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PIEZO-FIBER COMPOSITE SENSOR TAILORING USING GENETIC ALGORITHM

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Abstract. *The active aeroelastic control aims the reduction or elimination of harmful fluid-structure interaction effects. More recently, piezo-fiber composites, made from piezoelectric fibers embedded into composites, represent a major technological breakthrough for the manufacture of aerospace intelligent structures. The design and synthesis of intelligent systems requires some effort to assess adequate sensor and actuator positioning and performance. Typically, sensors location or arrangements have been determined by using optimization approaches, in order to get the optimal performance in a particular system application. In the smart structures literature, it is usual to find investigations on PZT sensors arrangement optimization based on modal responses. Piezo-fiber composites may furnish appropriate framework to enhance sensor effective, in special when composite structures are considered. Moreover, each piezo-fiber composite sensor may be optimized, allowing adjustments of their internal laminate and PZT fibers, thereby reducing the number of required sensors and improving their integration to the primary structure. This paper presents an investigation on piezo-fiber composites optimization viewing their application as modal sensors or filtering. In this context, sensor tailoring is suggested by configuring the internal layers. The piezo-fiber composite sensor is assumed with internal layers and an extra embedded PZT fibers. Optimization is performed to each layer direction by exploring a metrics on sensor response in modal coordinates for a range in the frequency domain. The finite element modeling is used to represent the dynamics of a uniform plate structure and the piezo-composite. The genetic algorithm is considered as optimization tool using modal parameters to achieve a cost function.*
Keywords: *structural dynamics, modal filter, piezoelectric, composites, finite element analysis, genetic algorithm.*

1. INTRODUCTION

One scope of structural dynamics is focused in vibration control, based on theories and concepts to achieve this purpose. Modal control is an important method, which join control strategies whit modal analysis, as was developed by Meirovitch, who used the independent-space control concept associated with modal filters to control the system [7]. Modal filters arose from need to make the dynamical response of a system into correspondent vibration modes, in the way to preserve the target modes and filter the residual ones. A special phenomenon which highlights the modal filter importance is the spill-over effect, which can be avoided with the targets modes isolated to be controlled with a better performance.

Several studies are done to project and optimize modal filters that can be defined as a sensors array, with location and topology parameters to be determined according to the interest modes. The application of piezoelectric (PZT) material as a sensor, are growing up in the recent studies, due to its capability to obtain voltage answer of an applied strain.

Some piezoelectric devices can be assembled to create a sensors embedded in structures, especially, with composites materials. This application is broadly used in SHM (structural health monitoring) to do a real-time investigation of composites fracture mechanisms, improving the safety of composites application [2].

Mechanisms to transfer mechanical energy from ambient vibration, into electrical energy also use piezoelectric devices, creating a particular harvesting technology. These devices can be projected to offer the appropriate charge to supply some electric devices [12].

The PZT coupling effect, can also be simulated by Finite Element Method (FEM) that correspond as an important tool to be joined with optimization algorithms and obtain a robust project of modal filters.

Several studies and efforts to improve the type of elements used in FEM are developed to obtain better results and model validation. Lam [5] developed an element based on classical laminated plate theory to composites containing PZT's. The aim of this element was active vibration control problems, which uses the Hamilton's Principle for basics formulation.

Abreu [1] had developed an important tool to vibration control projects that is a numerical method using finite element formulation, based on Kirchhoff's plate model. This methodology is applied in PZT's composites laminates, and has offered good results comparing with commercial FEM software's.

So, while efforts have been done to improve the FEM techniques and its results, as consequences, the modal filter idea was developed and new technologies would be achieved. The two types of filters configuration are arrays of discrete sensors, which is the most used method, and continuous distributed sensor as a films bonded in all structure.

Preumont [10] had done a comparison between two types of modal filters. For the discrete configuration he used a glass plate with 32 bonded sensors and would obtain the FRF's point to point, relating the position of each sensor with some weighting coefficients, and so, would compare the FRF with an expected modal filtered answer. Using distributed sensor, he could determine the band frequency which this method was most efficient. This work also provides a modal filter methodology of design.

Ramesh [11] had analyzed the optimal placement of sensor and actuator pairs, searching for good controllability without significant observability losses. He had chosen the linear quadratic regulator as a control strategy, and use the genetic algorithm for optimization. After compare finite element model with an experiment, it was possible to obtain the searched methodology.

Friswell [4] studied the continuous modal filter with constant thickness PVDF film, optimizing its shape inside plates. The author used FEM to evaluate the sensibility of determined modes. So, optimization was aimed to the PVDF film boundaries shape which guarantees the best sensibility for a target mode.

Several works in discrete modal filters topic was done and generating important methodologies of filters design, as the methodology developed by Pagani [8]. He did an optimization of location and topology of the PZT sensors also determining the minimum number of sensors to observe the target modes. He used the software ANSYS to build the finite element model of a plate to do sensor array analysis. Using the Genetic Algorithm (GA) the author could develop a robust technique.

This paper has the purpose of optimize a modal filter with the three first modes of a thin aluminum plate that contains one piezoelectric sensor tailoring. This device, bonded at center of structure, contains two glass fiber layers that its lamina angle would be changed. So, a GA would be implemented to optimize and evaluate the sensibility of the laminas angle in the modal filter function of this sensor. To obtain the target modes, some structural dynamical responses, using specifics FRF's, are required and compared with an ideal situation. The model would be developed in ABAQUS FEM software, which provides good connection with MatLab routine and other analysis tools.

