Sinop University
Journal of Positive Science International

Journal of Positive Science International, 1 (1), 1-11
Research Article
Issue:2025

Investigation of Dynamic Characteristics of Nomex Composite Sandwich Plate

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Abstract

This study investigates the dynamic characteristics of Nomex composite sandwich structures, which are widely utilized in extensive engineering fields such as aerospace, marine, and automotive industries due to their numerous advantages, including high strength, vibration and sound insulation, and thermal resistance. Considering that these structures typically operate under dynamic conditions, understanding their dynamic properties, such as resonance frequencies, vibration modes, and damping ratios, is crucial for their efficient and safe operation.

In the presented study, the resonance frequencies, vibration modes, and damping ratios of Nomex composite sandwich plates were determined using the Experimental Modal Analysis (EMA) method. It was observed that the structure exhibited a significant vibration damping ratio at the vibration modes corresponding to its resonance frequencies.

Keywords: Nomex composite sandwich structures, Dynamic analysis, Modal analysis, Resonance frequency, Vibration mode shape, Damping ratio

Received Date: 13.05.2025

Revision Date: 16.06.2025

Accepted Date: 16.06.2025

Published Date: 30.06.2025

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Nomex Kompozit Sandviç Plakanın Dinamik Özelliklerinin İncelenmesi

Özet

Bu çalışma, yüksek mukavemet, titreşim ve ses yalıtımı ve termal direnç gibi sayısız avantajları nedeniyle havacılık, denizcilik ve otomotiv endüstrileri gibi kapsamlı mühendislik alanlarında yaygın olarak kullanılan Nomex kompozit sandviç yapıların dinamik özelliklerini araştırmaktadır. Bu yapıların genellikle dinamik koşullar altında çalıştığı düşünüldüğünde, rezonans frekansları, titreşim modları ve sönümleme oranları gibi dinamik özelliklerini anlamak, verimli ve güvenli çalışmaları için çok önemlidir.

Sunulan çalışmada, Nomex kompozit sandviç plakaların rezonans frekansları, titreşim modları ve sönümleme oranları Deneysel Modal Analiz (EMA) yöntemi kullanılarak belirlenmiştir. Yapının, rezonans frekanslarına karşılık gelen titreşim modlarında önemli bir titreşim sönümleme oranı sergilediği gözlemlenmiştir.

Anahtar Kelimeler: Nomex kompozit sandviç yapı, Dinamik analiz, Modal analiz, Rezonans frekansı, Titreşim mod şekli, Sönüm oranı.

Geliş Tarihi: 13.05.2025

Revizyon Tarihi: 16.06.2025

Kabul Tarihi: 16.06.2025

Yayın Tarihi: 30.06.2025

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To cite this article:
Şen, M., Yıldız, Y. O., Yiğid, O. & Kara, S. E. (2025). Investigation of Dynamic Characteristics of Nomex Composite Sandwich Plate, Positive Science International, 1 (1), 1-11.

1. Introduction

Nomex honeycomb structures are extensively utilized across numerous engineering disciplines due to the multitude of advantages they offer. Their low specific weight, coupled with high strength and rigidity characteristics, renders them a superior performance core material in systems operating under dynamic loads, such as those found in aerospace, marine, and automotive industries. Their low density facilitates the creation of lightweight systems, thereby promoting energy efficiency, while their excellent mechanical properties contribute to enhanced structural integrity. Furthermore, their effectiveness in vibration and sound insulation improves operational comfort. Additionally, their thermal resistance ensures durability in challenging environmental conditions. When employed in sandwich composites, these structures significantly enhance impact resistance and contribute to crashworthiness through their energy absorption capabilities. The flexibility inherent in their manufacturing processes allows for production in various geometries and specifications, tailored to diverse application requirements. With all these benefits and superior attributes, Nomex honeycomb structures provide lightweight, durable, safe, and high-performance engineering solutions.

