**Structural Engineering and Mechanics**, *Vol. 52, No. 6 (2014) 1209-1224*
DOI: http://dx.doi.org/10.12989/sem.2014.52.6.1209 

# A modified multi-objective elitist-artificial bee colony algorithm for optimization of smart FML panels

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*(Received December 11, 2013, Revised August 4, 2014, Accepted August 20, 2014)*

**Abstract.** In Current paper, the voltages of patches optimization are carried out for minimizing the power consumption of piezoelectric patches and maximum vertical displacement of symmetrically FML panels using the modified multi-objective Elitist-Artificial Bee Colony (E-ABC) algorithm. The voltages of patches, panel length/width ratios, ply angles, thickness of metal sheets and edge conditions are chosen as design variables. The classical laminated plate theory (CLPT) is considered to model the transient response of the panel, and numerical results are obtained by the finite element method. The performance of the E-ABC is also compared with the PSO algorithm and shows the good efficiency of the E-ABC algorithm. To check the validity, the transient responses of isotropic and orthotropic panels are compared with those available in the literature and show a good agreement.

**Keywords:** smart fiber metal laminated panel; modified elitist-artificial bee colony algorithm

## 1. Introduction

Lightweight composite materials are extensively used in various branches of engineering, in particular in the aerospace industry due to its superior performance. FMLs consist of alternating layers of reinforced polymeric composites and metal sheets (aluminium, magnesium and/or titanium) in a way that metal sheets are outer layers protecting the inner composite layers without taking the poor fatigue strength of metal sheets and the poor impact strength of composite layers.

Several researchers have reported different studies on vibration reduction and active vibration control of plates using piezoelectric sensors and actuators. Lee (1990) described theory of laminated piezoelectric plates with governing equations and reciprocal relations for the design of distributed sensors/actuators. Onoda and Hanawa (1993) used the genetic and simulating annealing methods to choose the optimal locations of the actuators in static shape control. Koconis *et al*. (1994) developed a solution scheme to find the optimal control voltages by minimizing an error function between the deformed shape and the desired shape. Lam *et al*. (1997) and Moita *et al*. (2005) developed finite element models, respectively based on the classical and higher order theories, for the active control of composite plates containing piezoelectric sensors and actuators,

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http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

using the Newmark method, to calculate the dynamic response of laminated structures. Han and Lee (1999) used genetic algorithms (GA) to find suitable locations of piezoelectric sensors and actuators of a cantilevered composite plate with considerations of controllability, observability and spillover prevention. Significant vibration reduction for the first three modes (controlled modes) has been achieved using the coupled positive position feedback in the vibration control experiment. Loja *et al*. (2001) applied a family of higher order B-spline finite strip models to the static and free vibration analysis of piezolaminated plates, with arbitrary shape and lay-ups, loading and boundary conditions. Garcia Lage *et al*. (2004) used a finite element formulation based on Reissner mixed variational principle for the analysis of piezolaminated plate structures. Robaldo *et al*. (2006) proposed a finite element formulation for the dynamic analysis of laminated plates embedding piezoelectric layers based on the principle of virtual displacements (PVD) and an unified formulation. Montazeri *et al*. (2008) utilized PSO to find the number, position and size of PZT sensors and actuators for active noise and vibration control of a simply supported laminated thin plate. They used the Hankel singular values of the state-space model of the system as the cost function to obtain the positions such that the closed-loop system is able to damp the maximum number of modes with an acceptable control effort and minimum complexity of the control system. Kang and Tong (2008) optimized the topologies of PZT actuators and control voltage simultaneously by a method of moving asymptotes. Julai and Tokhi (2010) used genetic algorithm and particle swarm optimization for vibration suppression of flexible plate structures with all edges clamped. They designed the controllers based on direct optimization of the location of the detector and secondary source, and the controller parameters based on minimizing the MSE level of the error signal. Kapuria and Yaqoob Yasin (2013) examined the efficacy of directional actuation and sensing using piezoelectric fiber-reinforced composite (PFRC) actuators and sensors in active vibration suppression for the first time for smart fiber metal laminate (FML) plates.

In the present paper, power consumption and vertical displacement optimization of symmetrically smart FML panels is studied using a modified multi-objective Elitist-Artificial Bee Colony (E-ABC) algorithm. In order to reduce the calculation time, the elitist strategy is used in Artificial Bee Colony algorithm. The design variables are the voltages of patches, panel length/width ratios and edge conditions. The performance of the E-ABC is compared with the PSO algorithm and shows the good efficiency of the E-ABC algorithm.

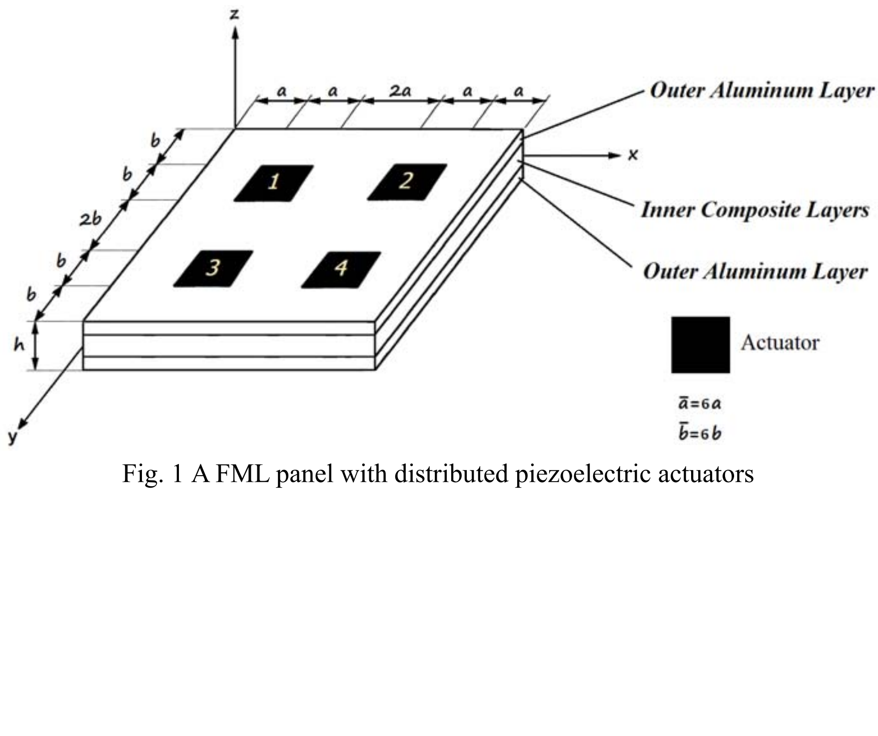


Fig. 1 A FML panel with distributed piezoelectric actuators

## 2. Formulation of the optimization problem

Fig. 1 shows a FML panel ($\bar{a} \times \bar{b} \times h$) with distributed piezoelectric actuators that are bonded on the surface of the panel. The results given in this paper are those for thin symmetrically FML panels. They have been determined through the use of classical laminated plate theory (CLPT) and, thus, the effects of shear deformation through the laminate thickness are precluded in this study. The governing equations are obtained from the principle of virtual work and further adapted to finite element formulations.

