Uluslararası İleri Doğa Bilimleri ve Mühendislik Araştırmaları Dergisi
Sayı 9, S. 128-140, 8, 2025

Araştırma Makalesi

International Journal of Advanced Natural Sciences and Engineering Researches
Volume 9, pp. 128-140, 8, 2025

Research Article

IJANSER
https://as-proceeding.com/index.php/ijanser
ISSN:2980-0811

Analysis and Determination of Natural Frequencies of Hybrid Composite Layers by Acoustic Measurement

Ali Bedirhan Topan[2], Ziya Özçelik[*]

[1]*Department of Mechatronics Engineering, Faculty of Technology, Selcuk University, Konya, TÜRKİYE*
[2]*Department of Mechatronics Engineering, Faculty of Technology, Selcuk University, Konya, TÜRKİYE*

[*]*(zozcelik@selcuk.edu.tr) Email of the corresponding author*

(Received: 07 August 2025, Accepted: 16 August 2025)

(6th International Conference on Engineering, Natural and Social Sciences ICENSOS 2025, August 10-11, 2025)

ATIF/REFERENCE: Topan, A. B. & Özçelik, Z. (2025). Analysis and Determination of Natural Frequencies of Hybrid Composite Layers by Acoustic Measurement, *International Journal of Advanced Natural Sciences and Engineering Researches*, 9(8), 128-140.

Abstract – In this study, the dynamic properties of hybrid epoxy-based composite laminates reinforced with carbon nanotubes (CNTs) and silicon dioxide (SiO_2) nanoparticles were investigated both experimentally and numerically, focusing particularly on the first mode natural frequencies. Composite specimens were fabricated using the vacuum bagging method in accordance with ASTM D638-14 standards and classified into three groups (K.1, K.2, and K.3) based on different reinforcement configurations. A non-contact acoustic resonance testing method was employed to identify the natural frequencies without causing any damage to the structure. The experimental results were compared with numerical modal analysis results obtained from the SolidWorks simulation environment. Among the tested samples, the K.1 group exhibited the most stable frequency response with an average of 5937.33 Hz, while K.2 and K.3 samples showed variations due to production inconsistencies. The percentage differences between experimental and numerical results ranged from 4.41% to 27.39%, highlighting the influence of nanoparticle dispersion, fiber orientation, and manufacturing accuracy on vibrational behavior. The findings demonstrate that the acoustic resonance method is a reliable and effective tool for frequency-based design and vibration-based structural health monitoring of composite structures.

Keywords – Hybrid Composites, Acoustic Vibration Analysis, Natural Frequency, Carbon Nanotubes (CNTs), Silicon Dioxide (SiO_2), Finite Element Analysis (FEA).

I. INTRODUCTION

In recent years, the demand for lightweight, high-performance, and durable materials has led to the widespread use of composite materials in various engineering fields, including aerospace, automotive, marine, and construction engineering. Composites are made up of a combination of various reinforcement materials and matrix systems, allowing for the creation of materials with a wide range of physical and mechanical properties. Among these materials, fiber-reinforced polymers (FRPs) are particularly favored due to their high specific strength, flexibility, and corrosion resistance. However, composites made with only one type of reinforcement material may exhibit limited properties. Hybrid composites, on the other hand, combine different types of reinforcement and filler materials to offer superior performance, allowing them to be used in a wider range of applications [1].

The study focuses on determining the modulus of elasticity (Young's modulus) of plastic structural components such as automotive rear lamp lenses by utilizing the natural frequency method and updated finite element analysis (FEA). In the study, the natural frequency of the test specimen was first obtained experimentally. Then, a finite element model of the same structure was created, and the difference between the model and experimental natural frequency values was analyzed. These differences were minimized by updating the elastic modulus, thereby producing a more accurate material model [2].

In the study conducted the natural frequency values of a composite cover were examined by incorporating a rib-reinforced design into the structure. The primary aim of the study was to analyze the vibration behavior of a structural component made of composite material and to evaluate how different rib configurations affect the system's natural frequencies. Using the finite element method (FEM), models with various rib geometries were created, and natural frequency analyses were carried out. The results showed that the inclusion of ribs led to an increase in natural frequency values, thereby enhancing the dynamic stiffness of the structure [3].

