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# Sensitivity Analysis on Composite Plates by Using Design of Experiments

**Luiz Fernando dos Santos Souza**

Department of Mechanical Engineering  
UDESC, Santa Catarina State University  
luiz03fernando11@gmail.com

**Volnei Tita**

Department of Aeronautical Engineering  
EESC-USP, University of São Paulo, São Carlos School of Engineering  
voltita@sc.usp.br

**Ricardo de Medeiros**

Department of Mechanical Engineering  
UDESC, Santa Catarina State University  
ricardo.medeiros@udesc.br

## ABSTRACT

The use of composite materials, mainly fiber reinforced polymer matrix, on structural components is increasing in the industry, challenging not only the manufacturing process but also the damage detection methods. The main objective of this work consists on showing the influence of the variations in project variables due to the manufacture process on the dynamic response of composite plates. Being aware of this influence it is possible to establish a range for the admissibility of the manufactured components for posterior analyses. For this, it is necessary to identify the most important parameters, which have effect on structural behavior, based on the manufacture process and how its impact on the dynamic response. To achieve these goals, a design of experiments method and computational analysis are used to conduct a set of numerical evaluations and identify the four most significant parameters among eleven variables related to the composite plate. The variables analyzed were width, length, curvature, ply orientation, thickness, Young's modulus in fiber direction, Young's modulus in transverse direction, shear modulus in ply plane and Poisson coefficient. These parameters were obtained from the experimental analysis of composite plates made of epoxy resin reinforced by carbon fiber, and it aims to obtain data from the variability of the manufacture process. First, free vibration analyses are carried out to find the natural frequencies by using commercial finite element software ABAQUS<sup>TM</sup>. Afterward, the set of Frequency Response Functions (FRFs) obtained from the variation of the most significant parameters were compared against the experimental FRF from reference plates showing the range obtained by the manufacture process used and discussing its effects on damage detection by vibration based methods.

**Keywords:** Structural Health Monitoring, Vibration-Based Methods, Composite Materials, Design of Experiments

## 1. INTRODUCTION

The knowledge about the structural integrity is quite important to prevent accidents and improve the maintenance program. As it is known, structures have a degradation of its material properties along the time due to different sources like environmental conditions, manufacture imperfections,

accidental events and imperfect design. Develop methodologies and systems to detect damages on the structure and evaluate its severity is of great importance to avoid a structural crash before the end of estimated life on the project. As listed by Adams [1] structural damages could have different sources like micro-structural defects, corrosion, residual stress, cracking, fastening fault, adhesive fault, and instabilities. This set of damages induces different behaviors of the material. Thus, aiming to maintain the safety and reliability of the component, it is necessary to inspect periodically.

Maintenance programs have the objective to verify the state of the structure health and evaluate its lifetime remaining to decide between repair or change the component, for this kind of analysis is possible to find several non-destructive techniques (NDT) [2]. Traditional maintenance programs are expensive and its efficiency is very closed to hypothesis made during project design. Methodologies that allow a continuous monitoring of the state of the structure are very interesting to reduce costs and optimize maintenance programs.

In aeronautical industry, 27% of an average aircraft life cycle cost is spent on inspections and repairs [3]. According to PeriyarSelvam et al.[4], there are two main ways to reduce direct maintenance costs, the first one is to improve inherent reliability and the second one is to achieve an optimum maintenance plan. Using a system to carry out structure health monitoring continuously the initial maintenance plan can be updated according to the state of the structure adding or delaying a component repair or replacement.

In this context, structural health monitoring (SHM) systems based on structural vibration behavior have been the focus of attention of many researchers in order to obtain tools to detect, localize and measure damages on structures, important remarks have been discussed by Doebling et al. [5], Sohn et al. [6] and Salawu [7] in reviews, and recent publications [8] [9] [10].

SHM systems use a set of sensors to acquire data from the structure properties aiming to determine if some significant change occurred. On vibration based methods the idea is that damage induces changes in physical properties ( mass, damping and stiffness) and then, changes in modal properties(natural frequencies, modal damping and mode shapes) could be detected [2]. Several experimental techniques have been developed to measure structural response, aiming to allow the real-time structure monitoring, smart materials like piezoelectric are used inner the composite structure instead of accelerometers.

