUATORS ON AN L-SHAPE BEAM USING PARTICLE SWARM OPTIMIZATION ALGORITHM

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ABSTRACT

In this paper, controlling the location of the tip of an L-shape beam under gravity field is investigated. The beam is covered with piezoelectric patches. The gravity filed moves the tip of beam downward and the actuators with induced voltage move the tip to the previous location. to optimize the best location and voltages for actuators, the particle swarm optimization algorithm code is developed. The results show that the best position for the most effective actuators is located at the corner of the beam. Also with considering the best location for patches, with lower induced voltage, the location of the tip of beam cab controlled. Also, the results show that with the optimum location of actuators and appropriate voltage lead to using minimum energy with the desired shape in the beam. The results are compared with those reported in previous work.

Keywords: L-shaped beam; optimization; particle swarm optimization; shape control.

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1. INTRODUCTION

Static shape control of a structure using the piezoelectric material as actuators has attracted much attention in recent years. In this area, piezoelectric actuators attached to the host plate and the strain is induced to the plate so that the shape of plate change as desired. Due to different reasons such as high price and capability of piezoelectric patches and different

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distributions of stress over objects, using more piezoelectric patches does not result in proper efficiency. In addition, identification of optimal installation locations of such materials is one of the primary problems of using these materials. Lin and Nien [1] used finite element formulation for dynamic and static modeling to control the adaptable shape of piezoelectric plates. They found out that the induced stresses affect the behavior of the plate significantly. Donthireddy and Chandrashekhara placed piezoelectrics between layers of a composite beam so as to control the shape of structure [2]. They used finite element solution to analyze the effect of piezoelectric on generated deviations and boundary conditions. Benjeddou et al. worked on finite element model to analyze the three variables: thickness drop, moderate axial displacement and relative axial displacement of core layers based on Euler–Bernoulli beam theory [3]. For this purpose, they adopted Timoshenko beam theory, placed two piezoelectric patches on both sides of the model and used piezoelectric patches between the models so as to determine the optimal status of each mode. In order to control the shape of composite beams based on deformation and effects of shear force, Eisenberger and Abramovich studied the location of piezoelectric patches on composite beams [4]. Because of high shear forces at layers of composite beam, they analyzed the width-to-length ratio of the beam at different voltage levels and controlled the model deformation. Agrawal et al. introduced finite element model for optimizing the status of the surface of a spatial sheet and minimizing its deformation using piezoelectric actuators [5]. They developed a finite element model and optimizing the location and voltage of piezoelectric actuators. Bruch et al. [6] studied on optimal location and current for application of piezoelectric patches. In their study, after controlling the shape of an elastic beam and determine the effect of location of piezoelectric patches, they investigate the different dimensions so as to reduce applied voltage to control the shape of the model. In order to control the optimal shape of smart structures, Chee et al. [7] introduced a designation similar to the voltage optimization method through heuristic and perceptual algorithms based on displacement, slopes, curves, electric input and effective anisotropy of mechanical operators. Waisman and Abramovich studied first-order shear deformation theory and used piezoelectric patches to control the shape of an aluminum beam [8]. They analyzed the effect of operators on the pin-force model and changed the size and location of piezoelectrics to determine different modes of controlling the shape of the model. Ishihara and Noda [9] considered the damping effect of transverse shear and calculated the shear force between layers through Newtonian viscosity law. They studied the shear stress generated between the layers and used natural frequencies on the model so as to control its shape. Luo and Tang [10] used piezoelectric actuators to worked on finite element simulation and adopted a method for optimization of electric potential so as to minimize the rotation of sheets and curved shaped. They consequently developed a design for controlling the shape of intended models. Adali et al. [11] changed the size and location of piezoelectric actuators so as to control the flexural deformation of a structure in the worst loading condition. They proved that their presented array is the best strategy for reducing the amount of voltage applied to actuators. Kudikala et al. [12] used genetic algorithm and introduced a finite element design for reducing the input control energy and mean squared deviation between desirable plates and actuated shapes through limiting the use of actuators. Gupta et al. [13] used actuators to increase the modal forces and offered an optimization criterion for determining the proper locations of piezoelectric actuators and controlling the shape of a beam. Golabi and Jafari [14, 15] attached