2. MODAL FILTERS ANALISYS

2.1. Finite Element Model

To achieve the intent of this work, a finite element analyses (FEA) would be parameterized and associated with some performance criteria, which would be required for optimization process. A simplified model was made to represent the structural dynamics of an aluminum plate with a sensor bonded on the plate center. Sensors are constituted by glass fiber laminate that has some piezoelectric ceramics strips embedded on the laminate surface, that compound the sensor tailoring configuration. A Python routine also was developed to parameterize the FEA model, and so, the parameters like the angle change, could be optimized. Other routines in MatLab could identify this parameters associated with a performance criteria, and use this data in the GA optimization.

The sensor configuration can be exhibited in figure 1. It has seventeen strips of PZT, with 0,38mm of thickness, which is distributed along the top surface of composites part. This part is compounded by two glass fiber layers with 0,5mm of thickness each one, that also is characterized as a unidirectional laminas. The composite matrix is considered isotropic, and the connection between the composites and PZT's is perfectly bonded. Other sensor dimensions can also be illustrated by figure below.

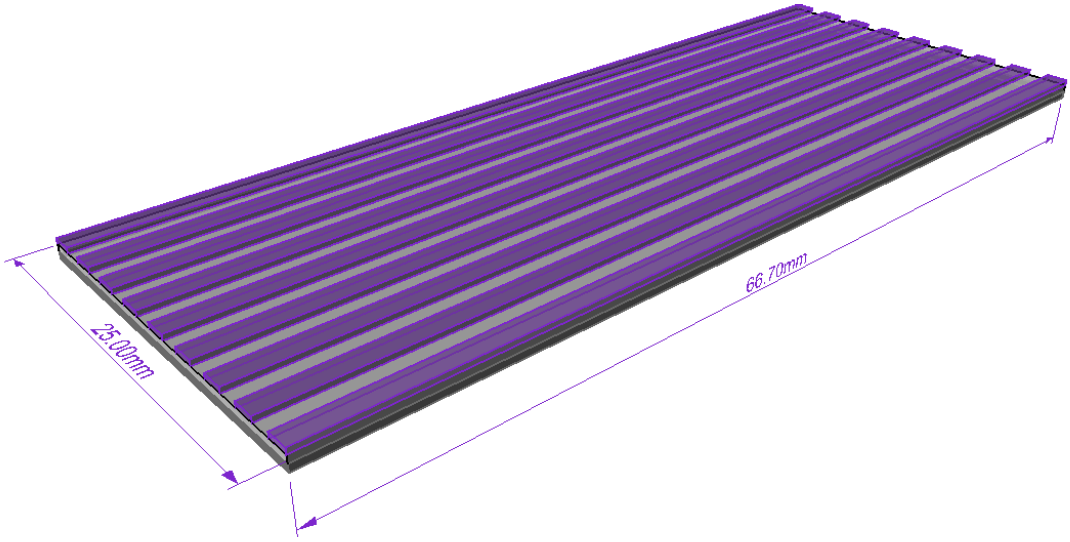

Figure 1. Sensor dimensions.

So, sensor is installed in the center plate, which has square dimensions of 400mm x 400mm and 2mm thickness.

The electrical signal provided by PZT's strips can be obtained by coupled effect which relates electric field whit mechanical deformation. This relation can be illustrated by the constitutive equations:

$$\begin{Bmatrix} T \\ D \end{Bmatrix} = \begin{bmatrix} C & -e \\ e^t & \varepsilon \end{bmatrix} \begin{Bmatrix} S \\ E \end{Bmatrix}. \tag{1}$$

In equation (1), "*T*" is the mechanical stress, "*D*" the electric displacement, "*C*" the stiffness component of elasticity, "*e*" the piezoelectric coefficient and "ε" the dielectric coefficient.

Piezoelectric material has its properties divided in dielectric, elastic and piezoelectric. Some simplifications are considered for this work defining the PZT's properties as a dielectric orthotropic, elastic orthotropic and transversely isotropic. Properties are specified in table 1. Then, equation (1) is developed in the follow matrix to specify the material:

$$\begin{Bmatrix} T_{11} \\ T_{22} \\ T_{33} \\ T_{12} \\ T_{13} \\ T_{23} \\ D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 & 0 & 0 & -e_{13} \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 & 0 & 0 & -e_{13} \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 & 0 & 0 & -e_{33} \\ 0 & 0 & 0 & C_{66} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 & 0 & -e_{15} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} & -e_{15} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & e_{15} & \varepsilon_{11} & 0 & 0 \\ 0 & 0 & 0 & 0 & e_{15} & 0 & 0 & \varepsilon_{11} & 0 \\ e_{13} & e_{13} & e_{33} & 0 & 0 & 0 & 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{Bmatrix} S_{11} \\ S_{22} \\ S_{33} \\ S_{12} \\ S_{13} \\ S_{23} \\ E_1 \\ E_2 \\ E_3 \end{Bmatrix}. \tag{2}$$

The glass fiber layers were defined as elastic orthotropic and transversely isotropic, due the unidirectional lamina consideration. Classical laminate theory was used to calculate the glass fiber composites interactions; so, the anisotropy of material was characterized as an orthotropic and transversely isotropic material, whose engineering constants are defined in table 2.