Rytter [11], established a system to classify the damage identification in four levels: Determination of the presence of the damage in the structure, Determination of the geometric location of the damage, Quantification of the damage severity, Prediction of the remaining service life of the structure. After an extensive literature review, an additional level on the Rytter's list has been proposed by [12], the identification of the kind of damage present on the structure.

As all manufacture process, the filament winding does not result in exact components, due to its method some uncertainties are inserted on the part, for example, thickness non-uniformity, fiber angle deviation, etc. Another factor that influences the final component are the elastic properties of the laminate, these can suffer variations due to the processing technique and cure profile [13].

A common technique to evaluate the significance of several variables on a process is the Design of Experiments (DoE), allowing to improve the efficiency of the essays and numerical runs.

Ilzarbe et al. [14] conducted a study summarizing 77 cases of practical DoE application in the engineering. All of the cases were published in important journals between 2001 and 2005. The type of design that is applied, the size of the experiment, the number of factors that influence the response variable, and the sector of application of the design are analyzed. A relevant result is that the traditional Taguchi's Method is one of the most used techniques to perform DoE, combining simplicity and efficiency.

Kleijnen [15] perform a comparison between various classical and modern DoE methods to provide an overview about of simulation experiments for sensitivity analysis and remarks its advantages and

drawbacks, showing that for designs using around 10 variables, classic methods are sufficient for a complete analysis.

In modeling data from a computer experiment, there is no need to be concerned with reducing variance, only bias due to model inadequacy. At the design stage, concepts like blocking and randomization are irrelevant, because one has a deterministic process. Sacks et al. [16] promoted a good general discussion of statistical problems in computer experiments, remarking these differences from traditional experiments.

Therefore, the present work study shows the sensitivity analysis of structure response on composite plates by using DoE. These analyses are very important to validate the robustness of vibration based methods as a tool in SHM systems. Hence, a set of parameters is evaluated by numerical analysis allowing to know the variation in FRF due to manufacture process, grouping results and suggesting a range of main parameters to assure the quality of damage detection.

## 2. MATERIALS AND METHODS

### 2.1 Experimental layout

An experimental apparatus was prepared to conduct the analyses of the composite plates manufactured for this study. In total, 7 composite plates were made of carbon fiber with epoxy resin (Carbon Fiber Reinforced Polymer - CFRP) by filament winding process. Each one has 8 layers oriented at  $0^\circ$  and with design dimensions of 305 mm of length and width 245 mm. These specimens were made at Navy Technological Center in São Paulo.

The natural frequencies and FRFs were obtained in the experimental analysis using accelerometers attached to the plates, as shown in Figure 1. The accelerometer is model 352A24 lightweight structure with sensitivity 102.34 mV/g.