Based on the classical laminated plate theory (CLPT), the displacement fields for a FML composite panel are given as (Jones 1975, Vinson and Sierakowski 1986)

$$\begin{aligned}
\bar{u}(x,y,z,t) &= u(x,y,t) - z\frac{\partial w(x,y,t)}{\partial x} \\
\bar{v}(x,y,z,t) &= v(x,y,t) - z\frac{\partial w(x,y,t)}{\partial y} \\
\bar{w}(x,y,z,t) &= w(x,y,t)
\end{aligned} \tag{1}$$

where $\bar{u}, \bar{v}$ and $\bar{w}$ are components of displacement at the arbitrary point, whilst $u$, $v$ and $w$ are corresponding ones on the middle surface ($z$=0).

The Von Karman linear strain-displacement relations are expressed as

$$\bar{\varepsilon} = \begin{Bmatrix} \bar{\varepsilon}_x \\ \bar{\varepsilon}_y \\ \bar{\gamma}_{xy} \end{Bmatrix} = \begin{Bmatrix} \bar{u}_{,x} \\ \bar{v}_{,y} \\ \bar{u}_{,y} + \bar{v}_{,x} \end{Bmatrix} \tag{2}$$

where $\bar{\varepsilon}$ is the in-plane strain vector.

Substituting Eq. (1) into Eq. (2), the in-plane strain vector is expressed as

$$\bar{\varepsilon} = \varepsilon + z\psi = \begin{Bmatrix} u_{,x} \\ v_{,y} \\ u_{,y} + v_{,x} \end{Bmatrix} + z\begin{Bmatrix} -w_{,xx} \\ -w_{,yy} \\ -2w_{,xy} \end{Bmatrix} \tag{3}$$

where $\varepsilon$ and $\psi$ are the in-plane strain vector at the mid-plane and the curvature strain vector, respectively.

The linear piezoelectric constitutive equations coupling the elastic and electric fields can be, respectively, expressed as the direct and converse piezoelectric equations as (Elshafei 1996)

$$\{D\} = [e]^T\{\bar{\varepsilon}\} + [\in]\{E\} \tag{4a}$$

$$\{\bar{\sigma}\} = [\bar{Q}]\{\bar{\varepsilon}\} - [e]\{E\} \tag{4b}$$

where $\{D\}$ is the electric displacement, $[e]$ is the piezoelectric stress coefficient matrix, $[\in]$ is the permittivity matrix, $\{E\}$ is the electric field intensity, $\{\bar{\sigma}\}$ is the in-plane stress vector and $[\bar{Q}]$ is the plane-stress stiffness coefficients matrix.

We assume that the electric field vector $\{E\}$ can be defined by the electrical potential $\phi$ as

$$\{E\} = -\nabla \phi \tag{5}$$

Since the thickness of the piezoelectric layers is very small, it is reasonable to assume that the electric potential functions yielding zero potential at the interface between the actuator and laminated substructure and provide a linear variation across the thickness of the actuator layer.

To derive dynamic equations of motion for the FML panels with integrated piezoelectric actuators, we use Hamilton's principle

$$\delta \int_{t1}^{t2} [T - U + W]\, dt = 0 \tag{6}$$

where $T$ is the kinetic energy, $U$ is the strain energy, and $W$ is the work done by the applied forces.

To account for the actuator's mass and stiffness, the piezoelectric layers are treated as other layers with different material properties in deriving the dynamic equations of motion.

The general expression for the element kinetic energy is

$$T = \frac{1}{2} \rho h \iint \left\{ \dot{u}^2 + \dot{v}^2 + \dot{w}^2 \right\} dxdy \tag{7}$$

The strain energy can be written as

$$U = \frac{1}{2} \iiint [\{\bar{\varepsilon}\}^T \{\bar{\sigma}\} - \{E\}^T \{D\}] dV \tag{8}$$

The work done by the applied forces can be expressed in the form

$$W = \iint \{d\}^T \{f\} dxdy \tag{9}$$

where $d$ is the column matrix of element freedoms and $f$ being the column matrix of forces at reference lines, which corresponds to d. Of course, the only non-zero entries in $f$ correspond to $w$ values in $d$ in view of the fact that the loading acts in the $z$ direction.

Substituting Eqs. (7)-(9) into Eq. (6) and using Eqs. (3)-(5) the dynamic matrix equation can be written as (Chandrashekhara and Agarwal 1993)

$$[M^e]\{\ddot{d}\} + [K^e]\{d\} = \{F^e\} + \{F_v^e\} \tag{10}$$

where $[M^e]$, $[K^e]$, $\{F^e\}$ and $\{F_v^e\}$ are the element mass matrix, the element elastic stiffness matrix, the external mechanical force vector and the electrical force vector, respectively.

For the whole structure, assembling the element equations gives the global dynamic equation

$$[M]\{\ddot{\bar{d}}\} + [K]\{\bar{d}\} = \{F\} + \{F_v\} \tag{11}$$

where $[K]$, and $[M]$ are the square symmetric, positive-definite structure stiffness and consistent mass matrices and $\{\bar{d}\}$ is a vector, which includes the degrees of freedom for the whole structure.

To obtain transient response of the plate for the total time, Newmark's direct integration technique is used. This technique involves parameters $\gamma$ and $\delta$ that control the accuracy and stability of the technique. The choice of $\gamma$=0.5 and $\delta$=0.25corresponds to a constant average-acceleration method, which is known to give an unconditionally stable algorithm in linear problems.

In this paper, our goal is to seek the voltage distribution of piezoelectric actuators that minimize the maximum vertical displacement of panel ( $\overline{w}^{\max imum}$ ) and energy consumption.

The energy consumed by the piezoelectric actuators is abstractly defined as (Sun and Tong 2003, Kang and Tong 2008)

$$E_k = z_0 V_k^T V_k \quad , \quad k=1\ldots4 \tag{12}$$

where $V_k$ is the voltage of piezoelectric patches and $z_0$ is a weighting coefficient representing electric conductance for the actuators ($z_0$=1).

