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Evaluation of modal frequencies obtained with the impact hammer technique on an epoxy matrix composite material reinforced with glass fibers

Evaluación de las frecuencias modales obtenidas con la técnica del martillo de impacto en un material compuesto de matriz epóxica reforzado con fibras de vidrio

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Abstract

A numerical-experimental methodology is presented to obtain the modal frequencies of polymeric composite materials reinforced with unidirectional fibers (glass fiber and epoxy resin) for possible aeronautical applications. The objective of this study is to compare the behavior of an isotropic material with an orthotropic one. This comparison is to observe the influence of the material properties on its performance under dynamic conditions, where the modal frequencies of a material can directly affect the performance of each element of a structure. The first case describes the numerical and experimental identification of the modal frequencies of an isotropic material (6065 T5 aluminum). The second case study is presented to show how this methodology is adapted to the composite material. The experimental results are obtained by applying the impact hammer testing method. The comparison provides new insights into the modal behavior of vibrations in composite materials. A significant finding of this work is to provide a detailed analysis of the behavior of a unidirectional composite material in terms of the fiber's orientation. Then, this work would be established the fundamentals of the composite material performance for rotative elements applications.

Modal frequencies, Composite materials, Modal analysis

Resumen

Se presenta una metodología numérico-experimental para obtener las frecuencias modales de materiales compuestos poliméricos reforzados con fibras unidireccionales (fibra de vidrio y resina epoxi) y evaluar su comportamiento en componentes aeronáuticos. El objetivo de este estudio es comparar el comportamiento de un metálico con uno material compuesto. Esta se realiza para observar la influencia de las propiedades del material en su respuesta en condiciones dinámicas, donde las frecuencias modales de un material pueden afectar directamente el funcionamiento de un elemento en una estructura. El primer caso fue identificar numérica y experimentalmente las frecuencias modales de un material isotrópico (aluminio 6065 T5), mientras que el segundo caso de estudio fue replicar la metodología en el material compuesto. Los resultados se obtuvieron a partir del ensayo modal con martillo de impacto y un modelo de elementos finitos. La comparación proporciona nuevos conocimientos sobre el comportamiento modal de las vibraciones en materiales compuestos. Un hallazgo significativo de este trabajo es proporcionar un análisis detallado de los comportamientos de un material compuesto unidireccional en términos de la orientación. Por lo tanto, trabajo, fundamenta las bases del desempeño de los materiales compuestos en elementos rotativos.

Frecuencias modales, Materiales compuestos, Análisis modal

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Introduction

The main advantage of substituting metals by composite materials is observed in the final weight of the elements, for example, Titanium alloys or Aluminum have densities of 4500 kg/m3 and 2700 kg/m^3 respectively, while glass or carbon fiber reinforced composites vary between 1400 and 2600 kg/m^3 [I]. As a consequence, air vehicles require less fuel for their operation and, in general, less economic resources to perform the take-off and landing cycles, which makes an aircraft whose constitution is mostly made of composite materials more efficient. An example is the latest models of Boeing and Airbus, the 787 and A350, where practically 50% of the total weight of the structure is made of carbon fiber reinforced plastic and various composite materials [II]. This is a tangible issue addressed with the implementation of new materials.

However, the analysis of the dynamic behavior of a composite material involves an increase in its complexity due to its orthotropic nature. In general, a composite material is composed of two elements, the matrix and the reinforcement, the former being continuous and the latter dispersed. If it is required to manufacture specific components with high structural performance, polymer matrix composites with long continuous fibers are used. For their manufacture, an arrangement of fibers is usually made on a resin layer whose thickness is less than one millimeter. From the above, we can define the matrix as an organic material that can be solid or glassy, where its main function is to keep the fibers together and in position, it also provides protection from the environment, provides a shape, gives ductility and transmits loads uniformly throughout the composite. On the other hand, the reinforcement mainly supports the loads applied to the material as a consequence of which it provides stiffness and strength [III] [IV] [V].

