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# Effect of piezoelectric patches segmentation and adhesive layer properties on the electromechanical coupling of smart structures

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*Abstract: Adhesive layer between surface-bonded piezoelectric patches and a host structure is responsible for transferring the mechanical stress and strain field; as a consequence, the performance of smart piezoelectric structures can be strongly influenced by the adhesive layer properties. However, such effect has not been extensively studied despite some works indicating a potential reduction in the transmissibility. Therefore, some aspects affecting the electromechanical coupling, such as the segmentation of the piezoelectric patches and bonding effectiveness are investigated in this work by means of parametric analyses of the adhesive layer properties (thickness, thickness uniformity and Young's modulus). This is done for a thin plate with surface bonded piezoelectric patches and results are obtained using a custom finite element model that accounts for adhesive layer properties.*

***Keywords: Piezoelectric materials, Energy harvesting, Finite element, Smart structures, Adhesive layer***

## INTRODUCTION

Piezoelectric materials have been extensively studied by research groups and considered for several industrial applications in search for adaptive structures (Chopra, 2002). These are widely employed as thin layer or patches adhesively bonded on thin flexible structures forming multilayered composite structures, which are used in airplanes, automotive vehicles or aerospace applications, for active (Sunar and Rao, 1999), passive (Moheimani, 2003) and hybrid active-passive (Trindade and Benjeddou, 2002) vibration control. Whether the piezoelectric patch works in actuator or sensor mode, the adhesive layer is responsible for transferring the mechanical strain between the piezoelectric patch and the host structure, this suggests that adhesive layer properties may have an important effect on the performance of the piezoelectric elements. However, this effect was not studied extensively although most works have shown observations that indicate a potential reduction of the transmissibility between host structure and piezoelectric patch.

Thus, the present work attempts to show the effect of the successive segmentation of the piezoelectric patch on the performance of the smart structures with surface-bonded piezoelectric patches, when a finite adhesive layer is present. For that, a customized finite element model is proposed to take into account the adhesive layer. Then, a parametric analysis is performed for a plate-like elastic structure containing a discrete distribution of piezoelectric patches. Results are obtained for different values of covered area.

## FINITE ELEMENT MODELING

The finite element method (FEM) is used to model a generic plate-like elastic structure containing a discrete distribution of surface-bonded piezoelectric patches. The developed mathematical model is thought to take into account important properties of the adhesive layer between the plate and piezoelectric patches such as thickness, Young's modulus and thickness non-uniformity. For this purpose, the adhesive layers and piezoelectric patches are modeled as solid materials, while the plate structure is modeled using a first-order shear deformation theory (FSDT) (Reddy, 2004), offsetting the node plane up to top surface to guarantee the assembly between this and nodes of the solid elements. A strain-voltage model is proposed considering linear and orthotropic piezoelectric materials. Thermal coupling is neglected. Thus, the equations of motion of the discretized volume, in matrix form, are given by

$$\begin{bmatrix} \boldsymbol{M} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} \end{bmatrix} \begin{Bmatrix} \ddot{\hat{\boldsymbol{u}}} \\ \ddot{\hat{\boldsymbol{V}}} \end{Bmatrix} + \begin{bmatrix} \boldsymbol{K}_u & \boldsymbol{K}_{uV} \\ \boldsymbol{K}_{uV}{}^T & -\boldsymbol{K}_V \end{bmatrix} \begin{Bmatrix} \hat{\boldsymbol{u}} \\ \hat{\boldsymbol{V}} \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F}_m \\ \boldsymbol{0} \end{Bmatrix} \tag{1}$$