The optimal design problem can be stated as follows

$$\begin{array}{lll} \textit{Find} & V=(V_1, V_2, V_3, V_4) & \\ \textit{Minimize} & \overline{w}^{\max imum} \ \ \textit{and} \ \sum_{k=1}^{4} E_k & \\ \textit{Subject to} & -400 \le V_P \le 400 & , \quad P=1\ldots4 \end{array} \tag{13}$$

The optimal voltages are searched with the modified E-ABC algorithm.

In the multi-objective optimization of FML panels, the objective functions combined with each other through the weighted summation method. The obtained single objective function is then optimized using modified E-ABC algorithm. To simultaneously minimize the maximum vertical displacement of panel and energy consumption, the objective function is considered in the form *f(V)* as a function of voltage of piezoelectric patches which is defined as (Sadr and Ghashochi Bargh 2012)

$$f_i(V) = W_1 \frac{(w^{\max imum})_i}{\sum_{i=1}^{s} (w^{\max imum})_i} + W_2 \frac{(\sum_{k=1}^{4} E_k\ )_i}{\sum_{i=1}^{s} (\sum_{k=1}^{4} E_k\ )_i} \tag{14}$$

where $W_1$ and $W_2$ are the weighting coefficients summing the two objective functions to have a single fitness function and $s$ is number of the best memorized solutions. In this paper, the optimization results are given for $W_1$=0.5 and $W_2$=0.5.

As seen, the roulette wheel scheme is employed in the objective function, in which each solutions ( $\overline{w}^{\max imum}$ and energy consumption) is assigned a value within the range [0, 1].

## 3. Modified Elitist-Artificial bee colony algorithm

The ABC algorithm is one of the most recently defined algorithms by Dervis Karaboga (2005), motivated by the intelligent behavior of honey bees. The artificial bee colony consists of three types of bees: employed bees, onlookers and scouts. Each food source corresponds to a solution to the optimization problem and the amount of nectar of a food source to the fitness of the solution. Employed bees exploit their food sources by conducting a local search in their neighbourhood. Onlooker bees are recruited to the food sources based on their quality values. High quality solutions have higher probability value for being selected. A local search is again conducted by an onlooker bee in the neighbourhood of the solutions chosen depending on the probability value. If a solution cannot be improved through a predetermined number of cycles, it is abandoned and a new random solution is produced to replace it.

In this study, ABC algorithm (Fiouz *et al*. 2012, Ozturk and Durmus 2013) is used as the optimization method and to improve the quality of the solution, the elitist strategy is used in the algorithm. In this strategy, the onlooker bee operator generates a more diverse set of solutions near the best solutions so far until the end of each cycle in the algorithm. From this modification on the onlooker bee, the term Elitist is added to the name of this version of the ABC. A parameter is defined to control the amount of generation of solutions near the best solutions. In the algorithm, this parameter is assumed 20% of the best solutions. Thus, the same number of solutions will always be generated from a solution. As the value of parameter increases, causing the ABC search to become more localized. Thus, using large value of parameter may prevent the ABC from finding the global optimum. A selection procedure based on the fitness function picks best food sources and replaces sources in algorithm. In addition, the E-ABC preserves only the best design in every cycle.

The elitist strategy can be stated as follows (Mezura-Montes and Velez-Koeppel 2010)

$$v_l^g = x_l^g + \phi_{ij}(x_l^g - x_{lj}) \tag{15}$$

where $j \in \{1, 2, ..., D\}$ is random generating index, $l$ is equal to the number of the best solutions depending on the value of defined parameter and $D$ denotes the number of optimization parameters. $v_l^g$, $x_l^g$ and $x_{lj}$ are a set of new feasible solutions near the best solutions, the best solutions and the feasible solutions, respectively. $\phi_{ij}$ is random number between [0,1]

Also, the search form of ABC is good at exploration but poor at exploitation. Therefore, to improve the performances of ABC, we also propose to make two other major changes by introducing the inertia weight and acceleration coefficient to modify the search process. The use of the inertia weight and acceleration coefficient provides a balance between global and local exploration and exploitation, and results in fewer iterations on average to find a sufficiently optimal solution.

The operation process can be expressed as the following form (Li *et al*. 2012)

$$v_{ij} = w.x_{ij} + 2(\phi_{ij} - 0.5)(x_{ij} - x_{kj})\Phi \tag{16}$$

where $k \in \{1, 2, ..., SN\}$ is random generating index, but $k$ must be different from $i$ and $SN$ is the size of food sources. $v_{ij}$ is the new modified feasible solution that depending on its previous solution $x_{ij}$. $w$ is the inertia weight which controls impacts of the previous solution $x_{ij}$. $\Phi$ is the acceleration coefficient that could control the maximum step size. However, if the global fitness is very large, bees are far away from the optimum values. So a big correction is needed to search the global optimum solution and then w and $\Phi$ should be bigger values. Conversely, only a small modification is needed, then $w$ and $\Phi$ must be smaller values. So in order to further improve the search efficiency of the bees, $w$ and $\Phi$ are decreased linearly from 0.9 to 0.4 during a run.

The convergence rate of objective function with the number of generations for E-ABC and PSO for symmetrically FML 8-layered square panel with $[Al/0/0/0]_S$ stacking sequence is shown in Fig. 2(a) and (b). It is clear from Fig. 2(a) and (b) that, for the optimization problem considered, E-ABC converges at a faster rate (around 6 generations) compared to that for PSO (around 8 generations) with the same initial populations. In addition, it is concluded that using of E-ABC provides a much higher convergence and reduced the CPU time in comparison with the PSO.

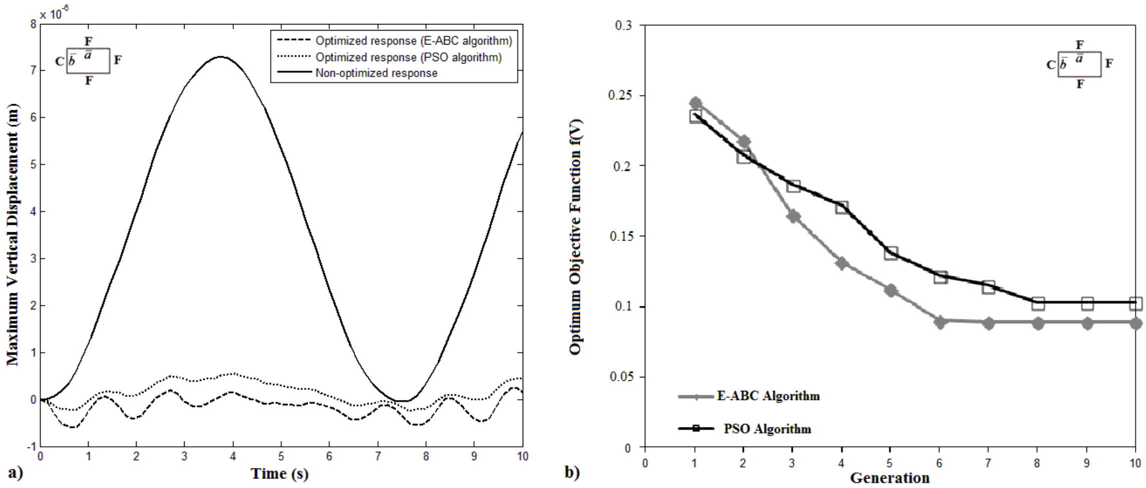


Fig. 2 Comparison of the E-ABC and PSO results for CFFF edge condition for symmetrically FML 8-layered square panel with the same generations