piezoelectric actuators at top and bottom of a hole in a plate and placed it under compressive strain. In addition, they placed the left and right side of the same hole under tensile stress and analyzed the concentration of stress around the hole in both models. They found out that the first mode enables direct control while the second mode enables indirect control of stress concentration around the hole. Luo and Tong [16] used topology optimization algorithm to analyze the placement of piezoelectric patches through a novel method and they obtained a proper formulation to control the model deformation. Schoeftner et al. [17] investigated on attaching the multiple piezoelectric patches on beam-shaped structures to minimize the deformation and they introduce the results for one-dimensional, 3D numerical and experimental analysis. Adali et al. worked on effects of elastic constraints and locations of piezoelectric actuators and obtained the highest bending of the elastic bonded sheet under definite and indefinite loads [18]. They concluded that optimal dimensions of actuators depend on largeness of generated movements.

In this paper, an L-shape beam is considered that all surfaces covered with piezoelectric patches. The beam is considered under the influence of its own weight. Using particle swarm optimization (PSO) algorithm, the best (minimum) voltage for piezoelectric actuators is obtained that the tip of the beam returns to its previous location. Then by deactivating the low effect piezoelectric patches, the optimum voltage for remaining patches are investigated. By continuing this procedure, the best location and voltages for piezoelectric patches are presented.

2. MODEL PROPERTIES AND SIMULATION

For implementation the particle swarm optimization algorithm, an L-shaped beam made of aluminum is considered. The vertical and horizontal length of the beam are 0.114 mm and 0.224mm respectively with 0.002mm thickness. The beam is fixed at the bottom and deflect under its weight. The surface of the beam is covered by 30 paired piezoelectric patches, 20 paired on vertical section and 10 paired on horizontal section (top and bottom). The piezoelectric patches are 0.01*0.01 mm squared with 0.001mm thickness made of PZT-4 material. The material properties of the beam and piezoelectric patches are presented in Table 1.

The tip of L-shape beam under its weight moved down and by induced voltage to the piezoelectric patches, the shape of the beam can be controlled and with proper voltage, the tip of the beam can be moved to its initial position. But the best condition is that with a minimum voltage, the tip of beam moved. To achieve the minimum voltage and the fact that witch piezoelectric patches have more effect on moving the tip of the beam, particle swarm optimization algorithm is used. For this purpose, a code is developed in Matlab for PSO algorithm and to find the location of the tip of the beam, finite element software is used to find the objective function for Matlab PSO code.

At the first step, the sum of all voltages for all piezoelectric patches is minimum according to PSO algorithm. Then, by comparing the voltages, the voltage of non-significant piezoelectric patches (piezoelectric with very low voltage) are eliminated and the optimization algorithm is implemented to find the minimum voltage for remaining piezoelectric patches. This procedure is repeated so that the most effective piezoelectric patches are determined.

Table 1: Material properties for beam and piezoelectric patches

Property of Aluminum				
Density		Young's modulus	Poisson's ratio	
2700		68.9e9	0.33	
Piezoelectric properties pzt-4(strain)				
E1 12	E1 13	E1 23	E2 11	E2 22
0	0	12.71	-5.207	15.08
E2 33	E2 12	E2 13	E2 23	E3 11
-5.207	0	0	0	0
E3 22	E3 33	E3 12	E3 13	E3 23
0	0	12.71	0	0
Piezoelectric mechanical properties pzt-4				
D1111		D1122	D2222	
139e9		74.28e9	115.4e9	
D1133		D2233	D3333	
77.84e9		74.28e9	139e9	
D1212		D1313	D2323	
25.64e9		82.24e9	25.64e9	
Dielectric properties pzt-4				
D11		D12	D22	
6.752 e -9		0	5.872 e -9	
D13		D23	D33	
0		0	6.752 e -9	

3. MATHEMATICAL MODEL

In a plate consists of a number of plies bonded together, each ply has a special principal orientation. The displacement field based on first-order shear theory is considered as:

$$u(x,y,z) = u_0(x,y) + z\theta_x(x,y) \quad (1)$$

$$v(x,y,z) = v_0(x,y) + z\theta_y(x,y) \quad (2)$$

$$w(x,y,z) = w_0(x,y) \quad (3)$$

where, "u_0", "v_0" and "w_0" are the displacement components at mid plane of the plate in the x, y and z direction respectively. It is assumed that the displacements vary linearly along the thickness.