Numerous researchers are conducting studies to determine the mechanical and dynamic properties of these significant engineering materials. Within this scope, a wide range of analytical, numerical, and experimental investigations have been carried out. In this context, some modelling approaches have been proposed to analyze the performance of engineering structures. Karakoç and Freund [1] presented an experimental method, independent of prior assumptions such as orthotropy, to determine the effective in-plane compliance matrices of Nomex honeycomb cellular structures. They processed deformation and stress data obtained from uniaxial tensile tests conducted at various material orientations, along with marker tracking techniques, using transformation and least squares functions, and subsequently calculated all effective in-plane elastic parameters. By comparing their experimental results with analytical solutions based on the deformation of idealized cell structures, they investigated the influence of cell geometry on the elastic properties. In another study, Liu et al. [2], developed a three-dimensional unit cell model to investigate the mechanical properties of Nomex honeycomb core under flatwise compression and the effects of bonding imperfections between the aramid paper layers in double-walled cells. This model, constructed based on actual geometry and material parameters, was validated by comparing its predictions with experimental results. The proposed model offers an effective tool for examining the mechanical behavior of Nomex honeycomb core and the influence of bonding quality. Castanie et al. [3], proposed a multi-level approach for modeling low-velocity/low-energy impacts on metal-skinned Nomex sandwich structures. In this proposed multi-level method, the sandwich structure is modeled using Mindlin plate elements, and the calculated static contact law is implemented in a nonlinear spring located between the impactor and the structure. This allows for the prediction of the dynamic structural response to low-velocity/low-energy impacts, achieving good correlation with dynamic experimental tests. The method relies on the crushing law obtained from a simple compression test of the honeycomb core, eliminating the need for specific tests on the complete structure and indicating the localized nature of the event. In [4], the researchers investigated the mechanical behavior of Nomex honeycomb core under transverse loading, experimentally and numerically. They modeled the resin-paper-resin layered honeycomb cell walls using a meso-scale finite element model they developed. Xie et al. [5], explored the response and mechanical properties of Nomex honeycomb sandwich panels under low-velocity impact. Their investigations focused on the effects of parameters such as honeycomb core density, face-sheet thickness, punch diameter, and impact energy on impact loads and failure modes. They detailed the effects of different deformation types, including plastic buckling of face sheets, folding of cores, deformation of face sheets, and plastic buckling and fracturing of cores. Furthermore, they examined the strength and stiffness characteristics, impact resistance, and penetration resistance for varying densities of the honeycomb core.

Investigation the mechanical characteristics of Nomex sandwich structures is very important for safety and performance of these engineering structures. Zhou et al. [6], investigated the mechanical performance and energy absorption properties of two-layer Nomex honeycombs of different types through compression tests conducted on various combinations (same/different specifications, with/without clapboard), and compared these results with those of single-layer honeycombs. They highlighted that different combinations offer advantages and disadvantages for various application areas, emphasizing the need to select the appropriate combination based on design requirements. In [7], the effect of entrapped air on the mechanical response of Nomex honeycomb sandwich structures under flatwise compression was examined experimentally and numerically, given the significant amount of air trapped within their cells due to their low density. The influence of entrapped air was studied through tests on honeycombs with and without face sheets, and unit cell and multi-cell models were proposed, where this air was modeled using the Airbag and ALE (Arbitrary Lagrangian Eulerian) methods in the LS-DYNA software. Wang [8], investigated the dynamic cushioning properties of paper honeycomb sandwich panels using free drop and shock absorption principles. They examined the effect of honeycomb cell-wall thickness and length on cushioning properties, as well as the impact of density on energy absorption. In [9], a mathematical model was presented to describe the relationship between the energy absorption properties of paper honeycombs and ambient humidity, as well as their structural parameters. This model is a piecewise function that separately addresses the energy absorption of the honeycomb's four distinct deformation stages and relates the energy absorption capacity to the thickness-to-length ratio of the honeycomb cell, the mechanical properties of the cell-wall material tested under a controlled atmosphere, and the relative humidity. The developed model can predict the energy absorption curves of paper honeycombs with varying thickness-to-length ratios in diverse humidity environments and demonstrates good agreement with experimental data, indicating its potential for practical applications such as design optimization and material selection of paper honeycombs. Giglio et al. [10], investigated the behavior of Al-faced and Nomex honeycomb-cored sandwich panels under three-point bending tests, experimentally and numerically. A detailed finite element model, developed using data from flatwise compression tests, accurately reproduced the sandwich panel behavior during testing. The numerical model was employed to examine the influence of parameters difficult to determine experimentally (such as friction and puncher position), revealing that friction affects local indentation and puncher position can modify local folding behavior, although it does not significantly alter the overall force-displacement response. In [11], the loading behavior of bolted Nomex honeycomb core sandwich panels was experimentally tested and modeled. The study aimed to predict the honeycomb local buckling load and identify a Nomex honeycomb material model. Bolt pull-out and flatwise tension tests were conducted, and finite element models of these tests were developed. An orthotropic honeycomb material model was identified through comparison with experimental data. The proposed model accurately simulates the linear portion of the bolt pull-out loading and closely predicts the onset of stiffness reduction, providing a good indication of the joint's allowable load. In another research, Park et al. [12], investigated the effects of elevated temperature and humidity on the strength and failure mode of carbon/BMI-Nomex composite sandwich joints. They conducted pull-out and shear tests under various humidity and temperature conditions, observing the behavior of the core and face sheets and the types of damage that occurred. Gilioli et al. [13], investigated the compression after impact (CAI) strength of aluminum-faced and Nomex honeycomb-cored sandwich panels, which are utilized in applications requiring lightness and energy absorption.