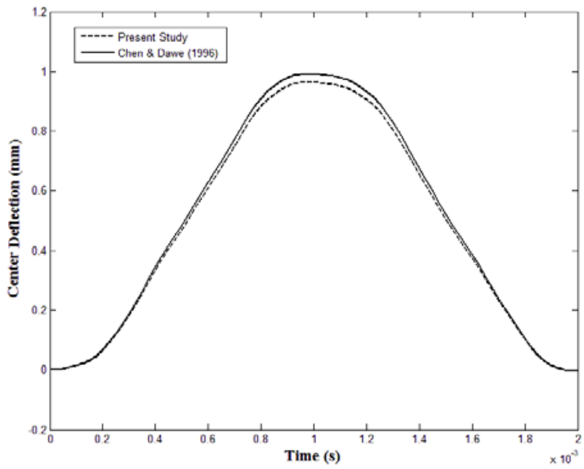


Fig. 3 Response of isotropic, square, simply supported panel to uniformly distributed step load

## 3. Results and discussions

The maximum vertical displacement and energy consumption of hybrid laminates is minimized for different panel aspect ratios, ply angles, number of layers, boundary conditions and thickness of metal sheets using the piezoelectric patches.

The laminates are symmetric and made of AS/3501 graphite/epoxy material (Vinson and Sierakowski 1986) (inner composite layers) and aluminum alloy 2024-T3 (Shooshtari and Razavi 2010, Ghashochi-Bargh and Sadr 2013) (outer aluminum layers). The material properties of the laminas and piezoelectric patches (Sun and Huang 2000) are given as below:

Composite layers: $E_1=138$ GPa, $E_2=8.96$ GPa, $G_{12}=7.1$ GPa, $\upsilon_{12}=0.3$, $\rho=1520$ kg/m$^3$

Aluminum layers: $E=72.4$ GPa, $\upsilon=0.33$, $\rho=2700$ kg/m$^3$

Piezoelectric patches: $E_1 = E_2 = 20$ GPa, $G_{12} = 0.775$ GPa, $\upsilon_{12} = 0.29$, $\rho = 1800$ kg/m$^3$,

$e_{31} = e_{32} = 0.046$ C/m$^2$, $e_{31} = 0$ C/m$^2$, $\in_{33} = 0.1062 \times 10^{-9}$ F/m

Each of the lamina is assumed to be same thickness ($h/\overline{a} = 0.01$). In FML panels with the double-thickness of aluminum layers, the thickness of composite layers are as mentioned before.

The transient responses of isotropic and orthotropic panels are compared with the results of numerical values carried out by Chen and Maleki, respectively.

Fig. 3 shows center deflection of square isotropic panel (100 mm×100 mm×1mm) under uniformly distributed step load of intensity $q$=0.0231 MPa over the whole panel surface with all edges simply supported. It is seen that the present result has excellent agreement with the one obtained by Chen and Dawe (1996). The material properties used in this example are:

$E = 205$ GPa, $\upsilon = 0.3$, $\rho = 7900$ kg/m$^3$

Fig. 4 illustrates time histories of non-dimensional center deflection of laminated square plates $[30/-30]_S$ under conventional blast load with the clamped edges. It is seen that there is a good agreement between results of present approach and the published paper (Maleki *et al*. 2012), for the transient responses of orthotropic panel. In this example, the following geometrical and material properties are used:

$\overline{a} = \overline{b} = 1.27\,m$, $h = 0.0254\,m$, $\rho = 1610$ kg/m$^3$

$E_1 = 131.69$ GPa, $E_2 = 8.55$ GPa, $G_{12} = 6.67$ GPa, $\upsilon_{12} = 0.3$

The conventional blast loading function and non-dimensional center deflection are defined as

$$q(x, y, t) = q_0 \left(1 - \frac{t}{t_2}\right) e^{-\alpha_1 t / t_2} \tag{17}$$

$$\overline{w} = 100 w \left(\frac{E_2 h^3}{q_0 \overline{a}^4}\right) \tag{18}$$

where $t_2$=0.004 s, $\alpha_1$=1.98, and $q_0$=68.95 kPa.

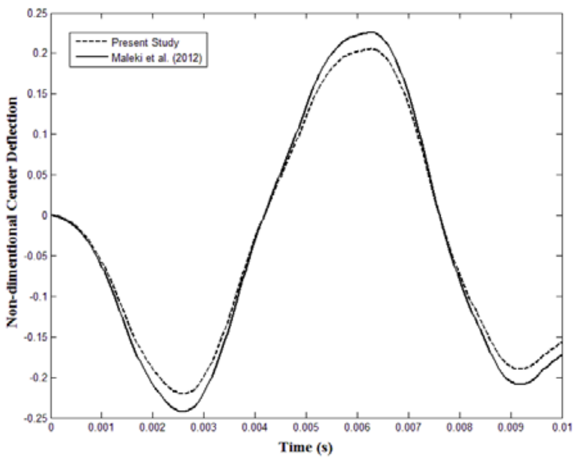


Fig. 4 Response of orthotropic, square, clamped panel to conventional blast load

Table 1 Maximum vertical displacement of the FML panels with $[Al/0/0/0]_S$ stacking sequence under uniformly distributed step load ($q$=0.0231 MPa)

| BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | | BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | |
|---|---|---|---|---|---|---|---|
| | | Non-optimized response | Optimized response (E-ABC algorithm) | | | Non-optimized response | Optimized response (E-ABC algorithm) |
| CFFF | 1 | 7.31 E -06 | 0.60 E -06 | CSCS | 1 | 13.90 E -08 | 1.86 E -08 |
| | 2 | 7.38 E -06 | 1.76 E -06 | | 2 | 12.46 E -08 | 5.21 E -08 |
| SFSF | 1 | 7.27 E -07 | 0.91 E -07 | CCFF | 1 | 3.59 E -08 | 1.34 E -08 |
| | 2 | 1.72 E -06 | 0.75 E -06 | | 2 | 18.62 E -09 | 0.72 E -09 |
| SSSS | 1 | 3.63 E -07 | 0.25 E -07 | CCCC | 1 | 10.74 E -09 | 6.75 E -09 |
| | 2 | 2.25 E -07 | 0.69 E -07 | | 2 | 10.21 E -10 | 6.01 E -10 |