Using the isoparametric relationships, the displacement and coordinates of the elements are defined as:

$$x = \sum_{i=1}^{n} N_i x_i \ , \qquad y = \sum_{i=1}^{n} N_i y_i \quad (4)$$

where "n" is the number of nodes in elements and N_i is the element shape functions. For

coupling the electric field vector and the elastic field, the linear piezoelectric constitutive equation can be expressed as:

$$\{D\} = [e]\{S\} + [\epsilon^S]\{E\} \quad (5)$$

$$\{T\} = [c^E]\{S\} - [e]^T\{E\} \quad (6)$$

with $[e]$ is the piezoelectric stress matrix, $[\epsilon^S]$ is the dielectric matrix, $[c^E]$ is the elastic constant matrix for piezoelectric material, $\{S\}$ is the strain vector and $\{E\}$ is the electrical field vector. The piezoelectric material is polarized in direction of thickness of plate.

To derive the equation for plate bounded with piezoelectric patches, Hamilton's principle was used. The electromechanical system based on this principle is presented as:

$$\int \delta(T - U + W_{ext})dt = 0 \quad (7)$$

where "T", "U" and "W_{ext}" are the kinetic energy, the potential energy and the work done by external forces. These parameters are described as"

$$T = \int \frac{1}{2}\vartheta\{\dot{q}\}^T\{\dot{q}\}dv \quad (8)$$

$$U = \int \frac{1}{2}[\{S^T\}\{T\} - \{E\}^T\{D\}]dv \quad (9)$$

$$W_{ext} = \sum \{q\}^T\{F_c\} \quad (10)$$

where $\{\dot{q}\}, \vartheta, \{T\}, \{D\}$ and $\{F_c\}$ are velocity vector, the mass density, the stress vector, electric displacement vector and the external applied force vector respectively in the volume of the structure.

4. IMPLEMENTATION THE PSO ALGORITHM

Particle swarm optimization (PSO) is an optimization algorithm based on the colony behaviors that presented by Kennedy and Eberhart [19]. In this algorithm, each bird (particle) worked with three parameters: position, velocity and fitness function.

In this algorithm, at the first step, the birds are located randomly in the space of solution and the velocity of birds is considered as zero at the first iteration. During the next steps, each bird wanders in the design space and saved the best previous location. The particles communicate their information to the other particles and affect the location and velocity of the other particles. The main phase for implementation the PSO algorithm are presented as [20]:

1. Assume the number of birds "N".

2. The initial position for each particle is considered randomly in the lower and upper band as "$X_1, X_2, ..., X_n$". The position of jth particle and its velocity in ith iteration are denoted as $X_j^{(i)}$ and $V_j^{(i)}$, respectively.
3. Evaluate the objective function for each particle as $f(X_1^{(0)}), f(X_2^{(0)}), ..., f(X_N^{(0)})$.
4. set the iteration number as $i=1$ and update the velocity of all particles. The zero value for the initial velocity of all particles is assumed.
5. In the ith iteration, find the historical best position of particles $X_j^{(i)}$ as $P_{Best,j}$, with the highest value of the function $f(X_j^{(i)})$, encountered by bird j in all the previous iterations.
6. In the ith iteration, find the historical best value of $X_j^{(i)}$ as G_{Best}, with the highest value of the objective function $f(X_j^{(i)})$, encountered in all the previous iterations by any of the N birds.
7. Find the velocity of bird j in the ithiteration as:

$$V_j^{(i)} = V_j^{(i-1)} + c_1 r_1 \left(P_{Best,j} - X_j^{(i-1)}\right) + c_2 r_2 \left(G_{Best} - X_j^{(i-1)}\right);\ j = 1,2,..., N \tag{11}$$

where, c_1 and c_2 are the individual and social learning memory respectively and are usually assumed to be 2. and are random numbers in the range 0 and 1.

8. Find the position of the jth particle in ith iteration as

$$X_j^{(i)} = X_j^{(i-1)} + V_j^{(i)};\ j = 1,2,..., N \tag{12}$$

9. Evaluate the objective function of particles as $f(X_1^{(i)}), f(X_2^{(i)}), ..., f(X_N^{(i)})$
10. If the positions of all particles converge to the same values, the algorithm is converged. If the convergence criterion is not satisfied, step 5 is repeated and $i = i+1$.