The study of dynamics in orthotropic materials is in development, since its implementation in industries such as aeronautics is becoming more and more common. Therefore, covering all possible combinations of operating and manufacturing conditions is essential to ensure the reliability of components made of composite materials.

The analysis can be approached with different techniques and theories: causing an external excitation to the element under study and finding its modal frequencies through the output signals [VI], considering the effect of the variation of in-plane loads and the stacking sequence in plates [VII], subjecting thin-walled beams to deformations and initial stresses [VIII], taking into account the effect of normal stresses in a laminate [IX] or the influence of factors such as the number of layers, thickness and orientation of the fibers of each one [X].

The focus of this work is to obtain the modal frequencies ω_i of two elements similar in dimensions, the first one made of Aluminum 6065 T5 and the second one of E-type fiberglass and epoxy resin.

The results are obtained theoretically, numerically and experimentally using the impact hammer method. The above in the metallic element to define the most appropriate methodology for each case.

From the results obtained in the metallic element, it is replicated in the finite element model, feeding it back with the mechanical properties of the composite material obtained from the physical characterization of this [XI]. The results of both cases are compared to describe the behavior and from the graphs obtained experimentally, hypotheses of the phenomenon of vibrations in composite materials are proposed.

The added value of the work is the experimental methodology and the analysis of the graphs of the vibratory response of the material.

Methodology

Since the behavior of composite materials under dynamic conditions is not consistent and predictable, it is necessary to have first a theoretical and experimental basis from which to start, in this case to analyze an isotropic material (Aluminum 6063 T5), there are a large number of studies, methodologies and formulations to predict the way in which materials of this nature react [XII].

One of the first objectives is to obtain an experimental methodology applied to the metallic material where the experimental results coincide or do not present relevant discrepancies with the results obtained analytically and numerically. The analysis condition will be beam-type elements with free-free boundary conditions, *i.e.*, there is no restriction of movement in any direction along the beam.

A simple metallic geometry is chosen to start the analysis, a 12.7 x 1.58 x 300 millimeters 6063 T5 aluminum slab section is used. The first five natural frequencies of this element are obtained analytically using formulas 1 and 2. Two equations from different authors are used to compare the analytical results [XIII] [XIV].

$$\omega_i = \frac{\lambda_i^2}{2\pi L^2}\sqrt{\frac{EI}{m}} \qquad (1)$$

$$\omega_i = \frac{K_n}{2\pi}\sqrt{\frac{EIg}{wL^4}} \qquad (2)$$

Where:
ω_i is the natural frequency, i=1,2,3,5....
E is the Young's modulus of the material..
I is the moment of inertia of the cross-sectional area of the element.
g is the acceleration of gravity.
L is the length of the element.
m is the self-weight of the material with respect to the element, $m = density * area$
$w = L * density * area * g$
λ_i constant dependent on boundary conditions and mode of vibration..
K_n constant dependent on boundary conditions and mode of vibration.

Once the values of the natural frequencies are obtained, the finite element software Abaqus CAE is used as a second validation method. The way in which the solution is reached by this method is based on dividing the model into smaller elements, this by meshing, by increasing the number of elements that make up the original element, the results are usually better approximated to the real phenomenon, however, it is not always the appropriate technique to reach the solution, in addition to the fact that increasing the number of elements consumes more computational memory.

In the finite element method it is possible to control the degree of solution used by each element, this is known as shape function, which allows defining the element in a linear or quadratic way. This function tries to resemble the behavior of an object of study after being subjected to the indicated stresses. The consequence of increasing the degree of the shape function is greater accuracy in the final results [XV].

Subsequently, experimental tests are performed to the element, the experiments are carried out with an impact hammer that has a sensor capable of measuring the force with which the element is hit, the blow generates a measurable vibratory response from an accelerometer that is attached to a specific point of the element, the data generated are collected through an array created in the LabVIEW® software. Finally, with the help of Matlab software, Frequency-Response Function (FRF) graphs of the material are generated and from the analysis of these it is possible to obtain the natural frequencies [XVI].