Table 2 Maximum vertical displacement of the FML panels with $[Al/45/-45/45]_S$ stacking sequence under uniformly distributed step load ($q$=0.0231 MPa)

| BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | | BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | |
|---|---|---|---|---|---|---|---|
| | | Non-optimized response | Optimized response (E-ABC algorithm) | | | Non-optimized response | Optimized response (E-ABC algorithm) |
| CFFF | 1 | 12.27 E -06 | 1.32 E -06 | CSCS | 1 | 15.98 E -08 | 2.75 E -08 |
| SFSF | 1 | 12.29 E -07 | 1.39 E -07 | CCFF | 1 | 3.61 E -08 | 1.31 E -08 |
| SSSS | 1 | 3.11 E -07 | 0.31 E -07 | CCCC | 1 | 11.87 E -09 | 8.80 E -09 |

Table 3 Maximum vertical displacement of the FML panels for $[Al/0/0/0]_S$ stacking sequence with double-thickness aluminum layers under uniformly distributed step load ($q$=0.0231 MPa)

| BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | | BCs | $\bar{a}/\bar{b}$ | Maximum vertical displacement (m) | |
|---|---|---|---|---|---|---|---|
| | | Non-optimized response | Optimized response (E-ABC algorithm) | | | Non-optimized response | Optimized response (E-ABC algorithm) |
| CFFF | 1 | 4.27 E -06 | 0.92 E -06 | CSCS | 1 | 7.25 E -08 | 0.62 E -08 |
| SFSF | 1 | 4.25 E -07 | 0.76 E -07 | CCFF | 1 | 17.92 E -09 | 5.30 E -09 |
| SSSS | 1 | 16.68 E -08 | 2.82 E -08 | CCCC | 1 | 5.41 E -09 | 3.33 E -09 |

The optimization results given in this paper are carried out for symmetrically FML panel under uniformly distributed step load of intensity $q$=0.0025 Pa over the whole panel surface with the different combinations of free (F), simply supported (S) and clamped (C) edge conditions. Consider the panel with known original shape and actuator configurations where the desired shape is specified (see Fig. 1). So the aim is to find the actuators voltages, which minimize the maximum vertical displacement of FML panels by consuming minimum energy. The effects of the edge conditions, panel length/width ratios, stacking sequences and thickness of metal sheets on the optimum design are shown for symmetric 8-layerd FML panels in Figs. 5, 6, 7 and 8 and in Tables 1, 2 and 3. As inferred from the results, the good efficiency of the E-ABC search strategy and its ability to provide high-quality solutions is confirmed for various solutions.

Tables 4, 5 and 6 also represent the optimal voltages of the piezoelectric patches, which minimize the maximum vertical displacement of FML panels by consuming minimum energy. In addition, the optimum voltages of patches are substantially influenced for edge conditions, thickness of metal sheets and $\bar{a}/\bar{b}$ ratios. As seen, the optimum voltages of the piezoelectric patches are not influenced substantially and approach a limiting value by changing the stacking sequences. It is also clear from Tables 4, 5 and 6 that the optimum voltages of patches 1 and 3 and optimum voltages of patches 2 and 4 approach a same value for symmetric boundary conditions.

Table 4 Optimum solutions for FML panels with $[Al/0/0/0]_S$ stacking sequence (Volt.)

| BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ | BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ |
|---|---|---|---|---|---|
| CFFF | 1 | [-400/-1/-400/-1] | CSCS | 1 | [-173/100/-173/100] |
| | 2 | [-304/41/-304/43] | | 2 | [47/-29/46/-29] |
| SFSF | 1 | [-326/55/-326/56] | CCFF | 1 | [-3/-280/-127/-59] |
| | 2 | [55/-37/53/-36] | | 2 | [-10/-6/-9/-7] |
| SSSS | 1 | [-400/-18/-400/-17] | CCCC | 1 | [-61/155 /-61/155] |
| | 2 | [49/-22/50/-21] | | 2 | [2/9/2/9] |

Table 5 Optimum solutions for FML panels with double-thickness aluminum layers and $[Al/0/0/0]_S$ stacking sequence (Volt.)

| BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ | BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ |
|---|---|---|---|---|---|
| CFFF | 1 | [39/-234/37/-232] | CSCS | 1 | [1/159/2/160] |
| SFSF | 1 | [-37/189/-37/187] | CCFF | 1 | [-6//-225/-91/-45] |
| SSSS | 1 | [29/242/29/242] | CCCC | 1 | [-85/54/-87/55] |

Table 6 Optimum solutions for FML panels with $[Al/45/-45/45]_S$ stacking sequence (Volt.)

| BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ | BCs | $\bar{a}/\bar{b}$ | $[V_1/V_2/V_3/V_4]_{Opt}$ |
|---|---|---|---|---|---|
| CFFF | 1 | [-400/0/-399/-1] | CSCS | 1 | [-173/98/-174/99] |
| SFSF | 1 | [-326/55/-326/55] | CCFF | 1 | [-2/-280/-125/-61] |
| SSSS | 1 | [-397/-15/-400/-17] | CCCC | 1 | [-61/154 /-61/154] |