The process for implementing the PSO algorithm on the problem is presented in Fig. 1.

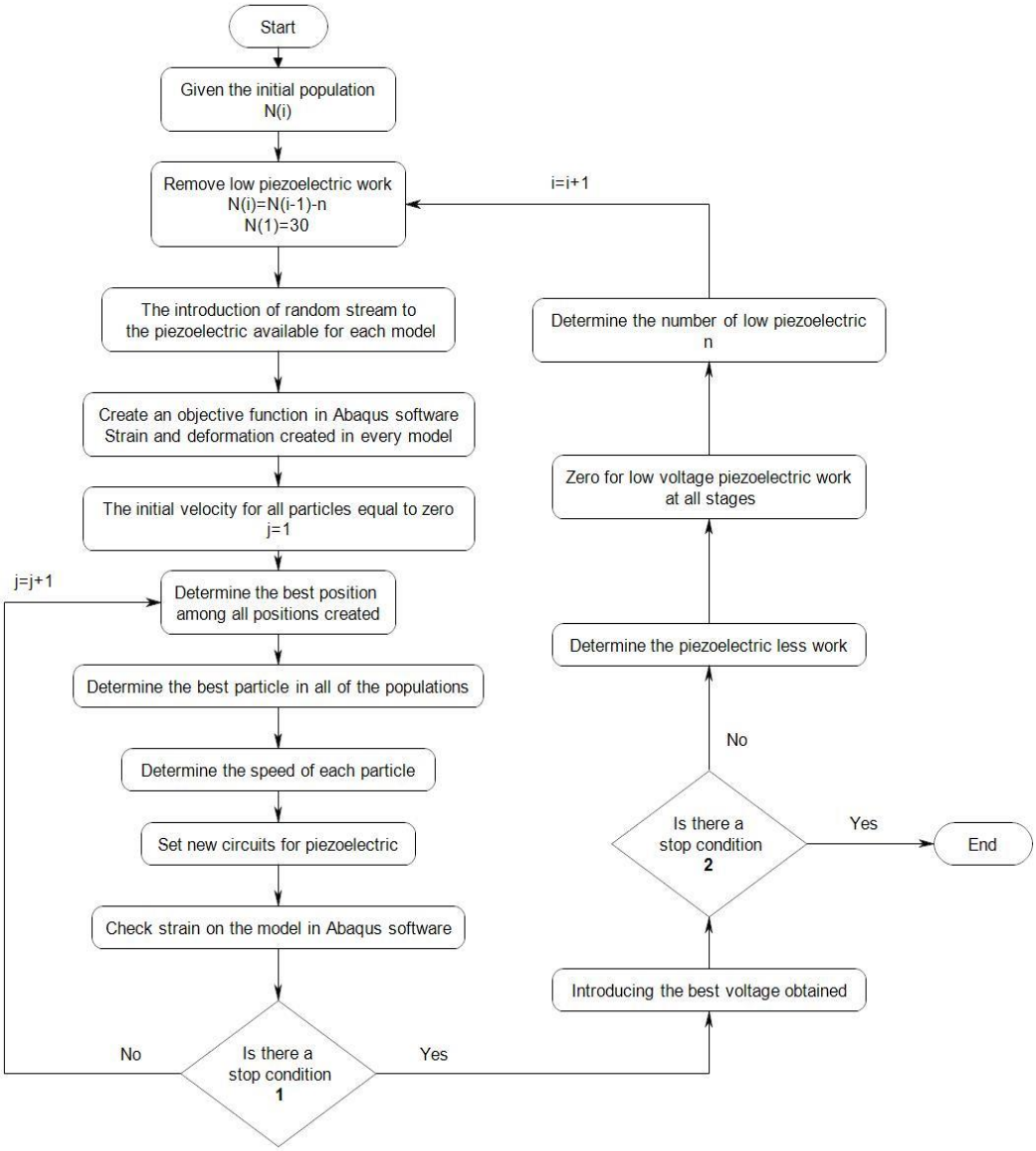

Figure 1. Flowchart for particle swarm optimization algorithm and problem definition

5. RESULTS AND DISCUSSION

After implementing PSO algorithm and optimization the problem, the active piezoelectric actuators and their voltage in each step are obtained. The results for voltage of piezoelectric actuators in the first step (for example) are presented in table 2 and the results for active\inactive piezoelectric patches are presented in eight steps in Fig. 2. It can be seen that the piezoelectric located near the tip of the beam and near the support point of the beam have been inactivating sooner. In Fig. 2, the red and white patches are active and inactive piezoelectric patches, respectively.