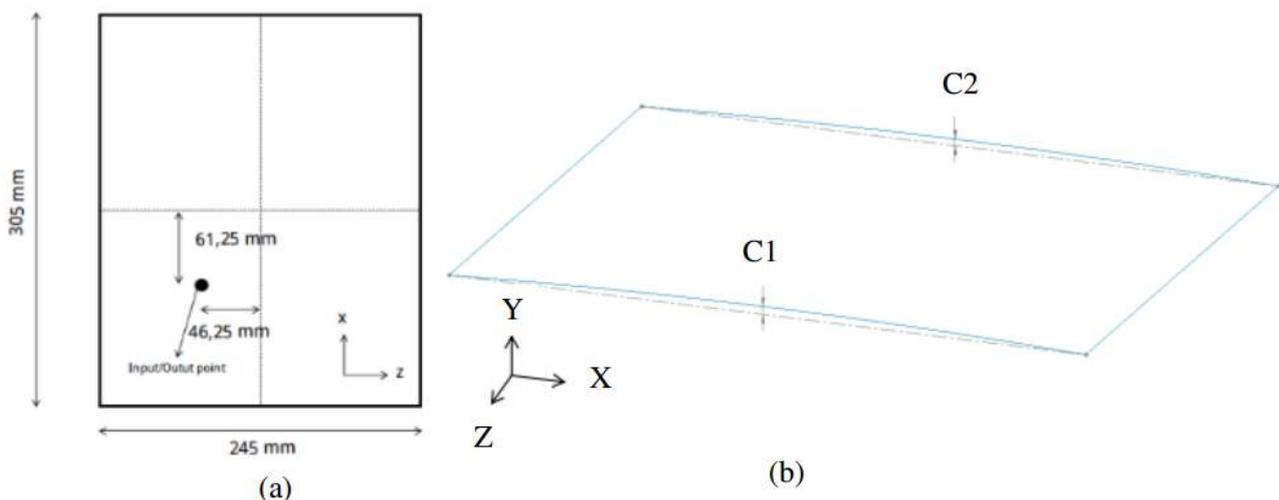


Figure 1. Schematic experimental (a) position of accelerometers and (b) curvature representation

The excitation for both sets of vibration tests was applied by using an impulse signal through an impact hammer PCB Model 0860C3 (Piezotronics). The input was set in the same position on the back side of the plate (Figure 1).

The set-up used in the experiments consists of a plate suspended by elastomeric wires, to simulate “free-free” boundary conditions, accelerometers as sensors and the impact hammer connected to LMS SCADAS Mobile equipment which was controlled by the Test.Lab software (LMS Test.Lab) (Figure 2).

The input provides an excitation over a wide range of the required frequencies. This is important



Figure 2. Complete experimental set-up

because different types of damage can affect different frequency ranges, and the resonant and anti-resonant characteristics of a structure may be good indicators of damage.

Considering the aeronautic scenario, in this experiment, the first eight modal frequencies are analyzed, then the signal acquired consists of 2048 points using the bandwidth of 0 to 512 Hertz. The acquisition time was 4 seconds with a resolution of 0.25 Hz.

Another experimental process carried out on this work was the 3D scanning of the composite plates. This procedure allowed to know the real geometric parameters as thickness, curvature, length and width. Analyzing these plates there are differences between the components even using a well-controlled manufacture process. Then, it is possible to obtain the most probable upper and lower limits for the plates manufactured with this process using an interval of 3 sigmas.

Table 1 summarizes the results of 3D scanning where one has the mean thickness as 2.1755 mm with a standard deviation of 0.0939 mm, resulting on an upper limit of 2.2279 mm and a lower limit of 2.1230 mm.

Table 1. Resume of 3D scanning results

Specimen	P1	P2	P3	P5	P6	P7	P8	Mean
Mean Thickness (mm)	2.2046	2.1992	2.2141	2.172	2.1755	2.1702	2.1733	2.1755
Measure points	328806	325753	321748	279490	307155	289386	305844	
Curvature C1	3.924	3.959	4.111	3.923	3.337	3.686	3.88	3.923
Curvature C2	3.219	3.666	4.324	4.319	4.816	4.639	4.765	4.324

The material properties of M10 *Hexcel*<sup>TM</sup> were studied by [17] [18] using mechanical characterization following the ASTM standards. The plates have a fiber volume fraction of about 63% and its properties are shown in Table 2.

On the filament winding process, there is the physical impossibility of manufacturing components with fiber directions at 0° perfectly. Then, a little deviation of the designed angle is introduced into the process.

Table 2. Hexcel M10 prepreg materials properties [18]

Property	Symbol	Value	Unit
Young Modulus at fiber direction	$E_{11}$	127	GPa
Young Modulus at normal to fiber direction	$E_{22}$	10	GPa
Density	$\rho$	1.58	kg/m <sup>3</sup>
Shear Modulus in ply plane 1-2	$G_{12}$	5.4	GPa
Shear Modulus in ply plane 2-3	$G_{23}$	3.05	GPa
Poisson ratio	$\nu$	0.34	
Tensile strength limit in fiber direction	$X_t$	1400	MPa
Compression limit in fiber direction	$X_c$	930	MPa
Tensile strength limit in transverse direction	$Y_t$	47	MPa
Compression limit in transverse direction	$Y_c$	130	MPa
Shear strength in ply plane 1-2	$S_{12}$	53	MPa

## 2.2 Computational Model

To conduct the sensibility study a computational model was implemented to obtain the dynamic response of the structure. For this work, the model discretization adopted was the element S8R5 that is commonly used for thin plates. This is a quadrilateral element, with eight nodes, reduced integration points and it has six degrees of freedom by node. The plates were modeled with 2989 elements and 9188 nodes like shown in Figure 3.