Table 1.Piezoelectric properties.

Piezoelectric strips properties	Value	Unit
C_{11}	127,20	GPa
C_{12}	80,212	GPa
C_{13}	84,670	GPa
C_{33}	117,44	GPa
C_{44}	22,989	GPa
C_{66}	23,474	GPa
e_{13}	-11,338	C/m^2
e_{15}	17,034	C/m^2
e_{33}	22,145	C/m^2
ε_{11}	27,71e-9	F/m
ε_{33}	33,64e-9	F/m

Table 2.Glass Fiber properties.

Glass Fiber properties	Value	Unit
E_{11}	25	GPa
E_{22}	25	GPa
E_{33}	5	GPa
G_{12}	4	GPa
G_{13}	4	GPa
G_{23}	4	GPa
ν_{12}	0,1	GPa
ν_{13}	0,1	GPa
ν_{23}	0,1	GPa

Where number “3”, in table 1, represents the piezoelectric fiber direction. Tables 1 and 2 are obtained by [9].

The aluminum plate was considered isotropic with Young modulus 23,1GPa and Poisson ratio of 0,33. These properties refer to AL 2024 T3, [6].

Due the several analyses required for the composites fiber angle optimization, some model simplifications are necessary to reduce the computational cost and the feasibility of analysis.

Then, this model is geometrically simplified as illustrated in figure 2, as well as, the type of element, the mesh configuration and boundary conditions. The main FEA objective is to obtain the displacement/force FRF, the voltage response and the first three natural frequencies, which data, would compared with the expected FRF in the optimization criteria.

Boundary conditions was set to get the desired results, fixing one plate extremity in all degrees of freedom and the other extremity vertex was excited with some sinusoidal concentrated nodal force, with unitary amplitude, which represents the input of FRF. It can be showed in figure 2.

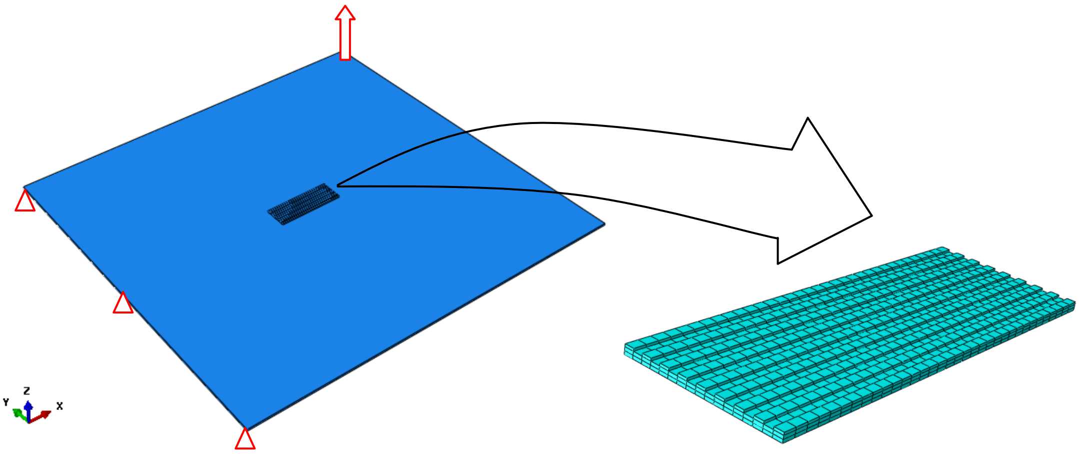

Figure 2.Sensor assembly.

The voltage output should be guaranteed applying the 0 volt condition on the strips bottom region of contact with the composites layers and another equipotential condition should be applied to the top of the strips. These conditions were in according to the polarization direction of the piezoelectric strips. So, the voltage output can be obtained.

It is also important to specify the type of contact between sensor and plate, which should be perfectly bonded. The finite element method calculus was done in ABAQUS to obtain the modal analysis and the FRF related with displacement and load excitation.

Solid and hexagonal elements with geometric linearity were used in all sections of the part. The ABAQUS element type used in, the aluminum plate and the two glass fiber layers of Patch, was C3D8I, which contains 8 nodes and 8 degrees of freedom. On the piezoelectric strips was used the piezoelectric element type C3D8E, which also contains 8 nodes and 9 degrees of freedom which one is related to voltage.

There are two unidirectional glass fiber layers, whose its angle of fiber align can be set in the python routine which describes all commands to set the finite element model in ABAQUS.

2.2Optimization Algorithm

Genetic algorithms are an optimization method that uses the evolution theory concept, to search the global optimal [3]. Each possible solution of a problem is faced as an “Individual” with an encoded “Chromosomes”. This codification is obtained by a “Genes” group that maintain individual’s characteristic. There also is a particular value for each Individual associated with its problem solution potentiality, which is common known as “Fitness”. So, there is a method, based in a binary numbers that allow crossing individuals represented by number that save its characteristics in genes.