Table 2: The voltage of piezoelectric actuators in first step (Voltage/Maximum Voltage)

Piezo 1	Piezo 2	Piezo 3	Piezo 4	Piezo 5	Piezo 6	Piezo 7	Piezo 8	Piezo 9	Piezo 10
0.1378	0.7533	0.026-	0.4789	0.1978	0.009-	-0.189	-0.037	0.1011	0.1678
Piezo 11	Piezo 12	Piezo 13	Piezo 14	Piezo 15	Piezo 16	Piezo 17	Piezo 18	Piezo 19	Piezo 20
0.0033	0.8456	0.3822	0.8756	0.7544	0.2867	0.2544	0.1244	0.7311	0.310
Piezo 21	Piezo 22	Piezo 23	Piezo 24	Piezo 25	Piezo 26	Piezo 27	Piezo 28	Piezo 29	Piezo 30
-0.004	-0.026	0.7189	0.5411	0.450	0.1033	0.4244	-0.257	0.1733	-0.198

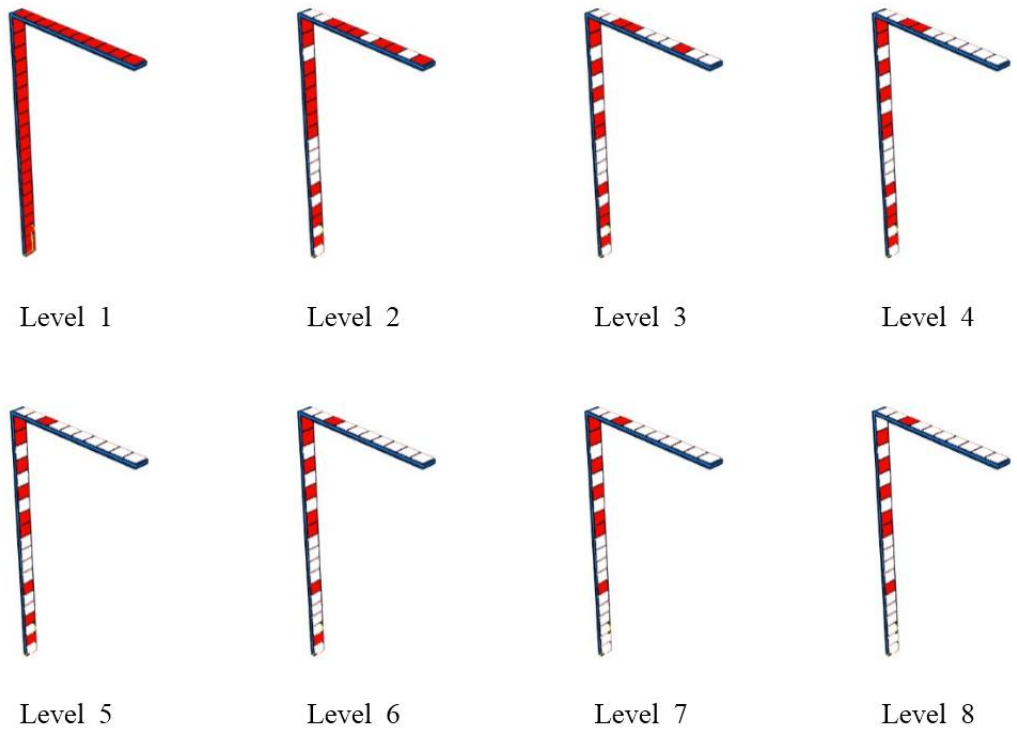

Figure 2. Location of active piezoelectric patches in each step

Fig. 3 shows the displacement of the tip of the beam according to the iteration in the optimization algorithm. It can be seen that in all steps, the patches can return the tip of the beam to the original location but with increasing the number of patches, it takes longer to achieve the best voltage.