Where the elementary matrices of mass, elastic stiffness (for constant electric field), piezoelectric stiffness and dielectric stiffness (for constant strain field) and the elementary vector of external applied forces are, respectively

$$\boldsymbol{M}^e = \int_\Omega \rho \bar{\boldsymbol{N}}_u^T \bar{\boldsymbol{N}}_u d\Omega_e\,; \quad \boldsymbol{K}_u{}^e = \int_\Omega \boldsymbol{B}_u{}^T \boldsymbol{c}^E \boldsymbol{B}_u d\Omega_e\,, \quad \boldsymbol{K}_{uV}{}^e = \int_\Omega \boldsymbol{B}_u{}^T \mathbf{e} \boldsymbol{B}_V d\Omega_e\,;$$
$$\boldsymbol{K}_V{}^e = \int_\Omega \boldsymbol{B}_V^T \boldsymbol{\epsilon}^{\boldsymbol{\varepsilon}} \boldsymbol{B}_V d\Omega_e\,; \quad \boldsymbol{F}_m{}^e = \int_\Omega \bar{\boldsymbol{N}}_u^T \boldsymbol{f} d\Omega_e \tag{2}$$

Where $\boldsymbol{c}^{E}$, $\mathbf{e}$ and $\boldsymbol{\epsilon}^{\varepsilon}$ are respectively the matrices of elasticity constants at constant electric field, piezoelectric constants and dielectric coefficients at constant strain field.

## Electric boundary conditions

Two types of electric boundary conditions will be considered for the piezoelectric patches, depending on the connection between top and bottom electrodes: short circuit (SC), and open circuit (OC). Therefore, assuming that all electrodes on bottom surfaces of the piezoelectric patches are grounded, if the electrodes of the piezoelectric patch are in SC, induced electric potential at the top electrode is also null $\boldsymbol{V} = 0$, consequently, Eq. (1) is reduced to

$$\boldsymbol{M}\ddot{\hat{\boldsymbol{u}}} + \boldsymbol{K}_{u}\hat{\boldsymbol{u}} = \boldsymbol{F}_{m} \tag{3}$$

On the other hand, if electrodes of the piezoelectric patches are in OC, the induced electric potential on top electrode can be calculate from the second row of Eq. (1) as

$$\widehat{\boldsymbol{V}} = {\boldsymbol{K}_{V}}^{-1}{\boldsymbol{K}_{uV}}^{T}\hat{\boldsymbol{u}} \tag{4}$$

substituting Eq. (4) in first row of Eq. (1), equations of motion similar to Eq. (3) are obtained

$$\boldsymbol{M}\ddot{\hat{\boldsymbol{u}}} + \boldsymbol{K}_{eq}\hat{\boldsymbol{u}} = \boldsymbol{F}_{m} \tag{5}$$

where the equivalent stiffness matrix $K_{eq}$ is given by: $\boldsymbol{K}_{eq} = \boldsymbol{K}_{u} + \boldsymbol{K}_{uV}{\boldsymbol{K}_{V}}^{-1}{\boldsymbol{K}_{uV}}^{T}$. Solving Eq. (5) for the mechanical dof $\hat{\boldsymbol{u}}$, the induced electric potential on top electrodes may be evaluated through post-processing from Eq.(4).

## CALCULATION OF THE EFFECTIVE ELECTROMECHANICAL COUPLING COEFFICIENT (EMCCe)

For a generic flexible structure with a discrete distribution of piezoelectric patches, it is possible to evaluate the structure's EMCCe provided by each piezoelectric patch. A general procedure to calculate the EMCCe based on modeling has been proposed (Trindade and Benjeddou, 2009). The i$^{th}$ modal parameters; mode $\boldsymbol{T}^{i}$ and natural frequency $\omega^{i}$, of a structure with a discrete distribution of piezoelectric elements for SC and OC electric boundary conditions respectively can be found from Eq. (3) and Eq. (5) as

$$\left({\omega_{SC}^{i}}^{2}\boldsymbol{M} + \boldsymbol{K}_{u}\right)\boldsymbol{T}_{SC}^{i} = 0; \quad \left({\omega_{OC}^{i}}^{2}\boldsymbol{M} + \boldsymbol{K}_{\boldsymbol{eq}}\right)\boldsymbol{T}_{OC}^{i} = 0 \tag{6}$$

Thus, the EMCCe of the structure, provided by a piezoelectric element, when it is vibrating in the i$^{th}$ mode shape is defined as

$$k_{i}^{2} = \frac{{\omega_{OC}^{i}}^{2} - {\omega_{SC}^{i}}^{2}}{{\omega_{OC}^{i}}^{2}} \tag{7}$$