In general, the experimental procedure consists of:

- Recreate the boundary conditions to be studied.
- Place an accelerometer in a specific point previously defined in the element.
- Hit the element with the hammer at specific points.
- Collect displacement and force data for each test.
- Perform data processing.
- Generate the Frequency-Response Function (FRF) of the element.
- Analyze the FRF plot to obtain the natural frequencies.

Figure 1 shows the general scheme of an impact hammer test, where two signals are used, an input signal which is the excitation caused by the impact hammer and an output signal, being the vibratory response of the element obtained through the displacement of the accelerometer. Both are measured with respect to the time elapsed in the test, collecting the data in real time. Impact force data are obtained in Newtons and displacement data in micrometers.

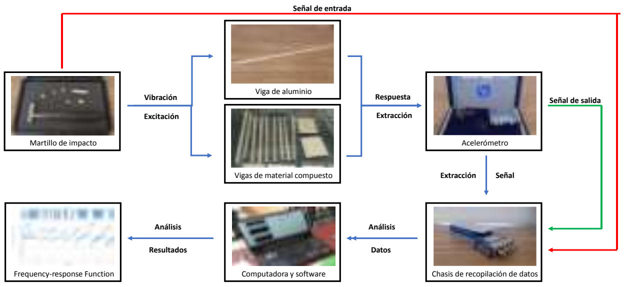


Figure 1 General scheme of the experimental impact hammer test

In the experimental tests, the boundary conditions are simulated by placing the element on a granite table to avoid as much as possible the influence of external elements on the accelerometer readings, at the same time, the beam is supported on sponges with the lowest possible density to avoid restrictions in its displacements in any direction. The accelerometer is attached to one end of the element (Figure 1). Subsequently, a vibratory response is generated by means of blows with the impact hammer at previously defined points of the element (Figure 2).

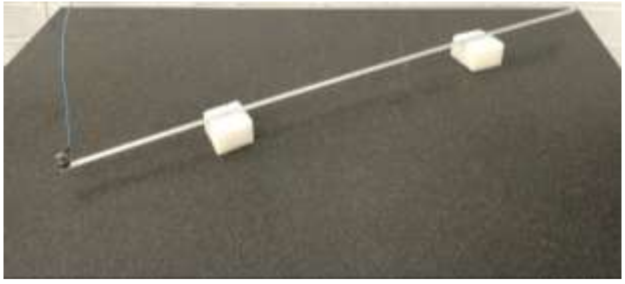


Figure 2 General configuration of the assay

Figure 3 Excitation of the element by impact hammer

Once the tests were completed, composite specimens (epoxy resin reinforced with E-type glass fibers) were fabricated, replicating as far as possible the dimensions of the aluminum element by means of the resin infusion process [XVII].

The properties of Aluminum 6065 T5, E-type glass fiber and EPOLAM 2015 epoxy resin used in this work are presented in Tables 1, 2 and 3 [XVIII].

Properties	
ρ (gr/cm^3)	2.7
E (MPa)	70000
G (MPa)	26300
ν	0.33
σ_C (MPa)	110

Table 1 Mechanical properties Aluminum 6065 T5

Properties	
ρ (gr/cm^3)	2.58
E_1 (MPa)	74000
G_{12} (MPa)	30000
ν_{12}	0.25

Table 2 Mechanical properties E-glass fiber

Properties	
ρ (gr/cm^3)	1.12
E_1 (MPa)	2420
ν	0.3
σ_{Fm} (MPa)	120
σ_{Tm} (MPa)	70

Table 3 Mechanical properties Epoxy resin EPOLAM 2015

Results

As first results we compared the values of the analytical frequencies using formulas 1 and 2 with those obtained in the Abaqus software in its linear and quadratic form functions. The data are presented in Table 4.