Zhou et al. [14], have utilized vibration-based methods for the debonding detection of Nomex honeycomb sandwich structures. In this context, external factors such as local constraints affecting the vibration response and factors such as surface mechanical properties and phenolic resin thickness of the honeycomb core have been investigated. In [15], the dynamic response of carbon fiber reinforced Nomex sandwich structure under ice ball impacts at different speeds and angles has been investigated, experimentally and numerically. In this way, the failure modes in aviation structures exposed to hail damage were simulated. Zhou et al. [16], investigated the orthotropic damping behavior and mechanism of Nomex honeycomb composites. In this context, they analyzed the sample dimensions for the measurement of frequency-dependent transverse shear moduli and damping coefficients of the honeycomb core structure. They investigated the effects of cell edge length and chord orientation on the damping properties.

The existing literature predominantly focuses on determining the mechanical properties of Nomex sandwich structures. However, considering their applications in dynamically loaded systems such as aerospace, marine, and automotive industries, understanding their dynamic characteristics is paramount for ensuring the safe and efficient operation of these systems. Knowledge of the natural frequencies of these structures is crucial for preventing significant issues like resonance. Furthermore, identifying their vibration mode shapes and damping ratios are key considerations for energy conservation, comfort, and safety. In this study, the dynamic characteristics (natural frequencies, vibration mode shapes, and damping ratios) of plate-like sandwich structures consisting of a honeycomb Nomex core and carbon fiber composite face sheets were determined using Experimental Modal

Analysis (EMA). This study aims to contribute to the literature by raising awareness and promoting the understanding of the importance of considering the dynamic characteristics of these structures.

2. Materials And Method

2.1. Preparation of Nomex Composite Sandwich Plate

For the face sheets of the sandwich test structure, 1 mm thick carbon fiber epoxy prepreg plates, manufactured by pressing under high temperature and pressure (fiber content of 60% by weight and 50% by volume, tensile strength of 775 MPa, elastic modulus of 60 GPa, and density of 1.5 g/cm^3), were utilized. Two pieces measuring 185x304 mm were cut from this plate to serve as the face sheets in the plate sandwich specimen. As the core material, a 1.5 mm high honeycomb Nomex material (phenolic aramid, density 29 kg/m^3) with a 3.2 mm cell size was employed. The honeycomb Nomex material was cut to the same dimensions as the face sheets and bonded between the two carbon fiber plates using epoxy, followed by curing at room temperature. This process resulted in the fabrication of the plate sandwich structure (Figure 1).