Fig. 4 shows the total voltage for all piezoelectric patches according to the iteration for each step. It can be seen that except step one, for all other steps by increasing the iteration, the applied total voltage for piezoelectric patches are increased and almost in 80 iterations the method is converged.

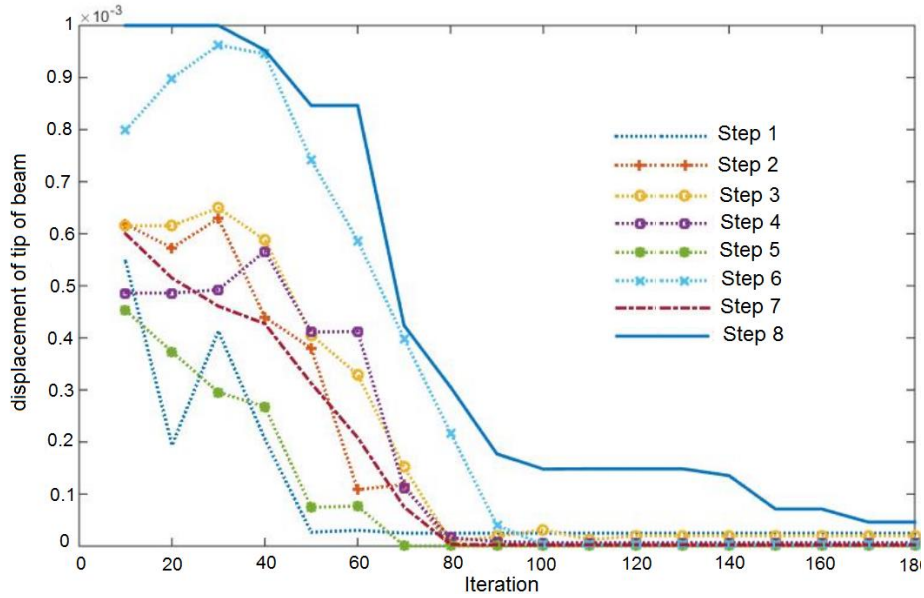

Figure 3. The deformation and strain rate of the model during the analysis

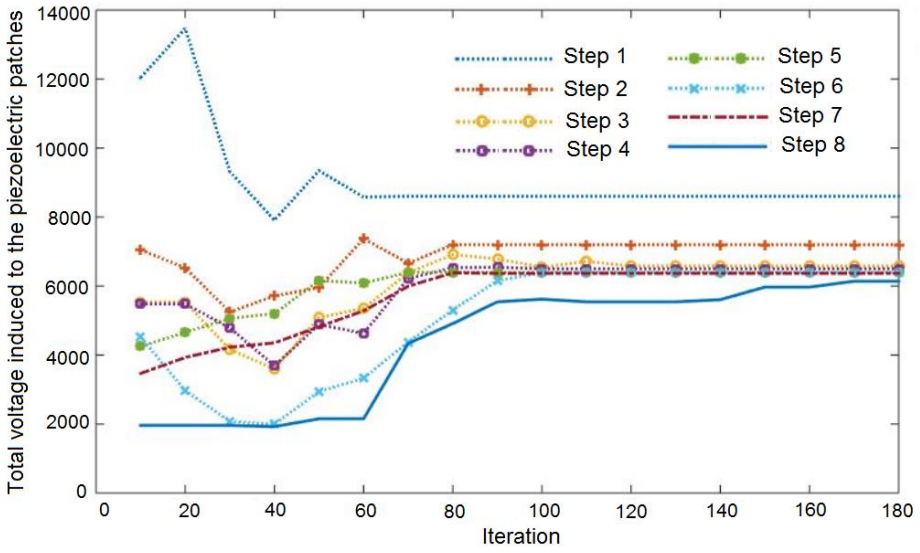

Figure 4. Total voltages applied to patches according to the iteration

But it should be mentioned that the purpose is to achieve the minimum voltage for piezoelectric patches and the tip of the beam is also returned to the first location. So the convergence criteria should consider the location of the tip of beam and voltage simultaneously to achieve the best results. For this purpose, the sum of displacement of the beam and the total voltage induced in all piezoelectric patches are considered as the objective function for particle swarm optimization algorithm.