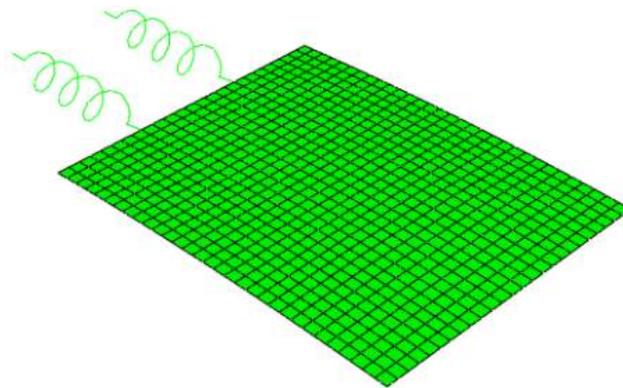


Figure 3. Computational model

Firstly, the modal analyses were carried using "Free-Free" boundary conditions, where to simulate this conditions the plate was suspended by elastomeric wires with spring stiffener of 10N/m like on the experimental setup. The acquisition parameters for the numerical model was the same as the experimental conditions, frequency bandwidth of 0-512 Hz for the modal analyses.

For the frequency response function, a dynamic analysis on the frequency domain was used with the same conditions previously described. In this step, a sinusoidal force was used as input in the same point of the data acquisition. In addition, the damping factors are entered by peak picking method, using as reference the experimental results. For a better approximation of the numerical method, it was used the damping factors mode-by-mode extracted from the experimental results. Therefore, for all simulation the same values of damping were used as shown in Table 3.

Table 3. Damping Coefficient

Frequency (Hz)	Damping(%)
61.35	1.23
153.772	0.50
163.497	0.64
226.081	0.63
255.113	0.68
333.019	0.56
336.376	1.79
362.036	0.55

### 2.3 Design of experiments process

The manufacturing process of a composite plate has a lot of design and process control variables, in this study it will be considered only the variables lied directly with the final component. The DoE prepared for this study consists on 2 main parts. Firstly, a fractional factorial design is applied to identify the four most significant variables that influence the structural response. After that, these four main variables are used to lead a full factorial design in order to obtain the correlations between the inputs and the FRFs.

The variables on the problem is eleven (Width (W), Length (L), Thickness (t), curvature 1 (C1), curvature 2 (C2), fiber angle direction (theta), Longitudinal elastic modulus ( $E_{11}$ ), Transverse elastic modulus  $E_{22}$ , Longitudinal shear modulus ( $G_{12}$ ), Poisson ratio ( $\nu_{12}$ ), considering a composite plate with all plies at 0 degrees. Each variable has two levels resulting on  $2^{11} = 4048$  experiments needed to cover all combinations. By this fact, a screening experiment is useful allowing to reduce the number of total experiments to run.

In this work, the screening experiment has been conducted throughout a two-level fractional factorial design. As on the computer experiments, there are no noise factors to influence the results, so a P-B 12 (i.e the 12-run Plackett-Burman design L12 Table) has been chosen. This clearly satisfies the criterion that the number of experimental trials required for an experiment must be greater than the degree of freedom associated to the main effects and the interaction effects to be studied in the experiment.

The variables level chosen for this work have resulted from an experimental analysis of geometric characteristics of 8 composite plates as aforementioned. From this analysis, the maximum and minimum values of W, L, C1, C2 are taken, and the 3 sigma thickness interval was used. For the material properties it has used data obtained by [18] as standard values, therefore it was used a variation of 10% for maximum and minimum values from the standard values, these values are summarized at Table 4.

The experimental layout for the first part of the analysis which allows all the factor settings is shown in Table 5. This set of experiments aims to get the four main parameters that influence the structural response function. The L12 Table consists on a configuration design where each combination of levels for any pair of factors appears the same number of times, throughout all the experimental runs.

The full factorial design in the second part of the DoE process is composed by 16 numerical configurations using the four most important variables found with this approach, these results are presented in the next section.