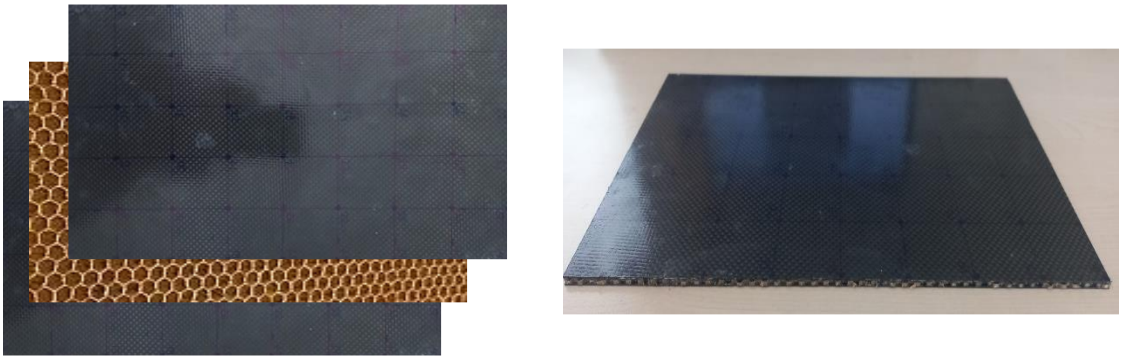


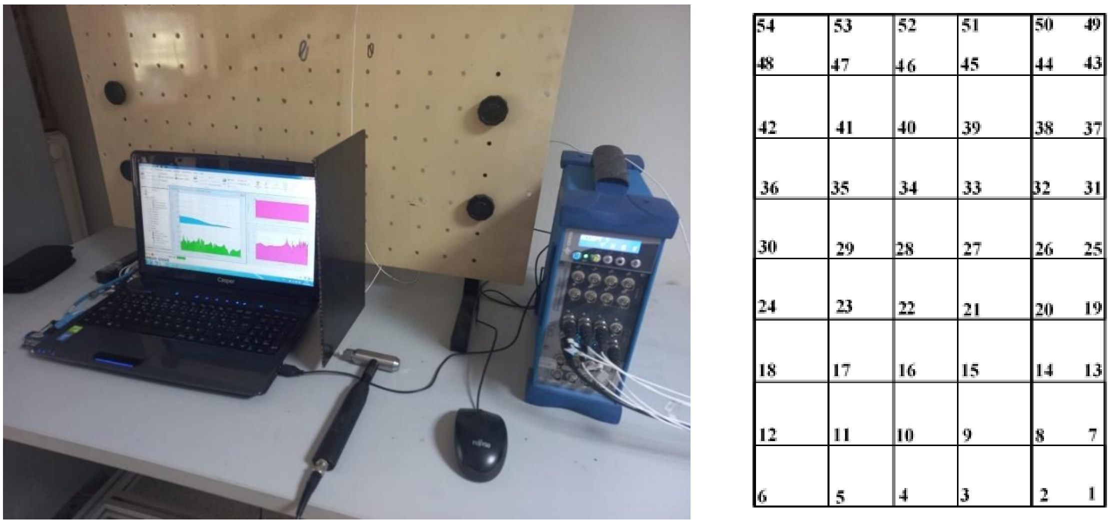
Figure 1. Produced Nomex composite sandwich plate

2.2. Determination of Dynamic Characteristics of Nomex Composite Sandwich Plate

Analytical, numerical, or experimental approaches can be employed to determine the dynamic characteristics of a system. However, in many engineering systems, identifying dynamic properties through analytical methods presents significant challenges and is sometimes not feasible. Similarly, the numerical modeling and dynamic analysis of structures with complex geometries can demand considerable effort and time. In this context, experimental methods offer notable convenience in various engineering applications. In the presented study, the dynamic properties of a sandwich structure with plate geometry, featuring a Nomex honeycomb core and composite face sheets, were obtained using EMA. Nomex composite sandwich structures, distinguished by their high strength, vibration and sound isolation capabilities, as well as advantageous thermal resistance, find applications across a broad spectrum of engineering fields, including aerospace, marine vehicles, and automobiles. Consequently, understanding their dynamic parameters, such as resonance frequencies, vibration modes, and damping ratios, is a critical prerequisite for the optimal and safe operation of these structures.