## DESCRIPTION OF THE PROPOSED ANALYSIS

In the present work, it is considered that the effective electromechanical coupling coefficient (EMCCe) strongly determine the performance of a piezoelectric patch bonded to a structure; whether this is working as sensor, actuator or as an energy harvesting device. The EMCCe represents the energy fraction that could be stored in the piezoelectric element when the structure vibrates in a given mode. This depends on the electromechanical coupling coefficient (EMCC ou $k_{ij}^{2}$) of the material and on the mechanical coupling between the piezoelectric element and the host structure, consequently it can be expected that the EMCCe will be smaller than the material EMCC (Trindade and Benjeddou, 2009).

Previous works indicate a potential reduction on the mechanical coupling between host structure and piezoelectric element due to the presence of an adhesive layer between them (De Faria, 2003; Tinoco *et al.*, 2010). On the other hand, segmentation of the piezoelectric patch can increase the value of the EMCCe, since it reduces the electric charge cancelation phenomena. However, excessive segmentation is detrimental due to the border effects in adhesive layer which may diminish the mechanical coupling between the piezoelectric patches and the host structure (Velasquez and Trindade). Therefore, a parametric analysis varying the segmentation level and the properties of the adhesive layer was proposed to evaluate their effect on the performance of structures containing piezoelectric patches.

It is assumed that a network of piezoelectric patches is to be bonded to a flexible plate structure so that the network should be effective transforming energy from the structural vibrations within a frequency-range that contains the first five resonant frequencies. A rectangular aluminum plate with at all edges clamped and dimensions $420 \times 320 \times 2$ [mm$^{3}$] is considered. The aluminum properties are: Young modulus $E_{Al} = 70$ [GPa], Poisson ratio $\nu_{Al} = 0.34$ and mass density $\rho_{Al} = 2700$ [Kg/m$^{3}$]. The adhesive layer has nominal thickness $e_{Ad} = 0.1$ [mm] and nominal properties: Young modulus $E_{Ad} = 2.7$ [GPa], Poisson ratio $\nu_{Ad} = 0.4$ and mass density $\rho_{Ad} = 1140$ [Kg/m$^{3}$]. The material used for the piezoelectric patches is a piezoceramic **PZT-5H** with thickness $e_{Al} = 0.5$ [mm], and electromechanical properties listed in Table 1. A uniform mesh of 42 x 32 elements has been used to discretize the aluminum plate and consequently adhesive layer and piezoelectric patches have also been discretized by a uniform mesh.

**Table 1 - Electromechanical properties of the PZT -5H**

| **Elastic properties (at constant electric field)** [GPa] | | | **Piezoelectric properties** $[\mathrm{C/m^2}]$ | | |
|---|---|---|---|---|---|
| $c_{11} = c_{22} = 127.2$ | $c_{12} = 80.2$ | $c_{13} = c_{23} = 84.7$ | $e_{31} = e_{32} = -6.6$ | $e_{33} = 23.2$ | $e_{15} = e_{24} = 17.0$ |
| $c_{33} = 117.4$ | $c_{44} = 23.5$ | $c_{55} = c_{66} = 23$ | **Dielectric properties** [nF/m] | | |
| **Mass density** $[\mathrm{Kg/m^3}]$ | | $\rho = 7500$ | $\epsilon_{11} = \epsilon_{22} = 15.09$ | $\epsilon_{33} = 12.69$ | |

A modal analysis has been performed and the first five mode shapes and natural frequencies of the clamped plate (without piezoelectric patches) are shown in Fig. 1. The effect of successive segmentation and variation of the adhesive layer properties is investigated for the mean value of the EMCCe of the first five vibration modes for a band of frequencies between the first and fifth modes of vibration of the structure.