Table 4. Factors and its levels considered for DoE analyses

Factor	Level 1	Level 2	Unit
Width (W)	243.71	246.96	mm
Length (L)	303.6	306.5	mm
C1	3.17	4.68	mm
C2	2.53	6.12	mm
Theta	-0.01	0.01	degrees
Thickness (t)	2.12	2.23	mm
$E_{11}$	114.3	139.7	GPa
$E_{22}$	9	11	GPa
$G_{23}$	2.745	3.355	GPa
$\nu_{12}$	0.306	0.374	
$G_{12}$	4.86	5.94	GPa

Table 5. Numerical configurations based on L12 table

	W	L	C1	C2	theta	t	$E_{11}$	$E_{22}$	$G_{23}$	$\nu_{12}$	$G_{12}$
Run1	243.71	303.5	4.68	6.12	-0.01	2.12	114.3	9	2.745	0.306	4.86
Run2	243.71	303.5	4.68	6.12	-0.01	2.23	139.7	11	3.355	0.374	5.94
Run3	243.71	303.5	3.17	2.53	0.01	2.12	114.3	9	3.355	0.374	5.94
Run4	243.71	306.5	4.68	2.53	0.01	2.12	139.7	11	2.745	0.306	5.94
Run5	243.71	306.5	3.17	6.12	0.01	2.23	114.3	11	2.745	0.374	4.86
Run6	243.71	306.5	3.17	2.53	-0.01	2.23	139.7	9	3.355	0.306	4.86
Run7	246.96	303.5	3.17	2.53	-0.01	2.12	139.7	11	2.745	0.374	4.86
Run8	246.96	303.5	3.17	6.12	0.01	2.23	139.7	9	2.745	0.306	5.94
Run9	246.96	303.5	4.68	2.53	0.01	2.23	114.3	11	3.355	0.306	4.86
Run10	246.96	306.5	3.17	6.12	-0.01	2.12	114.3	11	3.355	0.306	5.94
Run11	246.96	306.5	4.68	2.53	-0.01	2.23	114.3	9	2.745	0.374	5.94
Run12	246.96	306.5	4.68	6.12	0.01	2.12	139.7	9	3.355	0.374	4.86

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Numerical sensitive analysis

##### 3.1.1 Factors screening by modal analysis

As previously explained, the first part of this work is to conduct a screening process to identify the most important factors that influence the modal response. For this, it has carried out twelve modal analyses using the parameters shown on Table 5 and eight eigenfrequencies obtained for each run.

The results of the modal analyses are summarized in Table 5, this set of response variables were used to verify the importance of each factor. Thus, for each natural mode, there is a scale of influence from the factors, being necessary compound the influences to determine the final list of most important variables.

Table 6. Natural frequencies (Hz) obtained during the screening process.

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
run1	52.46	108.55	138.88	199.26	224.12	263.26	289.24	308.33
run2	60.99	124.00	161.38	232.03	260.47	304.22	336.16	358.92
run3	57.70	99.870	146.43	199.61	228.56	254.96	296.77	322.38
run4	57.69	112.52	152.32	218.08	245.47	282.46	317.65	337.34
run5	55.11	118.41	151.90	208.02	234.32	296.37	325.50	326.74
run6	54.94	103.03	144.80	229.46	250.82	267.15	301.90	335.65
run7	52.36	107.20	143.26	220.58	242.39	275.23	306.11	324.32
run8	60.42	109.37	153.31	231.56	258.17	273.07	310.08	352.00
run9	55.04	114.09	150.60	209.75	235.94	289.53	321.82	325.94
run10	57.34	114.52	151.32	197.45	227.44	282.29	315.21	323.65
run11	60.03	105.54	152.43	207.82	238.02	267.00	308.91	335.65
run12	51.96	107.73	137.62	218.14	239.44	262.70	286.50	319.73

As a parameter to define the factors influence on the modal response is used the mean difference between the factors influence on modal response weighted by the percentage variation of the level as shown by equation 1, as

$$IF = \frac{abs(ME1(x) - ME2(x))}{PV} \quad (1)$$

where ME1(x) and ME2(x) are the mean of the results influenced by level 1 and level 2 of factor x, respectively. PV is the percentage variation of the factor x and IF is the influence factor. To obtain an global result about the influence of each factor the sum of IF were considered, the final results are shown by Table 7.