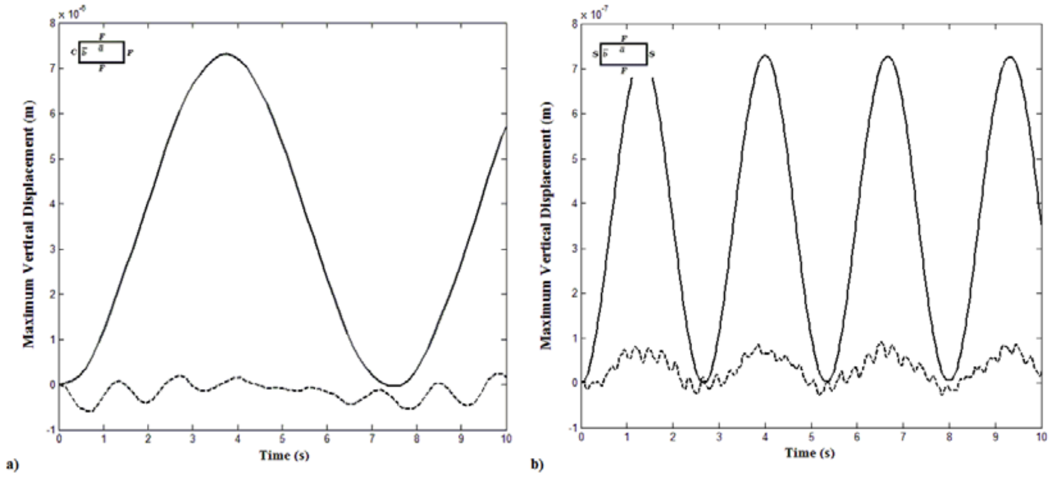


Fig. 5 Optimum solutions of symmetric 8-layered FML panels obtained by E-ABC algorithm for different boundary conditions and $[Al/0/0/0]_S$ stacking sequence ($\bar{a}/\bar{b}=1$) : (a) CFFF, (b) SFSF, (c) SSSS, (d) CSCS, (e) CCFF, (f) CCCC;—Non-optimized response, ---Optimized response

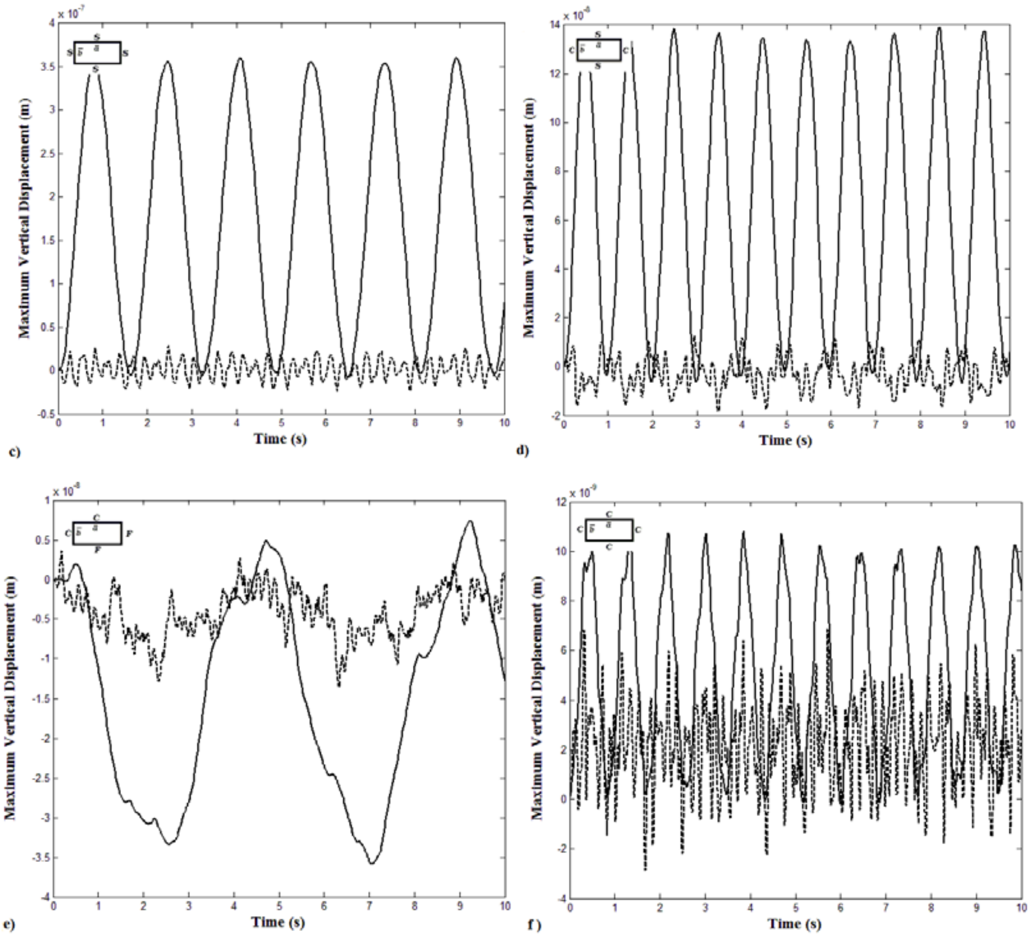


Fig. 5 Continued

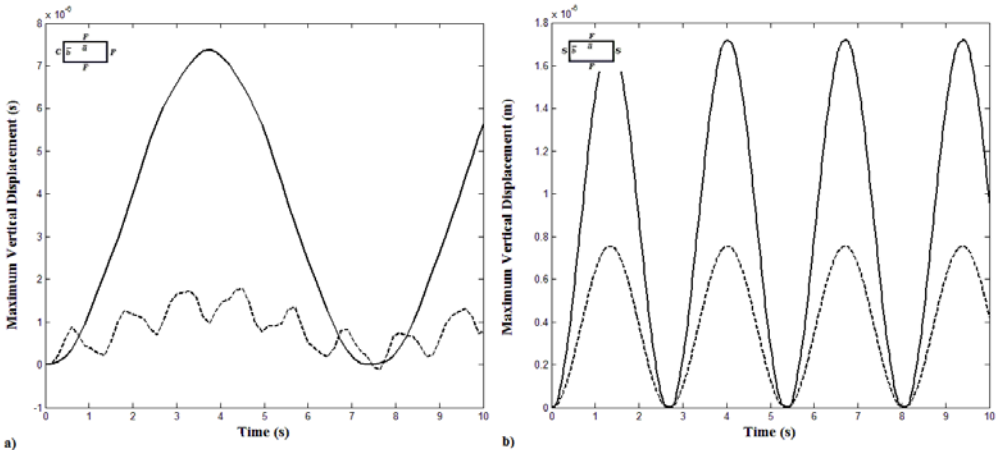


Fig. 6 Optimum solutions of symmetric 8-layered FML panels obtained by E-ABC algorithm for different boundary conditions and $[Al/0/0/0]_S$ stacking sequence ($\bar{a}/\bar{b}=2$): (a) CFFF, (b) SFSF, (c) SSSS, (d) CSCS, (e) CCFF, (f) CCCC;—Non-optimized response, ---Optimized response