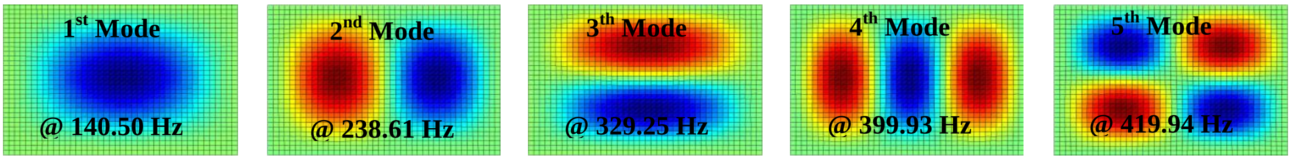


**Figure 1 - First five mode shapes of vibration and its natural frequencies for the clamped aluminum plate**

## Parametric analysis

The mean global structure's EMCCe for the first five modes of vibration is evaluated for an initially unique piezoelectric patch bonded on the plate's surface, which is centered and has rectangular shape. Then, keeping the total covered area by piezoelectric material, this patch is segmented into two parts symmetrically with respect to the y-axe and again the mean EMCCe for this new configuration is evaluated. Next, the segmentation is done again, but this time symmetrically with respect to the x-axe, obtaining four patches at total. This procedure is performed for successive times aiming to obtain the EMCCe values for configuration with one, two, four, eight, sixteen, thirty two and sixty four patches. Afterwards, the completed described procedure is performed for reduced covered areas: 57.14%; 38.10%; 28.57%; 19.05%; 14.29%; and 9.52%. Several evaluated configurations with different covered areas are shown schematically in Fig. 2.

For the parametric analysis, evaluated parameters of thickness and Young's modulus took values from a ten parts their nominal value up to ten times their nominal value, logarithmically spaced. For thickness non-uniformity evaluation, the sloping angle was generated by mean of the inclusion of a thickness difference between ends of the patch (simultaneously in x and y axis direction). To prevent distortion on results due to trend, a normal distribution function was adopted for the thickness difference values. The influence on the EMCCe of each parameter is evaluated separately, keeping constant the others two in their nominal values.

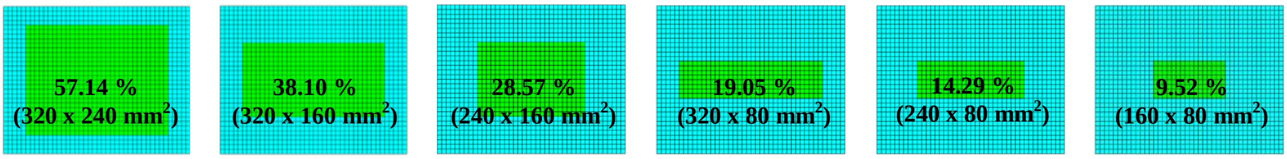


**Figure 2 - Schematic representation of evaluated areas in segmentation analysis**

## NUMERICALAL RESULTS

Results for successive segmentation for six different values of covered area are presented in figures 3 to 5. They have been achieved taking into account the electrical and mechanical uncoupling between patches. In Fig. 3 are shown obtained results for thickness of adhesive layer variation, these have been found for five different values of thickness of adhesive layer. In Fig. 4 are shown results when the Young's modulus of adhesive layer is varied, results for five different values of Young's modulus are found. And finally results for sloping angle variation are shown in figure 5.