These results show that Thickness, Length, Width and transverse modulus are the four most important factors, and it was expected, because these parameters are closed linked to mass and stiffness variation. However, Length and Width are well controlled and have no significant variations during the manufacture process. Then one can get it out of the list and add  $E_{11}$  and  $G_{12}$  that need greater control and quality on the manufacturing process. Another remarkable result is concerning the fiber direction angle, which one has no considerable influence on stiffness as shown in the ranking table notwithstanding have an important role on the materials strength.

Table 7. Results for the screening process and factor's ranking

	Sum of (ME1(x)-ME2(x))	PV	IF	Total Rank
W	10.93	1.0%	830.63	3
L	9.1	1.0%	929.84	2
C1	8.64	32.0%	26.77	8
C2	18.75	59.0%	31.97	7
theta	1.2	200.0%	0.60	11
thickness	81.66	5.0%	1655.40	1
$E_{11}$	56.44	18.0%	310.42	5
$E_{22}$	66.02	18.0%	363.13	4
$G_{23}$	1.56	18.0%	8.55	10
$\nu_{12}$	2.7	18.0%	14.84	9
$G_{12}$	45.73	18.0%	251.5	6

### 3.1.2 Frequency Response Function Analyses

After the screening study, the four main parameters (Thickness,  $E_{22}$ ,  $E_{11}$  and  $G_{12}$ ) were identified and can be used to conduct a full factorial design. These analyses are carried out throughout a dynamic model aiming to obtain the FRF's for each numerical test configuration. The Table 8 shows the entire set used to obtain the results that can characterizes a reference plate.

Table 8. Full factorial numerical configuration

Run	thickness	$E_{22}$	$E_{11}$	$G_{12}$
1	2.12	9	114.3	4.86
2	2.12	9	114.3	5.94
3	2.12	9	139.7	4.86
4	2.12	9	139.7	5.94
5	2.12	11	114.3	4.86
6	2.12	11	114.3	5.94
7	2.12	11	139.7	4.86
8	2.12	11	139.7	5.94
9	2.23	9	114.3	4.86
10	2.23	9	114.3	5.94
11	2.23	9	139.7	4.86
12	2.23	9	139.7	5.94
13	2.23	11	114.3	4.86
14	2.23	11	114.3	5.94
15	2.23	11	139.7	4.86
16	2.23	11	139.7	5.94

The Figure 4 presents the FRF's obtained numerically and it is visible that the manufacture process have influence on the dynamic response of the component. To verify if these variations correspond to reference plates, the Figure 5 shows envelope of the numerical FRF's and experimental FRF's curves. This envelope was obtained by using the upper and lower values of the numerical results. Analyzing

the Figure 5, it can see the envelope having a good approach to involve the experimental values. These results are important to verify the strong influence of the manufacture process on the dynamic response of structures, and it implies the necessity of very robust methods to detect the presence of the damage, because the changes in structural response are significant.