To analytically determine the dynamic properties of the honeycomb structures that are the subject of this study, several equivalent model approaches have been developed [17], [18]. By analyzing the models created using these equivalent model approaches, the dynamic characteristics of the structures can be estimated approximately [19], [20]. However, due to factors such as the adhesives used in creating the honeycomb and sandwich structures, geometric irregularities, and measurement uncertainties, some errors are inevitable. Similarly, during the process of numerically determining the dynamic characteristics of honeycomb structures through FE analyses, measurement uncertainties, irregularities in the material structure, along with potential parametric errors in mesh generation and boundary conditions, can lead to numerical results that differ from the actual outcomes. Therefore, the results obtained through EMA provide reliable information in terms of reflecting the dynamic properties of the real system. EMA relies on measuring the responses of a structure at predefined coordinates to an applied excitation force. Through the obtained excitation and response data, Frequency Response Functions (FRFs) between the relevant coordinates are calculated. Representing the proportional relationship between the input and output of linear systems, FRFs offer comprehensive information about the dynamic behavior of these systems. Subsequently, the modal model of the structure is created using these calculated FRFs. From this modal model, fundamental dynamic parameters of the structure, such as natural frequencies, vibration mode shapes, and damping properties, can be determined.

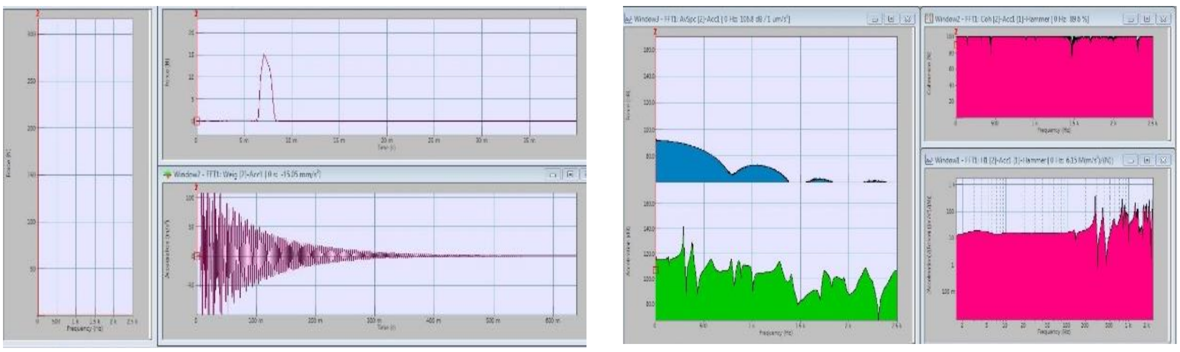
In the EMA test conducted in this study, a modal hammer (Kistler-9724A200) was used to excite the test structure, and the responses of the system to the excitation force were measured using a uniaxial ICP-type accelerometer (Dytran-3097A2). The excitation and response data were acquired using a vibration analyzer (Oros-OR36), and the dynamic characteristics of the test structures were determined by analyzing the collected data with NVGate software. Initially, for the EMA, the test structure was meshed, and excitation and response coordinates were marked on it. For this purpose, the rectangular sandwich plate structure was divided into 40 equal parts of 37x38 mm^2, creating a total of 54 coordinate points (Figure 2b). The test structure was suspended from a stand by its two corners using small drilled holes and thin thread. This setup aimed to achieve free boundary conditions for the structure. The accelerometer used to measure the system's responses was attached to the bottom corner point of the test structure using wax. The reason for attaching the accelerometer to the bottom corner point (coordinate number 1) was that this point was movable in all vibration modes within the investigated frequency band, meaning it did not coincide with any nodal points. If the accelerometer were located at a nodal point (stationary point) in any vibration mode, it would not be possible to obtain any vibration information. A visual representation of the EMA test system is provided in Figure 2a.