Modal frequency	Analytical value 1	Analytical value 2	Linear Abaqus	Quadratic Abaqus
1	92.09	91.99	86.79	91.99
2	253.68	253.57	239.28	253.61
3	497.50	497.11	469.19	497.28
4	822.32	821.74	775.83	822.25
5	1229.36	1227.54	1159.40	1228.70

Table 4 Analytical and numerical modal frequencies in Hertz

Analyzing the obtained values, it becomes evident that the quadratic analysis in the finite element software practically eliminates the margin of error with respect to the analytical results.

Figure 2 compares the modal frequency 5 using the quadratic shape function. A total of 45000 elements were generated for the model, replicating the geometry of the Aluminum sill section.

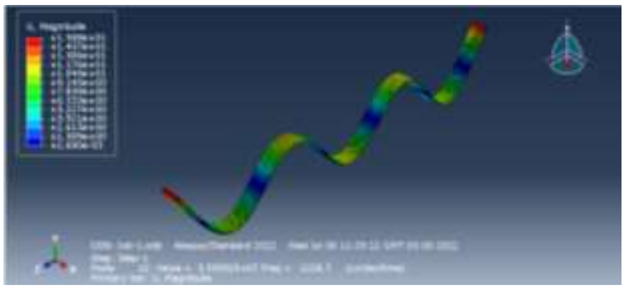


Figure 4 Fifth modal frequency with value 1228.7 Hz.

Seventy experiments were carried out, 42 of which were successful. From the total number of samples, the values of the first five natural frequencies were obtained, making an average to compare with the analytical and numerical results, which are presented in Table 5.

Modal frequency	Experimental values
1	75.21
2	201.65
3	538.11
4	890.2
5	1231.32

Table 5 Experimental modal frequencies in Hertz.

After the analysis of the aluminum element and the fabrication of the composite specimens, a physical characterization of the material is carried out in order to calculate its mechanical properties from the rule of mixtures [XI]. The properties shown in Table 6 are obtained.

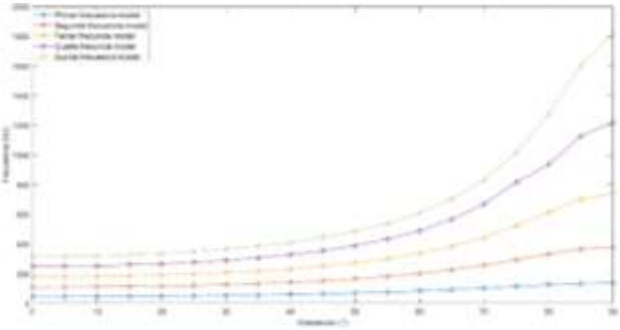
Properties	
ρ (gr/cm^3)	2.009
E_1 (MPa)	47501.74
E_2 (MPa)	6684.54
ν_{12}	0.26
ν_{21}	0.036
G_{12} (MPa)	6169.02
G_{23} (MPa)	3.22

Table 6 Mechanical properties of composite material

Due to the complexity of the manufacturing process and the lack of control of dimensional parameters such as thickness during the manufacturing process, fiberglass specimens with dimensions of 14.54x2.48x300 millimeters were obtained. With an average layer thickness of 0.031 millimeters.

With the values in Table 6 and the dimensions of the specimens, the finite element model is fed back.

It is considered that the composite beams have 8 stacked layers whose orientations are equal in each one and of constant thickness, in order to analyze the most fundamental behavior of the material. Simulations are performed at different orientations to observe the behavior of the modal frequencies with respect to the orientation of the unidirectional fibers in a composite.



Graph 1 Values of the first five modal frequencies in a composite material with respect to the orientation of its unidirectional fibers

From graph 1, it is evident that, as the orientation of the fibers increases, so do the values of the modal frequencies, in the first instance this is due to the increase in the stiffness of the material when the fibers are aligned to its longitudinal axis.