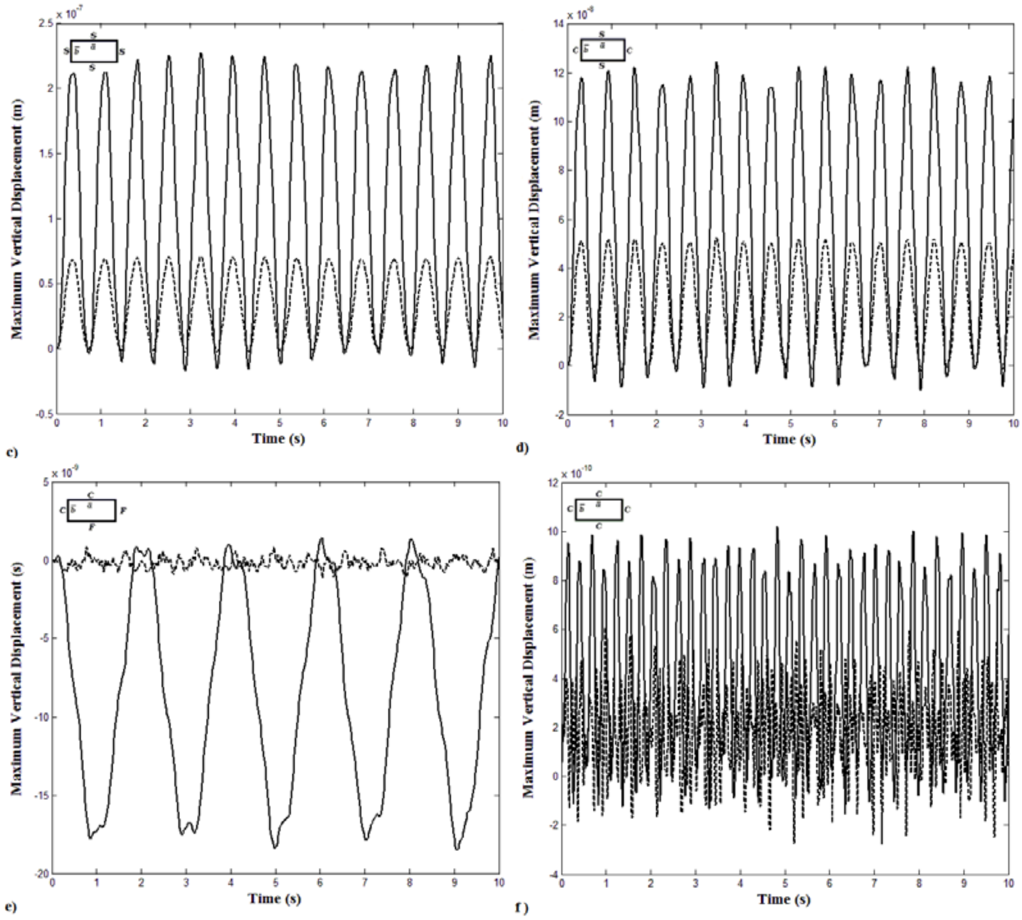


Fig. 6 Continued

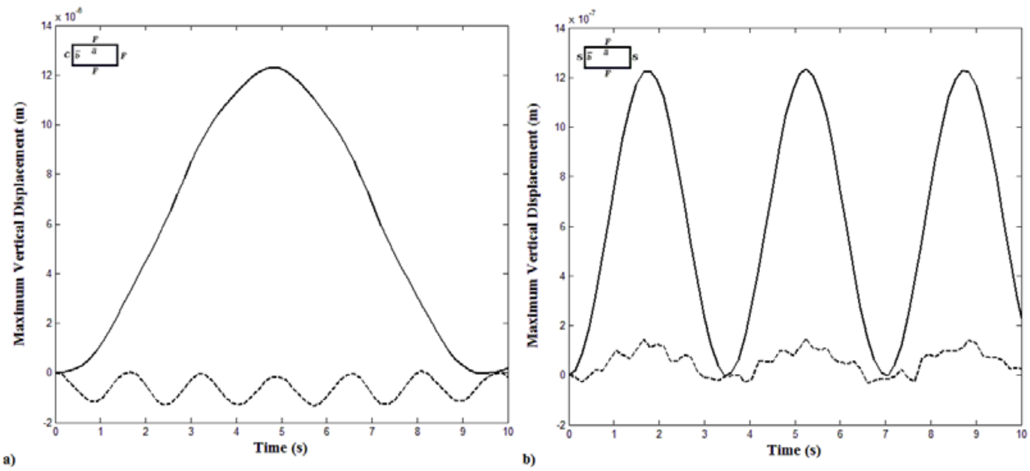


Fig. 7 Optimum solutions of symmetric 8-layered FML panels obtained by E-ABC algorithm for different boundary conditions and $[Al/45/-45/45]_S$ stacking sequence $(\bar{a}/\bar{b}=1)$: (a) CFFF, (b) SFSF, (c) SSSS, (d) CSCS, (e) CCFF, (f) CCCC;—Non-optimized response, ---Optimized response