Then, to start the optimization process, some initial “Population” of individuals are randomly generated. This generation can decode its chromosome and apply its fitness

function, after new individuals are generated by combining individuals of the previous population. This process can be divided in the Individual selection, Crossover and Mutation. The first one is related with method and criteria that is used to choose individuals. The crossover create new individuals by change genes with the selected individuals, and the mutation which ensures that, with low probability, a few genes are modified and a new search space can be explored, thereby increasing the chance of achieving a global optimum. The process is repeated until a new complete population is established, thereby completing a generation. The algorithm is further iterated only if a termination criterion is not satisfied.
The identification process is based in the conventional GA as described by Goldberg [3].

The population is randomly generated and, at each generation, reproduction operators works until the size of this population is doubled. By sorting the new doubled population, the scheme discards the half with worst fitness values.

2.3 Angle Layer Optimization

Even with the finite element model done, we need to establish a connection with the optimization algorithm. The GA works creating one angle population at random, based on the angle range of interest. This angles need to be qualified according with how it may be more able than others, to achieve the project objective. When this qualification is done by the FEA, the population crossing can be made to obtain the new generation, which would be qualified by the FEA again, and this process repeats until the best generation would be founded.

After each crossing, the algorithm makes elitism pre-definition, comparing the new generation with the previous one, and then, the best members are selected to compound the next generation to be crossed.

Definition of how a specific angle configuration is better than other, is associated with how it can improve the modal filter objective, that is obtain the modal response of structure minimizing the sensor structural dynamical influence on the plate's response. When sensor is bonded at plate, the natural frequencies and peaks of resonance can be changed. Then, the use of laminate composites purpose is reduce this stiffness and mass influence of sensor, in way to optimize the laminas angle.

This work, consider the first three modes to be observed as a modal filter mission. So, analysis of an aluminum plate, without sensor was done to obtain the displacement/force FRF that we are searching for. It is the clean FRF. Figure 3 illustrate the modes animation, and figure 4 shows the clean FRF obtained with force at one corner's plate as input, and displacement at center's plate as output.

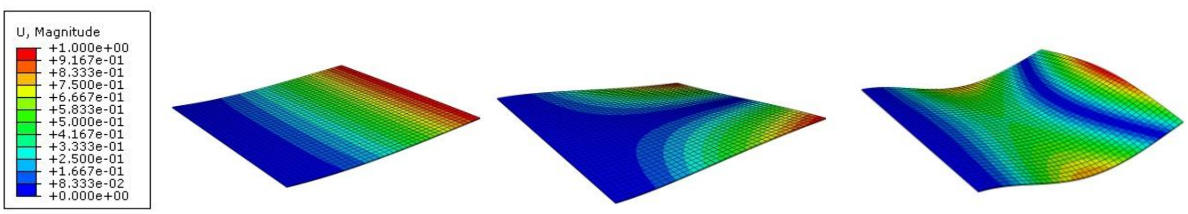

Figure 3. The first three illustrated modes (first mode from left and third mode from right).

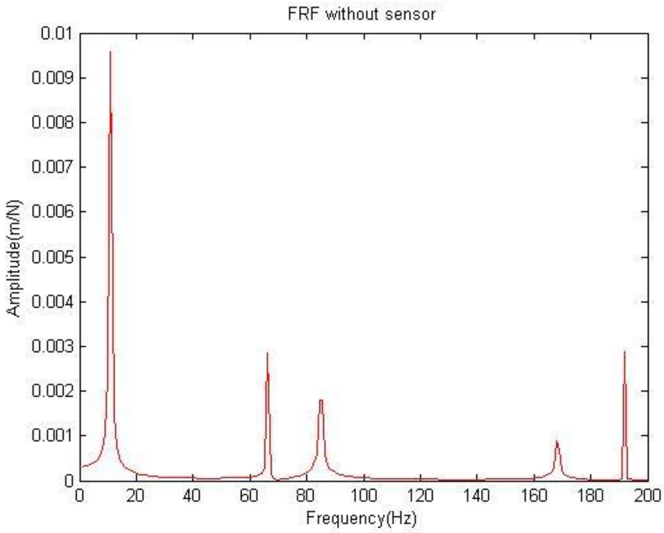

Figure 4. FRF (displacement/force) of aluminum plate without sensor.

As can be seen, the second mode have no displacement at center's plate, and it would not be obtained with sensor centralized, which reveals that second mode should not appear at figure 4 FRF.

After take awareness about the searched FRF, a metric, that approaches the response between the clean plate and the plate with sensor, would be developed. The concept is to calculate the peaks and frequencies and compare the difference of the same parameters from the clean plate. Minimizing these differences is the same to optimize the laminate angles.

The metric that determines the qualification of one specific angle configuration, can be obtained with the follow adopted method:

1 – For each population member, the FRF and the natural frequencies is obtained from a text file by finite element analysis.

2 – The first three peaks of that FRF are subtracted of the clean FRF correspondent peaks. This value cannot be negative, to avoid the sensor as an amplifier function.

3- The same procedure is done for the first three natural frequencies, and the modulus of that difference is also calculated.

4 – Then, for each case, the result of this both differences (peaks and frequencies) is summed.

5 – The inverse of add obtained is defined as a fitness number, which is the qualify metric for each member.