(a) **(b)**

Figure 2. (a) EMA test setup; (b) sandwich plate meshing and coordinate planning

The test structure was excited at all designated coordinates using three consecutive impacts of the modal hammer. This procedure enabled the extraction of Frequency Response Functions (FRFs) between each excitation point and the accelerometer location. A critical aspect of the testing process was maintaining consistency in the hammer impact location across repeated trials. The vibration measurement frequency range for the test structure was selected to encompass the first 8 bending and torsional vibration mode shapes. Another crucial aspect was ensuring that the sampling frequency met the Nyquist criterion. Taking this into account during the measurements, the sampling frequency was set to twice the maximum frequency value within the investigated measurement range. Measurements were conducted in the 0-1500 Hz frequency bandwidth with a frequency step of 0.625 Hz. Furthermore, as the responses of the test structure were observed to approach zero within the measurement durations, it was not necessary to apply any windowing functions during the measurements. This ensured that there was no additional damping effect introduced by the measurement process. One example of the measurement signals obtained for excitation and response on NVGate program is shown in Figure 3.



(a) **(b)**

Figure 3. (a) Force (hammer) and response (accelerometer) signals; (b) FTF and Coherence graphs, in NVGate program.

3. Results & Discussion

Response and excitation data were obtained from 54 coordinate points determined on the Nomex sandwich structure examined as in Figure 2-b. Since it allows all mode shapes in the examined frequency band range to be seen, the accelerometer was placed at the lower corner (coordinate 1) point and the structure was excited from all 54 coordinates with the modal hammer to create the relevant FRFs. The FRFs with magnitudes and phases obtained with DMA test are given in Figure 4.

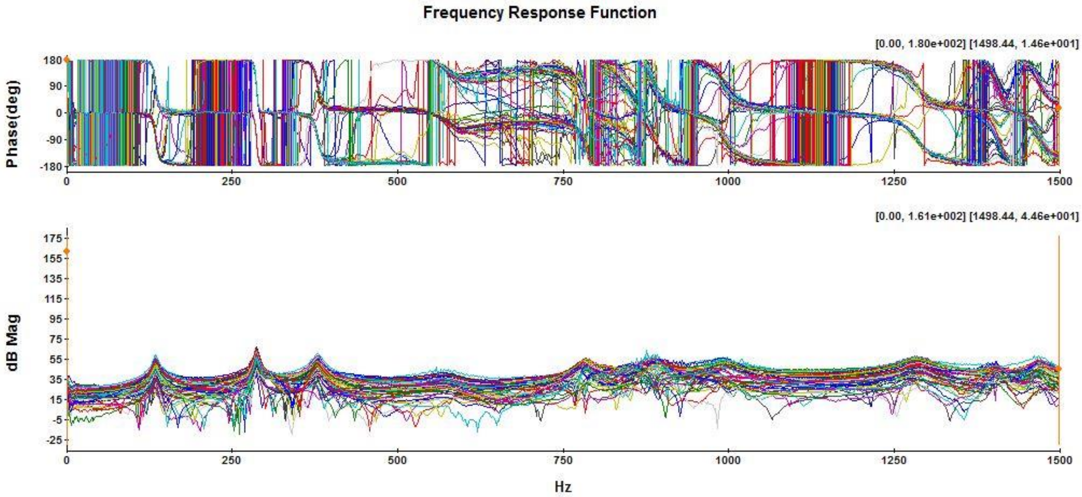


Figure 4. FRFs obtained for Nomex composite sandwich plate

In Figure 4 for the bottom graphs, the sharp peak values represent natural frequencies, while the reverse peaks indicate anti-resonances. In the FRF graphs, natural frequencies are clearly visible in each FRF. The peak points in all FRFs are clustered in the same regions because natural frequencies are a global characteristic of mechanical systems. Conversely, anti-resonance frequencies (the inverse peaks in the FRF graphs) can exhibit different values for each FRF. They may even appear in some FRFs while being entirely absent in others, as these are local characteristics of mechanical systems.

The natural frequency and damping ratio values obtained for the Nomex composite sandwich plate test structure are provided in Table 1 below.