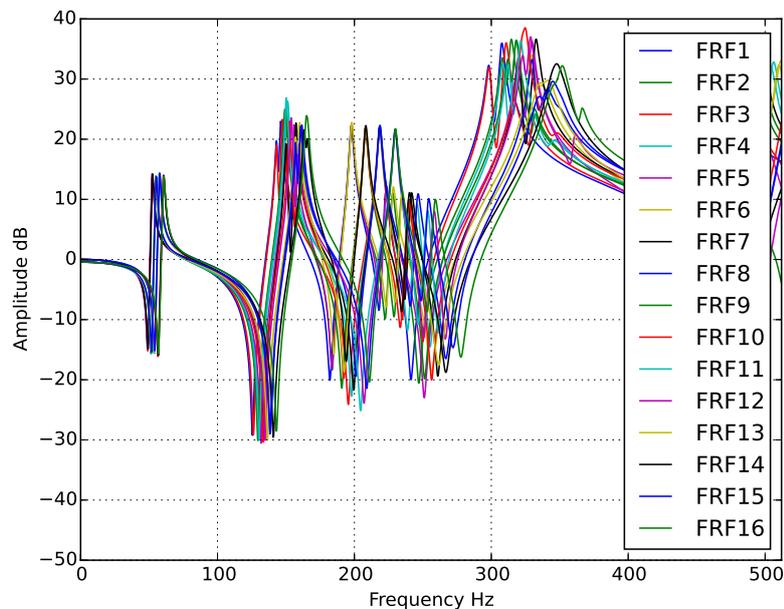


Figure 4. Numerical FRF curves

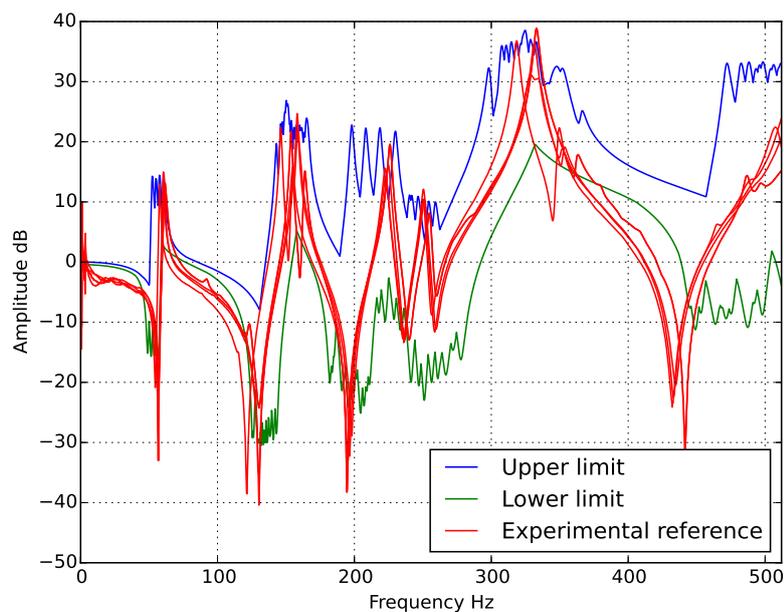


Figure 5. FRF envelop formed by the numerical results and experimental curves

With these results is possible to know the range of the main parameters when subjected to imperfections due the manufacture process.

This range could be used as a quality factor to determine if the initial state of a component is acceptable to be employed and monitored after the installation of a SHM system.

## 4. CONCLUSIONS

The search by more safety and reliable structures carried lots of researchers set their focus on SHM systems. Initially in civil engineering and more recently on mechanical and vehicular engineering. In both cases, SHM systems can help to improve mainly the maintenance activities, detecting damages and preventing against structural rupture due to unpredictable events during the component operation life cycle.

The most part of the SHM methodologies are based on the evaluation of a damage index, that comes from the comparative between the intact and damaged state of the component, for the intact case, the projected behavior are going to be influenced by the manufacturing process. Therefore, this work showed the sensibility of the main parameters involved on a composite plate that influence the dynamic response and obtain a range to establish the quality of the manufacturing process. This is important once that one can prevent erroneous results caused by excessive imperfections during a manufacture process.

A DoE was carried out to analyze and identify the most important parameters linked to the dynamic response of composite plates. For this, a set of computational analyses was used to obtain the modal frequencies and verify the influence of the parameters under study. As expected, the three most important parameters were thickness, width and length, but it is a trivial response and width and length are easily controlled during the manufacture process, then a better result from this analysis consists on classify thickness, transverse elasticity modulus ( $E_{22}$ ), longitudinal elastic modulus ( $E_{11}$ ) and shear modulus ( $G_{12}$ ) as the main parameters for the manufacture process.

The second part of this work used these four main parameters to run a full factorial experiment and obtain the FRFs of each configuration. These results, allowed to plot an envelop of the numerical FRFs and compare with the experimental results for reference plates, showing the range of variation in dynamic response caused by variations in thickness and materials properties.

This paper brings the discussion about the robustness of the SHM systems once that the manufacture process has an important role on final results. It is very important to have consistent information about the reference component and verify if its response is inner the envelop considered by the project data provided to evaluate if the manufacture process has not caused a big influence on it.

The knowledge about what are the main parameters and how they influenced the results is useful to conduct works that aiming adjust the numerical parameters to make the simulation represents more precisely the behavior of composite plates, allowing to predicting fails and degradation of the structures by numerical models while monitoring the real structure. Therefore, these results are of great value to future works on SHM systems.

## 5. ACKNOWLEDGEMENTS

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