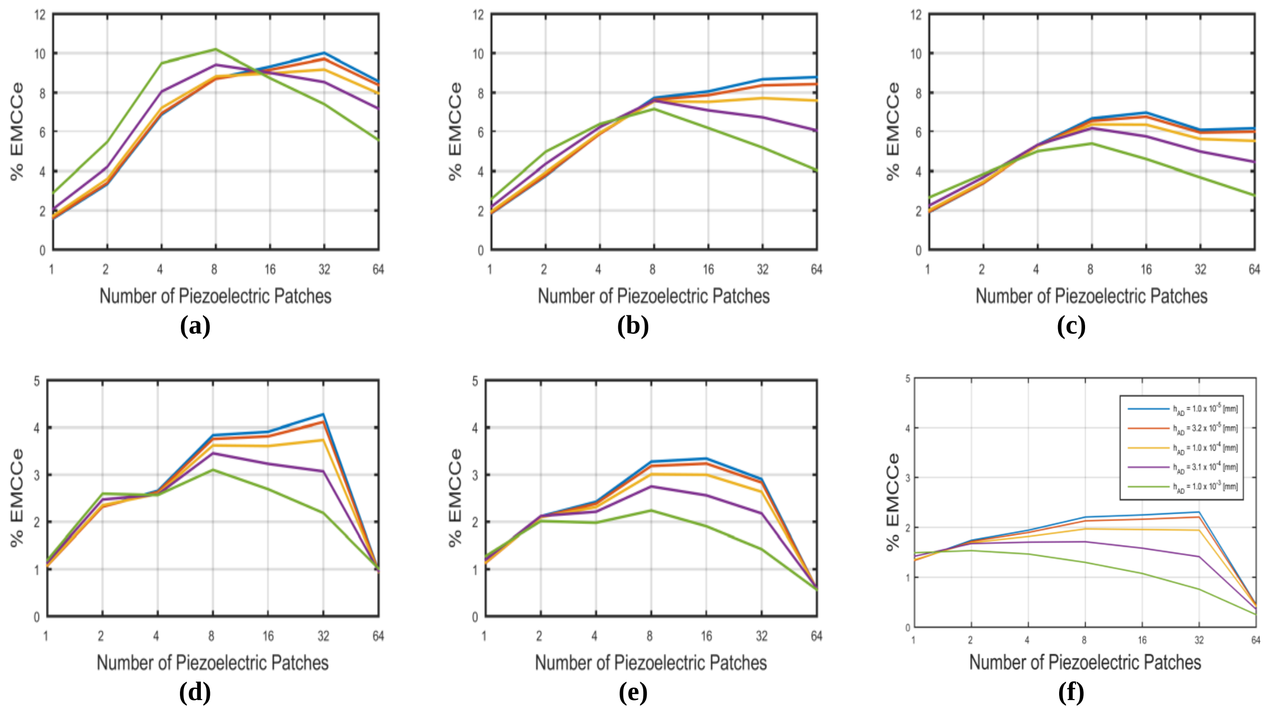


**Figure 3 - Mean value of EMCCe for different segmentation level as a function of the thickness adhesive layer for: (a) 57.14 %; (b) 38.10 %; (c) 28.57 % (d) 19.05 %; (e) 14.29; and (f) 9.52 % of covered area**

In general form, it can seen from figure 3, that the segmentation of the piezoelectric patch increases the mean value of the EMCCe for the specified band of frequencies. However, excessive segmentation is detrimental. The increase of the mean value of the EMCCe depends on the thickness of adhesive layer and on the percentage of covered area

For example for 57.14 % of covered area; the increase on mean value of the EMCCe due to segmentation is bigger for the biggest values of adhesive layer, this is true for all values of thickness of adhesive layer until the fourth level of segmentation (eight patches). From the eighth level of segmentation (sixteen patches), this continues to be valid only for the three smallest values of thickness, for the two biggest values of thickness, the mean EMCCe decreases whit the segmentation, and the decreasing is bigger for the biggest values of the thickness of adhesive layer. From the sixteenth level of segmentation (thirty two patches), the mean value of EMCCe decreases for all values of thickness, and the decreasing is bigger for the biggest values of thickness. For the rest of tested configurations with different values of covered area, it can see a similar behavior: initially, the mean EMCCe increases with the segmentation, and this increasing is bigger for the biggest values of thickness of adhesive layer, from the a level of segmentation the mean EMCCe starts to decrease with the segmentation for the biggest values of thickness of adhesive layer, and finally; from another level of segmentation, the mean EMCCe decreases for all values of thickness of adhesive layer.

Two interesting conclusions can be drawn from this first analysis; first: not always a bigger value of thickness of adhesive layer is detrimental for the performance of piezoelectric patches adhesively bonded. And second: the negative effect of the increasing of the thickness of adhesive layer is bigger how much the smaller the size of the patches. This suggests that there is an optimum patch size which maximizes the value of the mean EMCCe, and this depends on the thickness of adhesive layer, which is an uncontrollable parameter in experimental testing.