Mean idea is to minimize that differences, and so, maximize the fitness number of each configuration analyzed. The way of obtain the fitness number is illustrated by figure 5 with the arrows relating which amplitude differences to compound the fitness. Natural frequencies values also are shown to include in fitness calculus. The left graphic is an FRF example, with -45 degrees as angle 1 and 45 degrees as angle 2, and the right graphic represents the plate without sensor. Angle 1 represented by "a1" is the lamina angle that is in contact whit plate, and angle 2 represented by "a2" is the lamina angle that is above, in contact with piezoelectric strips.

The software's relation between the fitness calculus whit the FEA and the GA are illustrated by the calculus layout in figure 6.

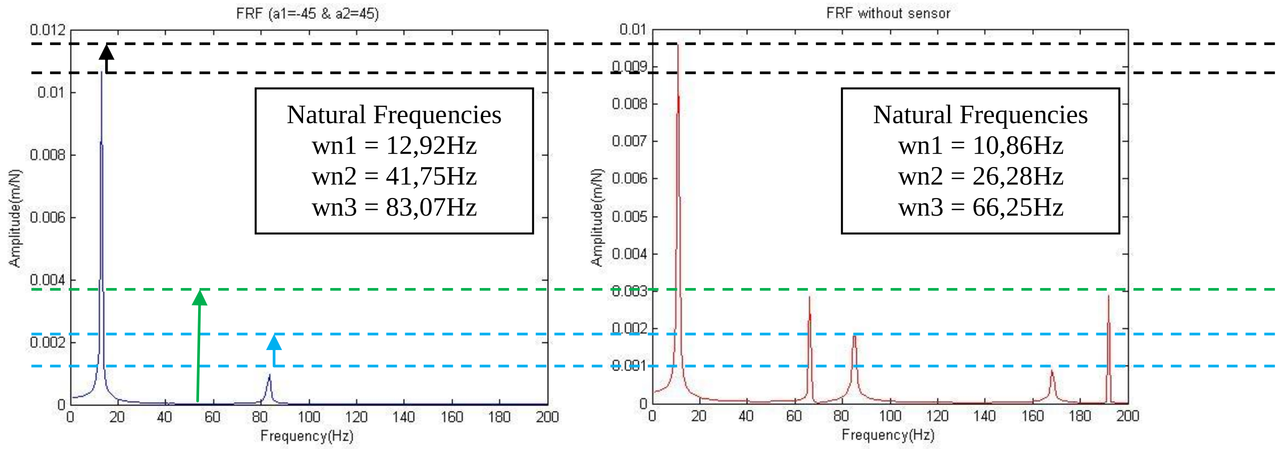

Figure 5.Fitness estimation.