The dynamic properties of composite materials, especially their vibration behavior, are critical in engineering applications. Structures are often subjected to dynamic loads, which directly affect the behavior of composite materials. Therefore, determining the natural frequencies, mode shapes, and damping ratios of a composite structure is of great importance during the design phase. Modal analysis is a widely used technique for characterizing the dynamic behavior of structures. This method helps in identifying the natural frequencies, mode shapes, and damping ratios, thus providing valuable insights into the structural integrity of the material [4].

Mota et al. (2008) demonstrated that the modal analysis technique can be effectively applied to anisotropic composite laminates, helping predict structural behavior under various dynamic conditions [5]. Similarly analyzed the natural frequencies and buckling loads of composite curved beams, highlighting the impact of geometric and material anisotropy on dynamic responses [4]. Furthermore, Kwon and Plessas (2014) explored the interaction between composite structures and fluid environments, focusing on fluid-structure interaction (FSI) effects and their influence on dynamic properties. These studies provide valuable data on the dynamic characterization of composites, but they also highlight the need for further research to fully understand the dynamic behavior of hybrid composites [6].

In addition to modal analysis, numerical methods such as finite element analysis (FEM) are also widely used to examine the dynamic behavior of composite materials. Dongare and Deshmukh (2012) performed static and modal analyses on composite shafts, modeling their behavior numerically and developing regression equations [7]. Pingulkar and Suresha (2016) used FEM to analyze the free vibration behavior of laminated composite plates, validating their models with experimental data, thus demonstrating the effectiveness of FEM in composite material analysis. These numerical analyses can assist in optimizing the dynamic performance of composite structures [8].

In the study conducted by Jalali, M. B. & Doğan, A. (2023), the free vibration frequencies of laminated composite honeycomb sandwich plates were comparatively examined under different boundary conditions and various stacking angles. The analyses were performed using the finite element method (FEM) [9].

Hybrid composite materials can be strengthened not only with fiber reinforcements but also with nanoparticles. In recent years, nanoparticles such as carbon nanotubes (CNTs) and silica (SiO_2) have been frequently used to enhance the mechanical and dynamic properties of composites. These nanoparticles strengthen the bonds within the material, thereby improving elastic modulus and fracture resistance. Çalışkan (2021) examined the mechanical properties of epoxy-based hybrid composites modified with CNTs and SiO_2 nanoparticles in his thesis, demonstrating the positive effects of nanoparticles on composite material performance. Nanoparticles can also improve the dynamic properties of composites, making the structures more stable and durable [10].

In this study, he discusses the determination of elasticity and shear modulus and modal damping rates of composite bars in tensile compression, bending and torsion states with the help of vibration analysis.

While frequency domain examinations were used to determine elasticity and shear modulus, short-time Fourier transform (STFT) method was applied to determine modal damping rates [11].

Cao, Yang, and Liu (2023) conducted a study based on nonlinear beam theory with the aim of analyzing the structural stability of high-speed underwater vehicles. In the study, considering the fluid-solid interactions exposed to underwater vehicles in motion, the effects of these interactions on the dynamic behavior of carrier structures were evaluated. One of the main findings of the study is that parameters such as elastic modulus and structural rigidity directly affect the natural frequency of the system. It has been shown that increasing the natural frequency increases the dynamic stability of the system under certain conditions, and the structure becomes more stable under critical loads. In addition, it has been emphasized that structural deformations are more limited in high natural frequency systems, and this is especially important in vehicles operating at high speeds [12].

Three different glass fiber reinforced composite/nanocomposite materials, nanoparticle additive (pure), nano clay and nano silica additive, were produced by vacuum-assisted resin infusion method. In the research, the free vibration natural frequencies of these materials were experimentally investigated and the effects of additives on dynamic behavior were comprehensively evaluated [13].

Resonance testing is a preferred method because it provides fast and efficient results in production processes. It allows results to be obtained in a shorter time compared to traditional mechanical tests and can be easily applied in mass production lines, which offers significant advantages in quality control processes. In addition, the resonance test can detect cracks, gaps, and other irregularities in the material with high accuracy, thus providing precise defect detection [14].

However, to understand and integrate the dynamic behavior of hybrid composites into the design process, both experimental and numerical analysis methods need to be combined. This study focuses on investigating the natural frequency behavior of hybrid composites reinforced with glass and carbon fibers and modified with CNT and SiO_2 nanoparticles. The samples were produced using the vacuum bagging method and tested experimentally using non-contact acoustic excitation techniques. The data obtained was validated through finite element analysis (FEA), and the study presents a new approach for dynamic stability and design optimization of hybrid composites.