Fig. 5 shows the results for considering the objective function (considering the location of the tip of the beam and total voltage) according to the iteration.

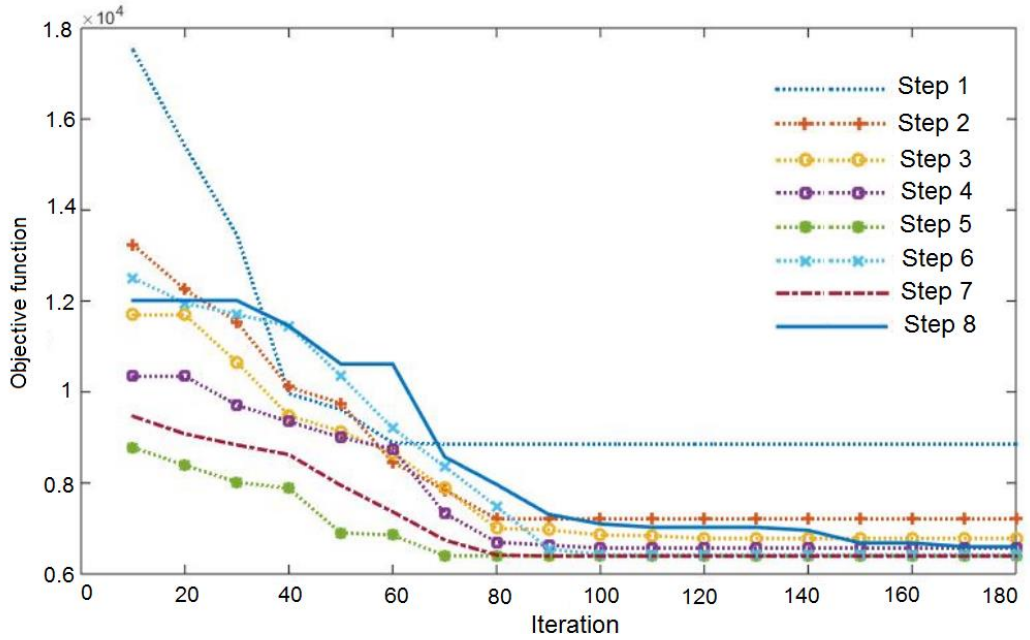

Figure 5. The objective function (displacement of the tip of the beam and total voltage) with iteration

Fig. 6 shows the number of piezoelectric patches in each step and the total induced voltage. It can be seen that in each step, the voltage increased almost linearly, but the rate of decreasing the active piezoelectric patches is decreased in each step. It should be considered that by this procedure it can declare that with about 15 pair piezoelectric patches, the minimum required patches is obtained. Also, this number of patches have more voltage to control the beam and according to Fig. 2, the best location of patches is specified around the corner of the beam.