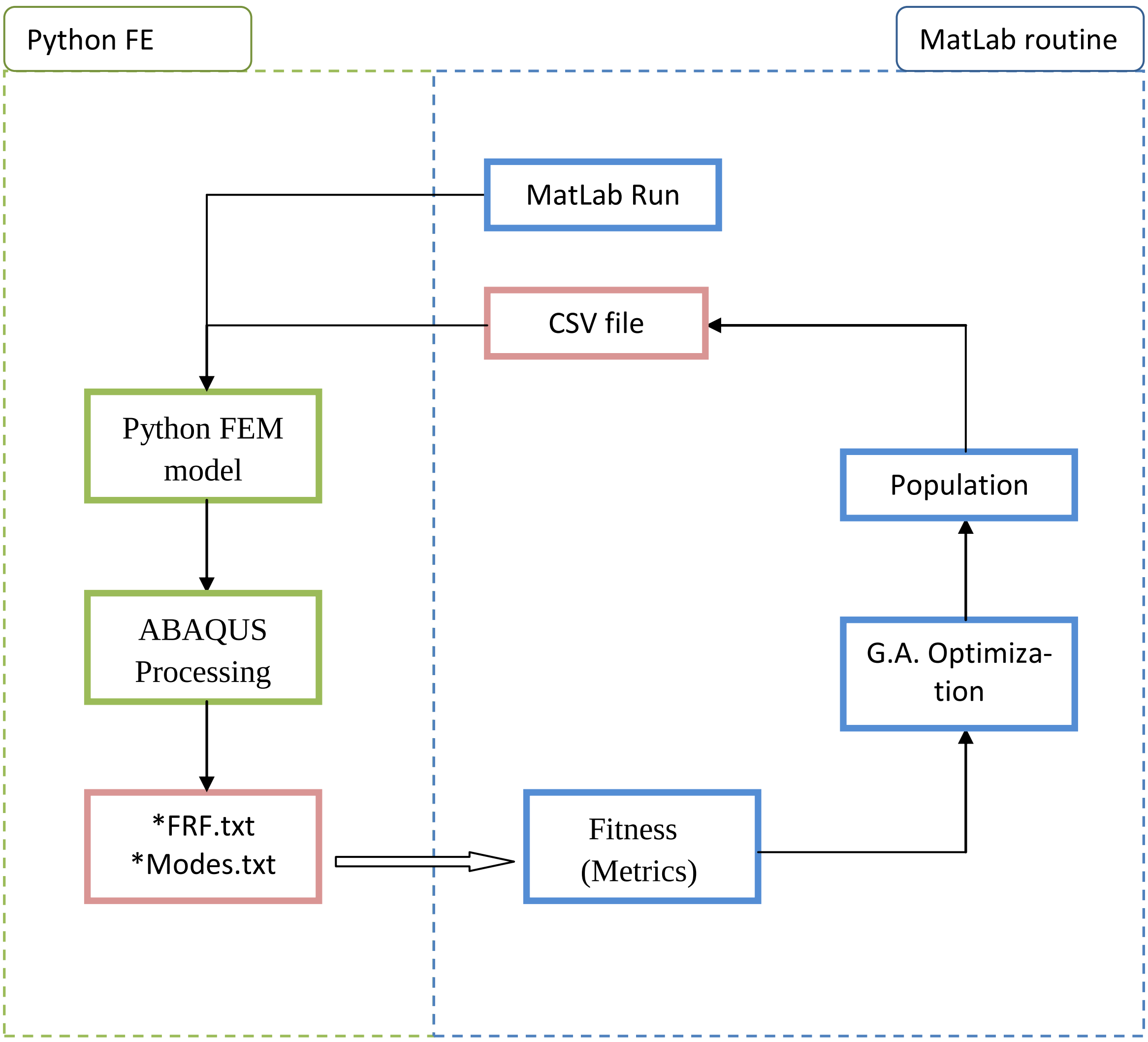

Figure 6.Layout of optimization process.

3. RESULTS

It was necessary to set de GA parameters that better works whit the related case. Considering angles varying between -90 to 90 degrees as layer direction, one parameter related with the divisions of this interval were assumed about 1 degree. The number of generations should be great, but, according with some tests, as figure 7 shows, optimization have been established for generation number smaller than 10. The population number was considered 20, intending to reduce computational cost. Number of crossover points and the crossover probability was adopted as 2 and 100% respectively.

Before start the optimization analysis, the angle change sensibility was observed using the basic cases of laminates, experimenting extreme configurations. Figure 6 shows the voltage/force FRF's of this cases. Voltage was used to obtain the magnitude of sensor signal without incorporate gains.

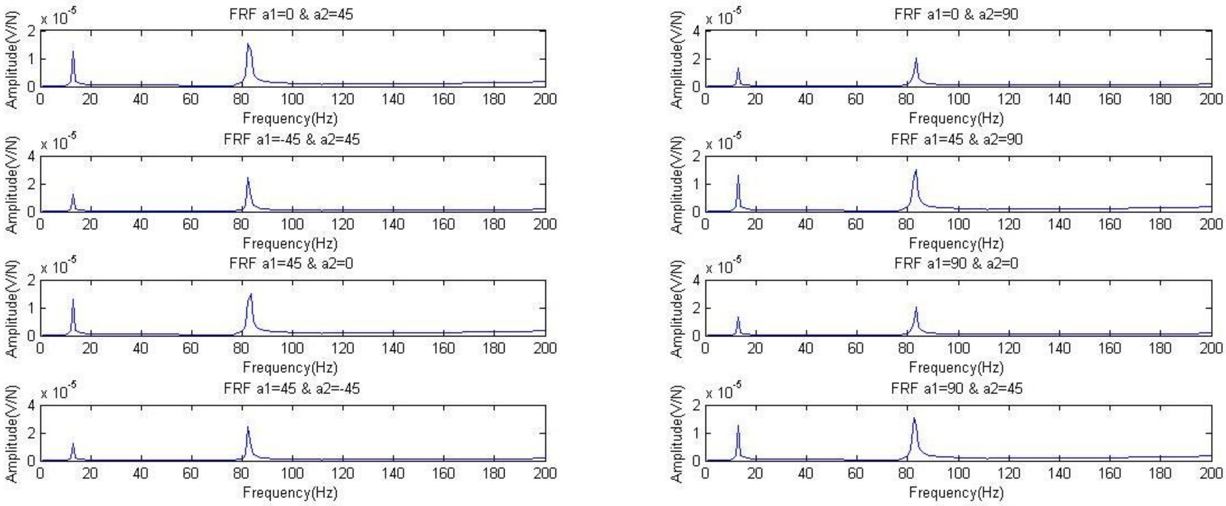

Figure 7. FRF's (voltage/force) of basic laminates.

Is possible to see that the electric signal has small magnitude, and its variation, even for the extreme cases, is also small. It reveals that is hard to obtain a robust optimization using this kind of FRF, which can result in a small fitness variation and then, small difference of laminates qualifications. Nevertheless, using displacement/force FRF, the qualify variation cannot substantially increase; and then, a little number of generations is used to optimize the laminate as can be seen at figure 8.

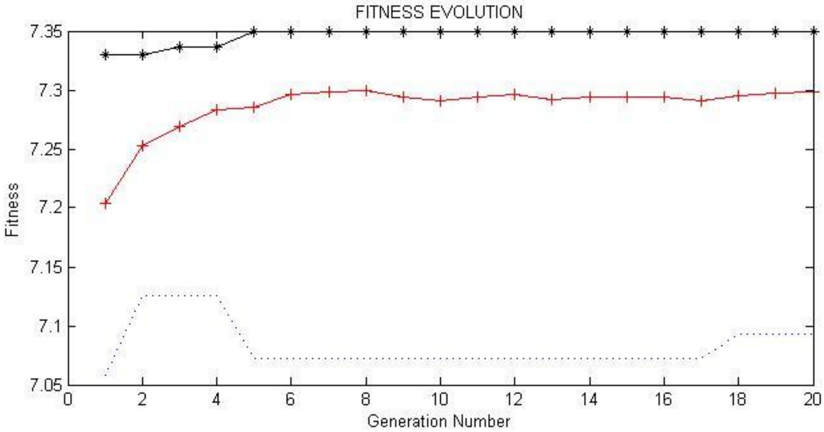

Figure 8. Fitness evolution.