The behavior of the mean EMCCe observed in the second analysis; when the Young modulus of adhesive layer is varied, is similar to observed in first one for all tested configurations. Segmentation increases the mean EMCCe for all values of Young's modulus until a specific level of segmentation, from this level the mean EMCCe starts to decrease for the two smallest values of Young's modulus. From another level of segmentation the mean EMCCe starts to decrease for the remaining values of Young modulus. The decreasing of the mean values of the EMCCe is bigger how much the smaller the value of the Young's modulus. Differences for the mean value of EMCCe for 8.5 [GPa] and 27 [GPa] can be neglected for all tested configurations.

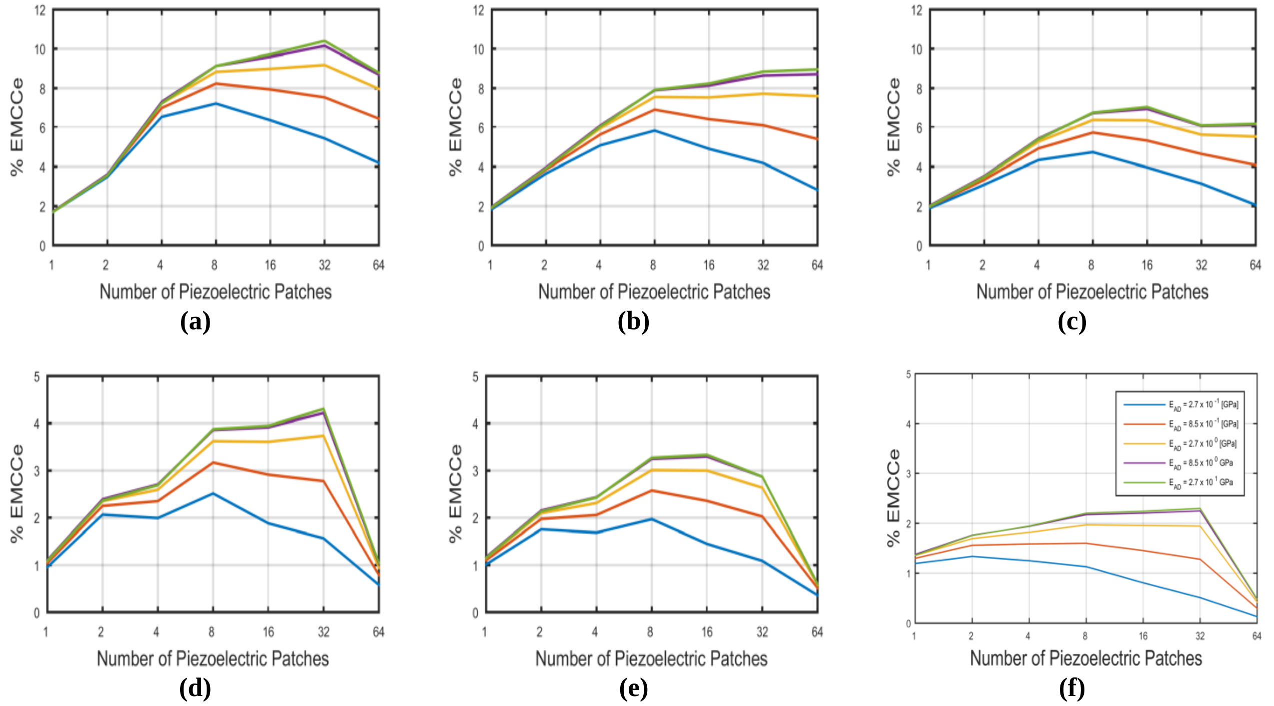


**Figure 4 - Mean value of EMCCe for different segmentation level as a function of the Young's modulus of the adhesive for: (a) 57.14 %; (b) 38.10 %; (c) 28.57 % (d) 19.05 %; (e) 14.29; and (f) 9.52 % of covered area**

Results obtained when the sloping angle is varied shown a less strong dependence of the mean EMCCe with this parameter. In general form, the behavior is similar to observed in the first and second analyses. The mean EMCCe increases with the segmentation for all tested configurations and for all values of sloping angle until a level of segmentation. From this level of segmentation the mean EMCCe starts to decrease for some values of sloping angle tested, and finally from another level of segmentation the mean EMCCe decreases for all values of sloping angle.