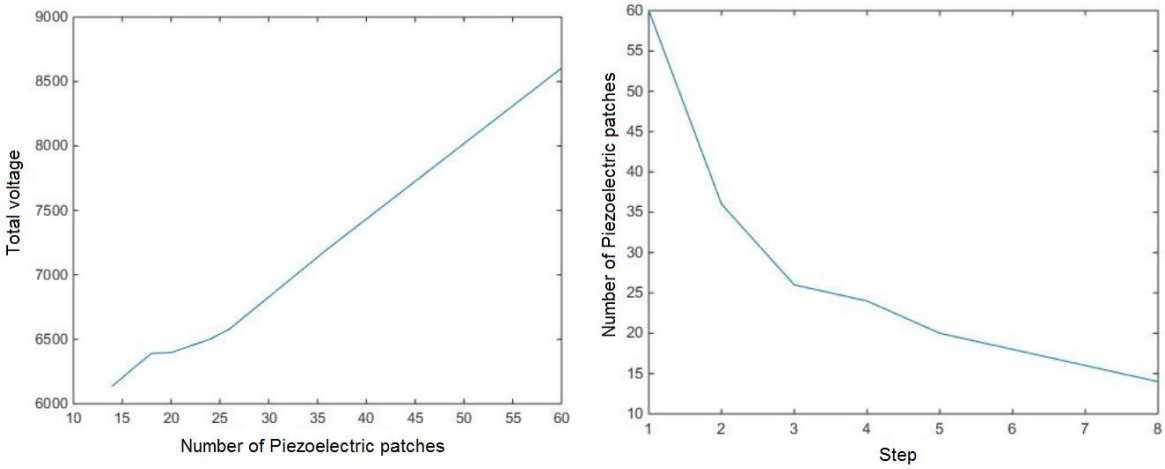

Figure 6. Number of piezoelectric patches in each step and total induced voltage

6. VALIDATING THE RESULTS

To validate the results and the procedure presented in this paper, the results compare with those reported in previous papers. For this purpose, a plate covered with piezoelectric patches are considered. The material and dimensions are considered as those considered with Luo and Tong [16]. The plate is clamped at the edge and the displacement of another edge of the plate is considered to compare the results. The results that presented in reference [16] and this paper are presented in Fig. 7 and table 3. It can be seen that the results have good agreement with those reported in the previous paper.

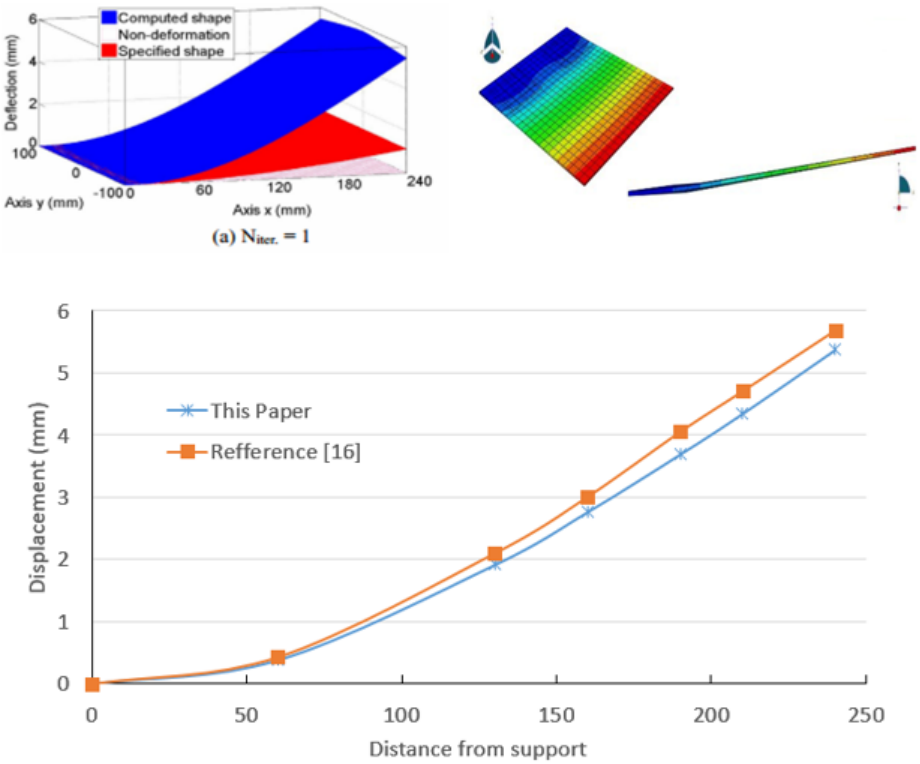

Figure 7. comparing the results in this paper and reference [16]

Table 3: Validating the results of presented paper and reference [16]

Control Point	**Displacement-This Paper (mm)**	**Displacement-Reference** (16) **(mm)**	**Error**
0	0	0	0
60	0.43	0.38	11.6 %
130	2.10	1.91	9 %
160	3.01	2.76	8.3 %
190	4.06	3.69	9.1 %
210	4.71	4.34	7.8 %
240	5.69	5.37	5.6 %

7. CONCLUSION

In this paper, an L-shape beam covered with piezoelectric patches is considered. The gravity filed moves the tip of beam downward and the voltages induced to the actuators move the tip to the first location. The voltage and location of actuators are optimum with particle swarm optimization algorithm. The results show that the best position for the most effective patches are located at the corner of the beam and with optimizing the voltage and location of patches, with minimum patches and induced voltage the location of the tip of the beam is controlled. Also, the results show that with the optimum location of actuators and appropriate voltage the shape of the beam can be controlled. The results are compared with those reported in previous work.

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