At seventh generation was possible to obtain the optimal laminate configuration that correspond to angle 1 as 58,8 degrees, and angle 2 as -07,8 degrees. This information can be verified in figure 9.

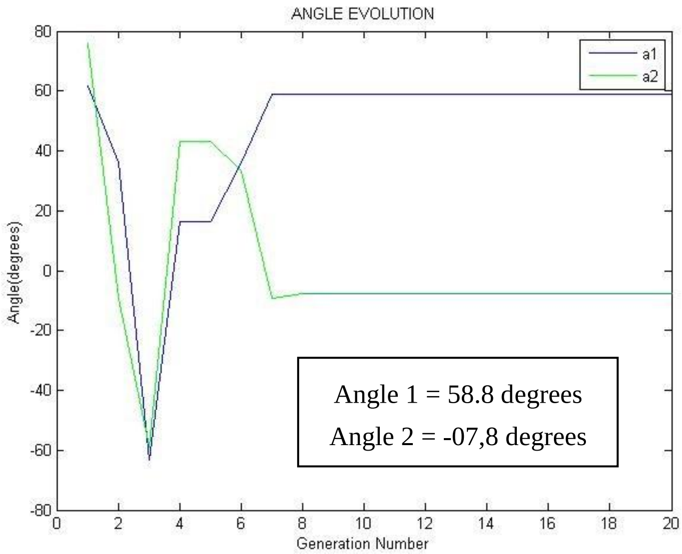

Figure 9. Angle optimization.

Comparing the plate with and without sensor themselves, the FRF response can be shown at figure 10, which reveals that the first mode has almost the same peak magnitude, but the natural frequency is ahead. The second mode was not obtained due the sensor position, and the third mode has delayed frequency and a reduced resonant peak. The optimization could reveal that, if the third peak of model approach of the clean plate peak, the first mode decreases substantially. Natural frequencies can be changed not only due the angle configuration but also according with the sensor size due the stiffness and inertia influence.

Plate with sensor change the plate's natural frequency as, first frequency change from 10,86Hz to 12,92Hz, the second change from 26,28Hz to 41,8123, and the third one changed from 66,25Hz to 82,94Hz.

Figure 10 shows the FRF comparison, highlighting the optimal laminate for this plate, and also makes a comparison with the case that only PZT strips are used as sensor, which reveals the differences between composites uses in sensors. Figure 11 shows the same idea using logarithmic scale.

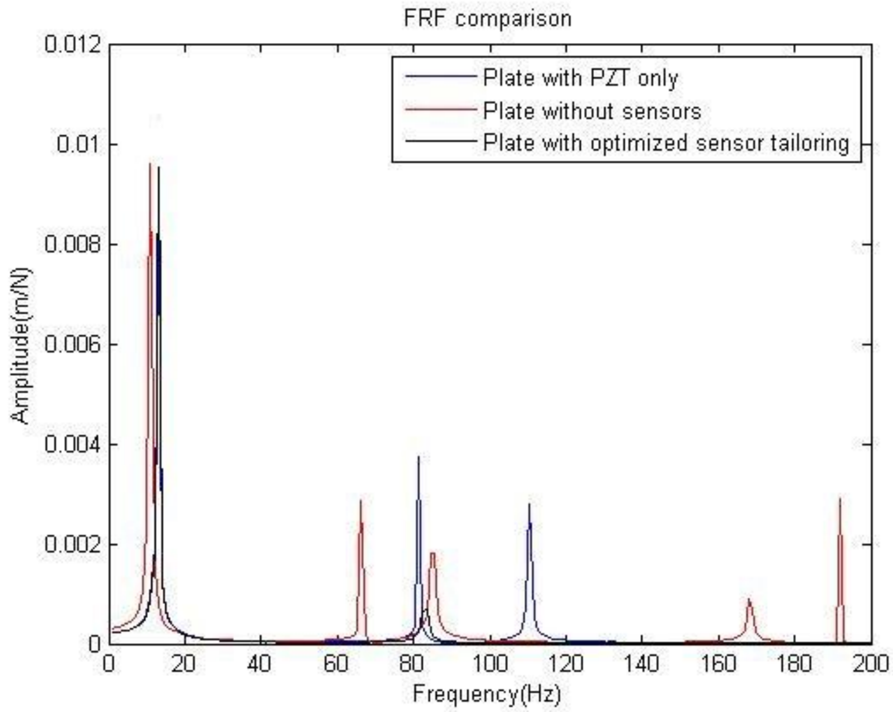

Figure 10. FRF comparison.