II. MATERIALS AND METHOD

A. Materials and Properties

In this study, epoxy resin (Fibermak F-1564) and hardener (Fibermak F-3486) were used as the matrix for carbon/glass fiber laminated composites. The epoxy resin has a viscosity of 1200-1400 mPa·s, and the hardener has a viscosity of 10-20 mPa·s. The mechanical properties of the resin are given in Table 1.

Table 1. Mechanical Properties of Epoxy Resin

Properties	Value	Unit
Density	1.1-1.2	(gr\cm^3)
Viscosity	1200-1400	mPa·s
Tensile Strength	60-65	(MPa)
Strength	110-125	(MPa)

B. Sample Preparation

Samples were produced according to ASTM D 638-14 tensile test standards. Epoxy resin and hardener were mixed in a 100/34 ratio, followed by degassing under vacuum at 22°C and 0.75 bar for 10 minutes. After degassing, the mixture was poured into tensile sample molds. A post-curing process was applied at 80°C for 8 hours. Nanoparticles were added at 0.5%, 1.0%, 1.5%, and 2% by weight, and the mixture was homogenized using ultrasonic and mechanical mixing methods. Sample specifications (CNT and SiO2) are presented in Table 2.

Table 2 Sample Specifications (CNT and SiO2)

Properties	Value	Unit
Density	1.1-1.2	gr/cm3
Viscosity	1200-1400	MPa.s
Tensile Strength	60-65	Mpa
Flexural Strength	110-125	Mpa
Modulus of Elasticity		N/m2
Poisson's Ratio	0,47	
Bulk Density	7,5	Kg/m3
Tensile Strength	1000	N/m2
Thermal Conductivity	0,2256	W/(m.K)
Specific Heat	1386	J/(kg. K)

C.Plate Production

Glass fiber was cut into 220×320 mm sizes and placed in a mold in 16 layers. Epoxy resin and nanoparticle mixture was applied layer by layer, followed by curing at 80°C under 0.3 MPa pressure. After curing, the composite laminates were cooled to room temperature, ensuring uniformity between layers.

Table 3. Vibration Tester Technical specifications

Frequency Measurement Range	50 -18000 Hz
Resolution	1 Hz
Output	Percentage of Change (Elasticity Modulus Change
Incite	Electromagnetic Hammer
Measurement Time	50 sn.

D. Vibration Data Acquisition Equipment

In this study, an experimental setup was established to perform acoustic measurement of composite plates. In the experimental setup, an impact hammer was used to give the samples an initial impulse, a microphone was used to detect vibration signals, and a computer was used to process these signals, and acoustic measurement was made (Figure 1). The samples are positioned so that one end is fixed to a rigid support, while the other ends vibrate freely. In the experiment, vibration was initiated by applying an initial impulse of 5 N to the samples with an impact hammer. The audio signals detected by the microphone attached to the fixed tripod, with a bandwidth between 50 Hz and 18000 Hz, were recorded on the computer (Table 3). The graphs of the measurement results obtained were drawn. Graphs of the recorded audio data were drawn to determine the frequency response or noise level. Table 2. shows the technical specifications of the acoustic vibration measurement setup.

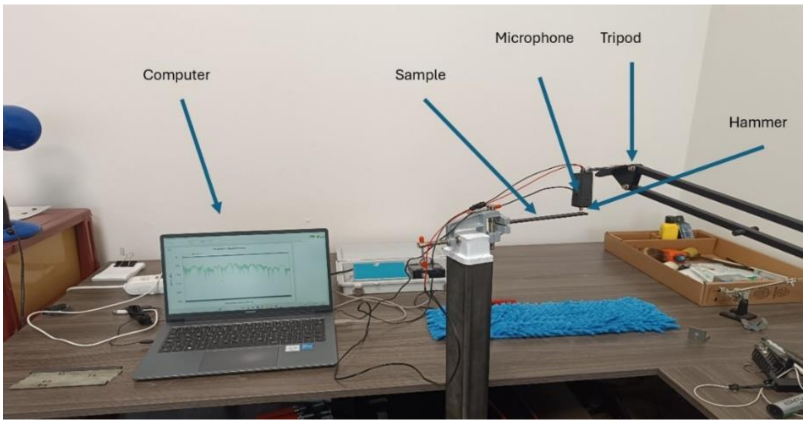

Fig. 1 Vibration Test Setup

Thanks to the natural frequency comparison, the vibration tester can non-destructively analyze parameters such as heat treatment, cracks, layer non-adhesion, fatigue, where the material flexibility changes, and can interpret the elasticity change numerically. The changing elasticity also changes the natural frequency of the material. With the Vibration Tester, the changing flexibility is analyzed very easily and contactless, ensuring that the finished products and intermediate products are of the same quality throughout the process. It can compare the elasticity of two objects in a non-destructive manner. It prevents accidents and losses by detecting mechanical fatigue in advance. Since there is no sensor loading, it provides accurate and fast measurement.