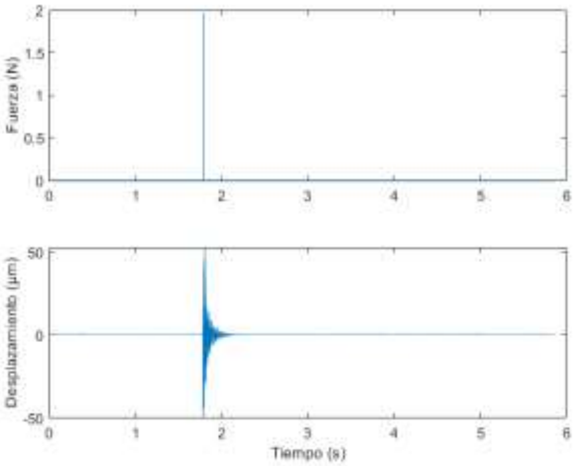
However, since there were discrepancies in the dimensions, it is relevant for the study to perform simulations of the elements of each material with the same dimensions. We will use those obtained in the specimens (14.54x2.48x300 millimeters) to perform the analyses. The results are presented in Table 7.

Modal frequency	Aluminum 6065 T5	90° composite material
1	143.71	137.65
2	396.13	379.04
3	776.58	741.91
4	1283.73	1223.8
5	1917.67	1823.02

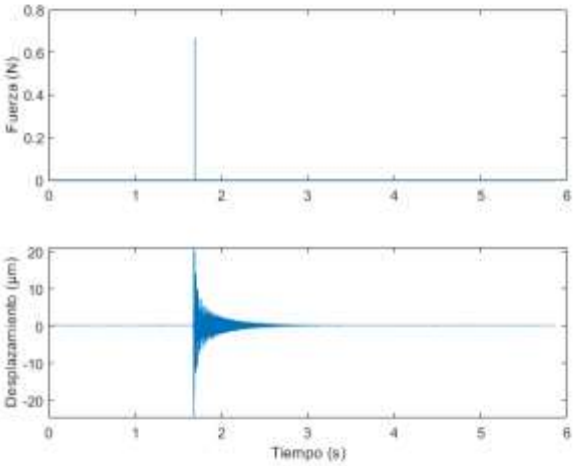
Table 7 Values of modal frequencies in elements of equal dimensions of aluminum and composite material in Hertz

During data processing, two graphs are obtained, the force of the hammer blow and the displacement of the accelerometer, both with respect to time. In metallic elements the displacement is constant and homogeneous, while in the composite material another phenomenon occurs (graphs 2 and 3).

When observing graphs 2 and 3 it is noticeable that, in spite of being the same material, the vibratory response differs greatly in one case with respect to the other. While the specimens with fibers oriented at 45° show a very fast energy dissipation, the 90° orientation requires more time to return to the resting state. This may be due to the individual damping ratio of the matrix and the reinforcement, as well as the significant influence of the material stiffness on the response, which is more relevant than the element dimensions.



Graph 2 Excitation force and element displacements with respect to time in glass fiber specimens with their fibers oriented at 45°



Graph 3 Excitation force and element displacements with respect to time in glass fiber specimens with their fibers oriented at 90°

Conclusions

Since the experimental, theoretical and numerical results of the metallic material tests do not present very high error ranges, it is possible to assure that the methodology can be replicated in composite materials.

The use of the quadratic shape function for the solution of the finite element model of the composite material component is recommended, since it provides results that are closer to the real phenomenon.

It was observed that, in unidirectional composite beams, the change in fiber orientation has a direct impact on the modal frequencies of the beams. Therefore, it is feasible to expand the study to other elements such as plates or shafts.

It is also observed that in aluminum and FRP components with the same dimensions, the first 5 modal frequencies are considerably close. This is of interest since theoretically two elements identical in dimension would have the same dynamic behavior.

A particular phenomenon was detected during the experimentation. This suggests further analysis of the vibrational responses of the composite material. Therefore, it is proposed to calculate the damping ratio present in the composite material, which is mainly attributed to the resin, since it has a more ductile behavior than the reinforcement.

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