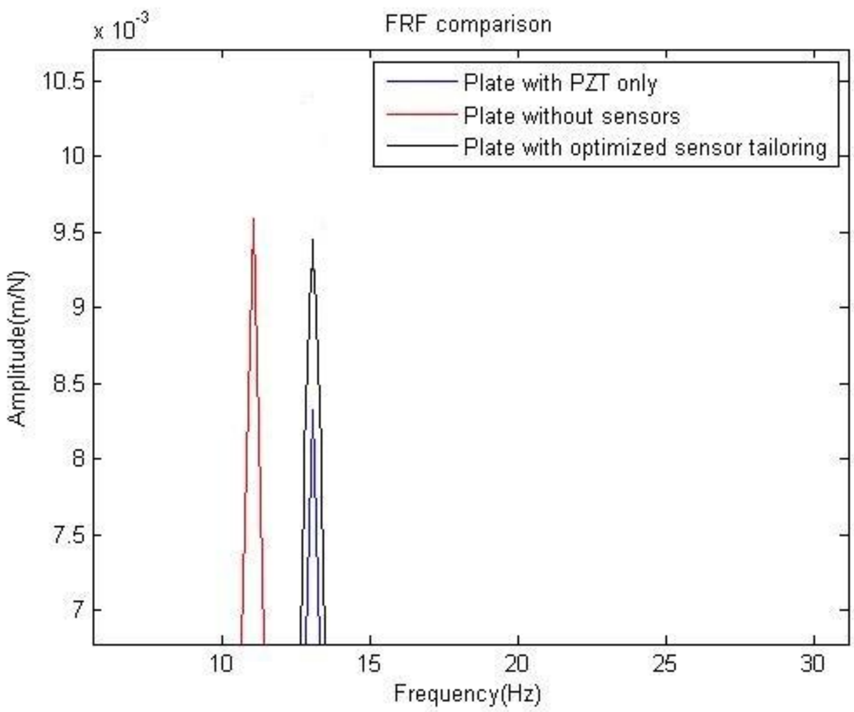

Figure 11. Amplitude zoom at first mode from figure 10.

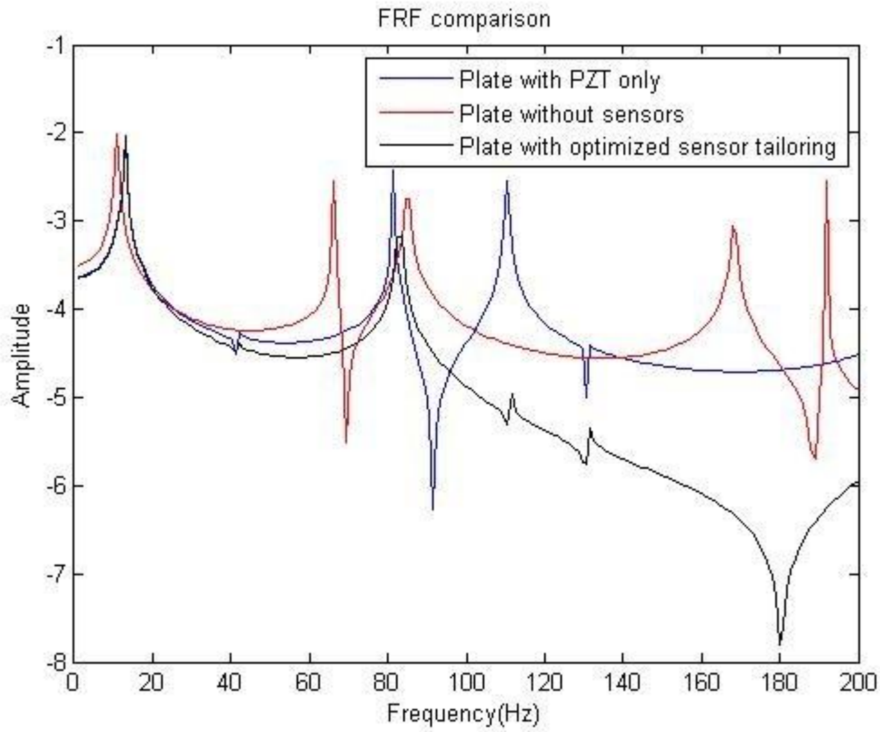

Figure 12. Logarithmic scale comparison.

Figures 10 to 12 can show that, when a sensor consist only by PZT strips, whit the same boundary conditions and loading excitation, the first mode peak is reduced while the third one is increased, as well as, the first natural frequency is ahead and the third one is late. Considering this isolated effect, is possible to note that the composite effect, at sensor tailoring, is to increase a little the first peak and reduce the third peak amplification created by PZT strips isolated. About the frequencies, the sensor tailoring could not approximate the first natural frequency, but could approach the third frequency.

4. CONCLUSION

The optimization could reveal that the angle change has not a great influence at the modal filter performance, but it can contributes to improve the modal filter performance, as well as observed at the PZT isolated performance comparison. It was possible to note that, there are some modes in which composites can works better, like the third mode of the model considered, which mix flexion with torsion. This kind of modes is interesting to aeroelastic analysis, for example.

The improvement founded can increase the benefits to consider other parameters at optimization, like dimension, position and material properties. The problem of change sensor's dimensions is how it can interfere at the natural frequencies, and sensor position can improve the mode sensibility according with the chosen target modes. The used example shows that the center position is determinant to disable the second mode sensibility. So the position is also important at the optimization.

This work suggest that using composites laminates can be one interest tool which provides a filtering properties of a piezoelectric sensor, exploring the lamina angle configuration, but this change isolated is not enough, and requirements as sensor dimension, number of sensors and position can be included in a optimization with expected better results.

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