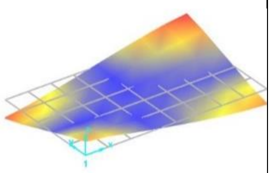
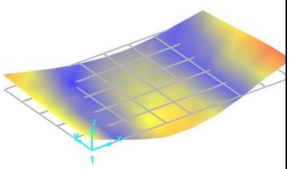
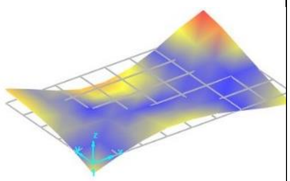
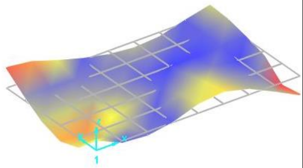
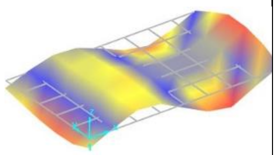
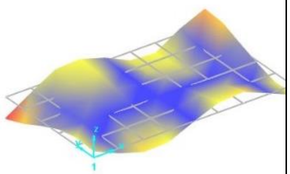
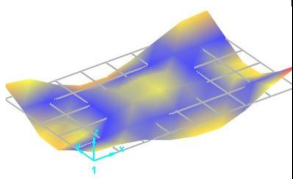
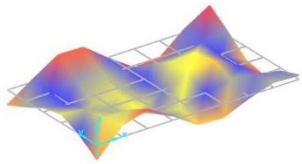
Table 1. Natural frequencies and damping ratios of Nomex composite sandwich plate

Modes	Frequency (Hz)	Damping Ratio (%)
1	134.968	1.725
2	287.292	0.421
3	378.941	1.071
4	572.598	3.770
5	783.110	0.908
6	882.487	0.579
7	993.675	1.668
8	1284.165	1.452

Table 1 presents the natural frequencies and corresponding damping ratios for the first 8 vibration modes of the sandwich test structure. It is evident that the test structure exhibits a notably successful damping performance.

The vibration mode shapes for each natural frequency for the test piece are obtained and given in Table 2 below.

Table 2. Mode shapes of Nomex composite sandwich plate

Vibration mode shapes			
Mode 1 	**Mode 2** 	**Mode 3** 	**Mode 4** 
Mode 5 	**Mode 6** 	**Mode 7** 	**Mode 8** 

The observed vibration mode shapes reflect those expected from thin rectangular plates of similar dimensions. Therefore, in applications where thin Nomex sandwich plate structures are utilized, design and calculations can be performed by considering that they will exhibit normal plate mode shapes.

The zero points (nodal lines) in the mode shapes could be suitable locations for positioning sensitive instruments or systems in applications where these structures are used. This is because these points remain stationary even during the structure's motion at its resonant frequencies.

Furthermore, sensitive components that need to be isolated from vibration can be placed at the anti-resonance points visible in the FRF graphs. For instance, if an anti-resonance is found in the transfer FRF between the coordinates where a harmonic force-generating component (such as a drive unit) and a sensitive part are located, effective isolation can be achieved.

4. Conclusion

This study investigates the dynamic characteristics of Nomex composite sandwich structures, which are frequently preferred in extensive engineering fields such as aerospace, marine, and automotive industries due to their various advantages, including high strength, vibration and sound insulation, and thermal resistance. Considering that these structures typically operate under dynamic conditions, determining their dynamic properties, such as natural frequencies, vibration modes, and damping ratios, is of great importance for their efficient and safe operation. In this presented study, the natural frequencies, vibration modes shapes, and damping ratios of a Nomex composite sandwich plate were examined using the EMA method.

- It was determined that the structure exhibited the highest damping feature at the fundamental natural frequency of Mode 1. In addition, it was observed that it had the lowest damping ratio in Mode 2 (the natural frequency in this mode is almost twice that of Mode 1). The damping ratio in all vibration modes examined except Mode 2 is over 0.5%.
- When looking at the vibration modes, it is seen that they overlap with the mode shapes of the free vibration modes of the rectangular thin plates.
- When looking at the FRF graphs, it is seen that the peaks of the resonance frequencies are quite clearly evident.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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