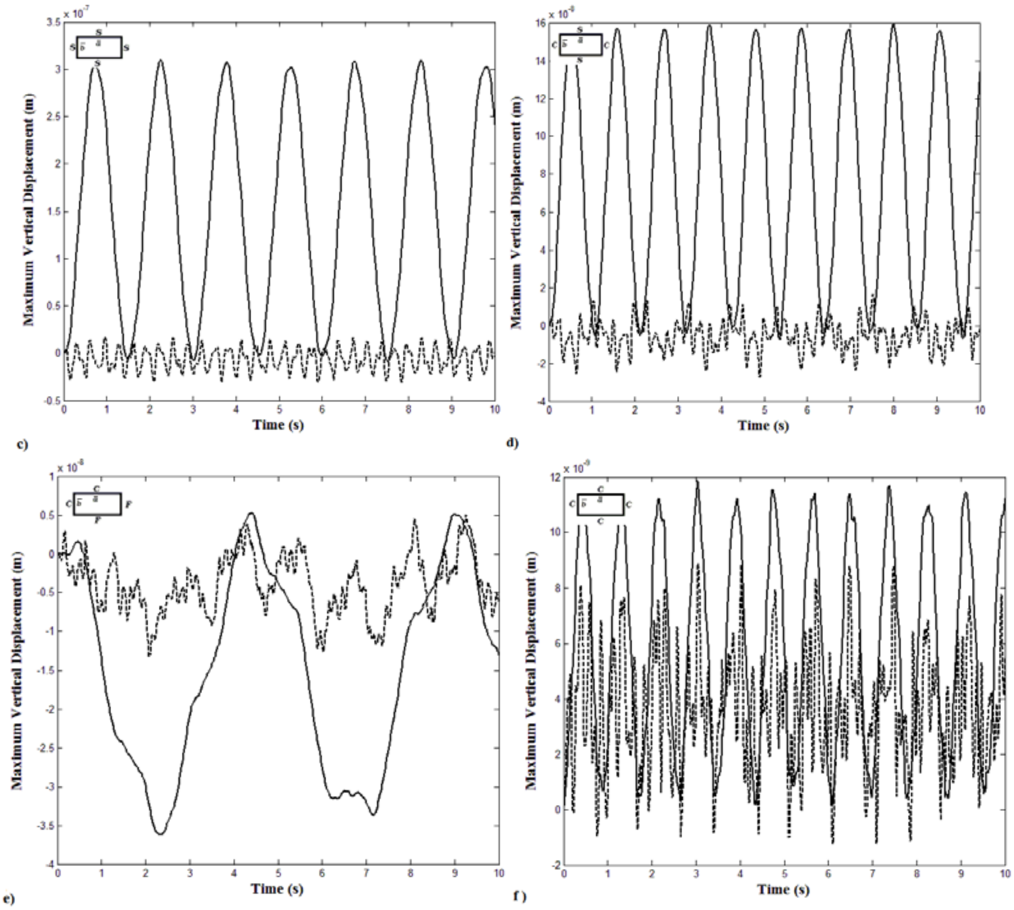


Fig. 7 Continued

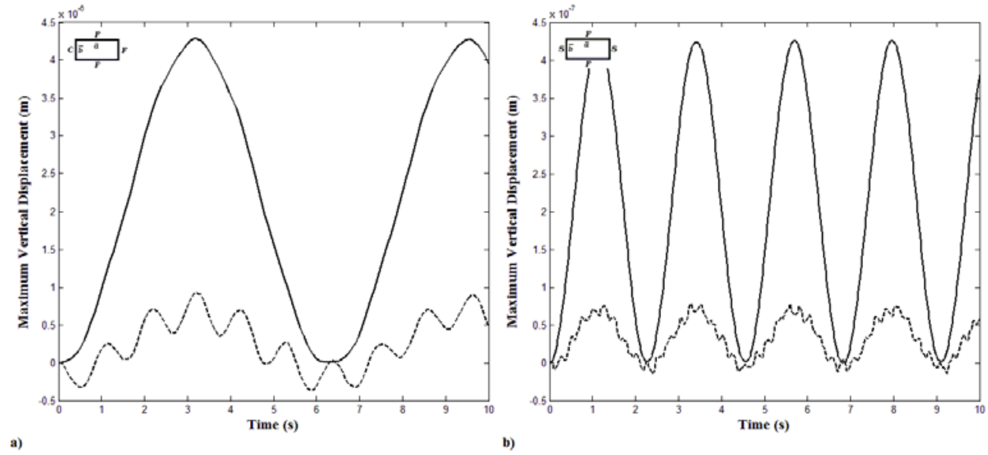


Fig. 8 Optimum solutions of symmetric 8-layered FML panels obtained by E-ABC algorithm for different boundary conditions and $[Al/0/0/0]_S$ stacking sequence with double-thickness aluminum layers ($\bar{a}/\bar{b}=1$): (a) CFFF, (b) SFSF, (c) SSSS, (d) CSCS, (e) CCFF, (f) CCCC;—Non-optimized response, ---Optimized response

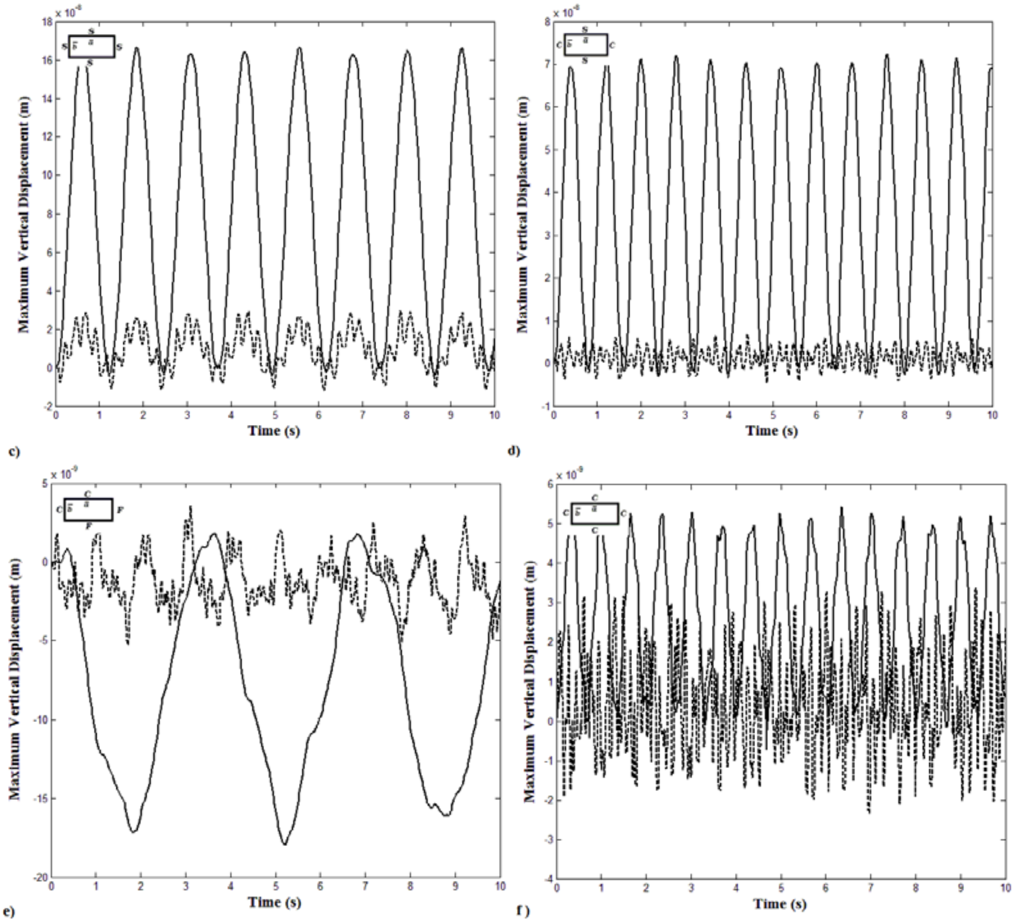

Fig. 8 Continued

## 4. Conclusions

In this study, the voltages of patches optimization were carried out for minimizing the power consumption and maximum vertical displacement of symmetrically smart FML panels by the E-ABC algorithm. The performance of the E-ABC was compared with the PSO algorithm and demonstrated the good efficiency of the E-ABC algorithm. As seen from the results, the E-ABC algorithm was successful in minimizing the power consumption and maximum vertical displacement of symmetrically FML panels using piezoelectric patches. In addition, the optimum voltages of patches were substantially influenced for edge conditions, thickness of metal sheets and $\bar{a}/\bar{b}$ ratios. As seen, the optimum voltages of patches were not substantially influenced and approach a limiting value by changing fiber orientations.

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