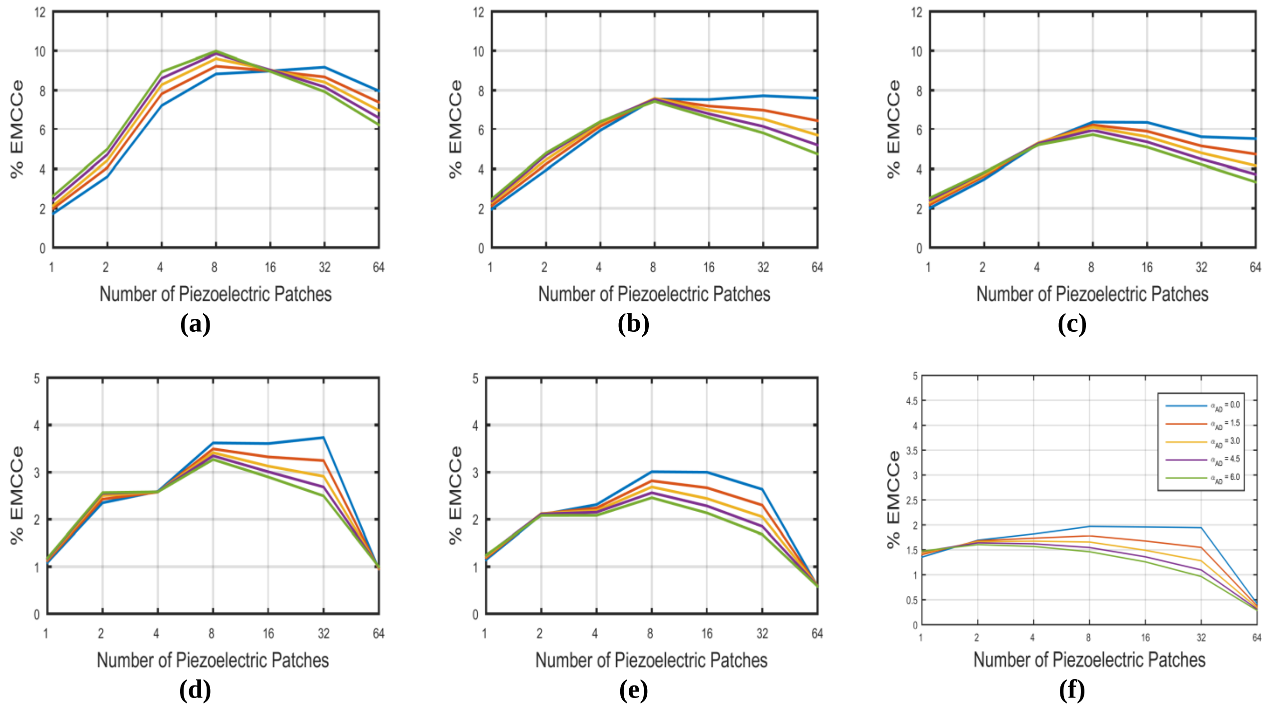


**Figure 5 - Mean value of EMCCe for different segmentation level as a function of the sloping angle of the adhesive for: (a) 57.14 %; (b) 38.10 %; (c) 28.57 % (d) 19.05 %; (e) 14.29; and (f) 9.52 % of covered area**

## CONCLUDING REMARKS AND FUTURE WORKS

Obtained results indicate, as expected, that the piezoelectric patch segmentation increases the mean value of EMCCe for a specific band of frequencies and therefore, this may improve the performance of structures containing piezoelectric patches since it reduces the electric charge cancellation phenomena. However, excessive segmentation is detrimental and it may be due to border effects in adhesive layer that may diminish the mechanical coupling between patches and host structure. This suggests that for a given geometry and percentage of covered area, there is a specific patch size, which maximizes the efficiency of conversion energy. On the other hand, results suggest that there are exits an optimal value for the thickness adhesive layer, since the mean EMCCe increases with the increasing of this one. It may be possible that this is happening due to a greater arm moment. Future works are being directed to evaluate the effect of the other adhesive layer parameters for a better understanding of the negative effects of excessive segmentation.

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