E. Materials produced for vibration tests.

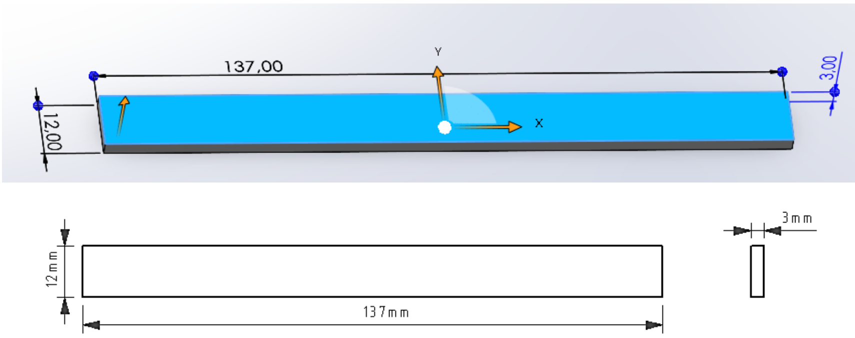

Fig. 2. Composite Samples CAD drawing

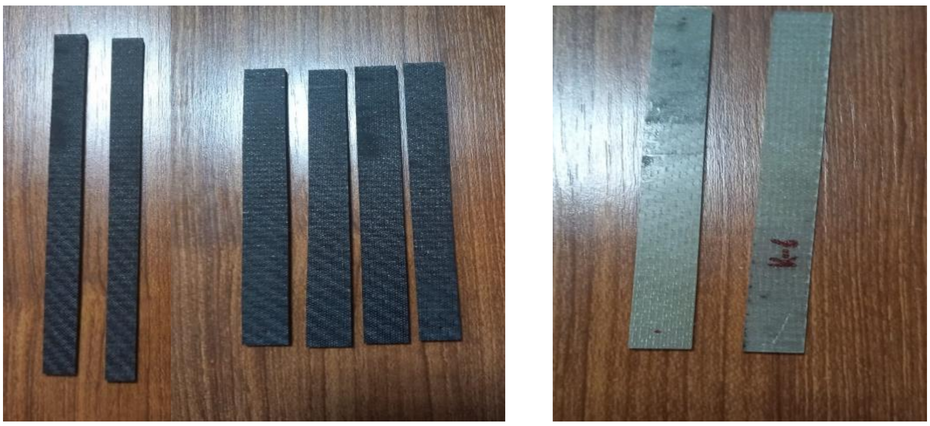

Fig. 3 Composite samples

Three points were determined on each sample and tests and values were taken on these points. In this study, it was aimed to determine the natural frequency values of the material by using the vibration test. Tests were performed using sample sizes in accordance with ASTM D 638-14 standards. To obtain accurate measurements, the test samples are conveniently fixed. In the case of using flexible connections, the joints are meticulously arranged, considering that the impact applied on the material can lead to an axis shift, which may cause incorrect results. Vibration detection was carried out with the help of pulses applied to the designated points. The numerical data obtained because of the tests were analyzed and interpreted graphically. The analyses were evaluated under appropriate test conditions and the results on the dynamic behavior of the material were reliably obtained. Figure 2 shows the CAD drawing of the test sample prepared in accordance with ASTM D 638-14 standards. Figure 3 presents the actual composite samples used in the experiments. This study showed that finite element analysis is an effective method for determining the natural frequencies of composite plates. A detailed examination of the effects of rectangular sections on natural frequencies provides important information to engineers during the design phase. The results obtained can be used to control the vibration behavior of composite plates and to obtain structural designs.

III. RESULTS

The vibration modes of flat rectangular bars are determined via virtual frequency curves in the frequency spectrum. By combining the peak values at the respective natural frequency, the approximate mode shape is obtained. Hertz (Hz), the unit of frequency, refers to the number of repetitions per second.

Strain is the rate of length change of a material and is often used in deformation measurements. The damping ratio represents the energy losses of the structures, and at low damping values, the damped and natural frequencies can be considered equal [15].

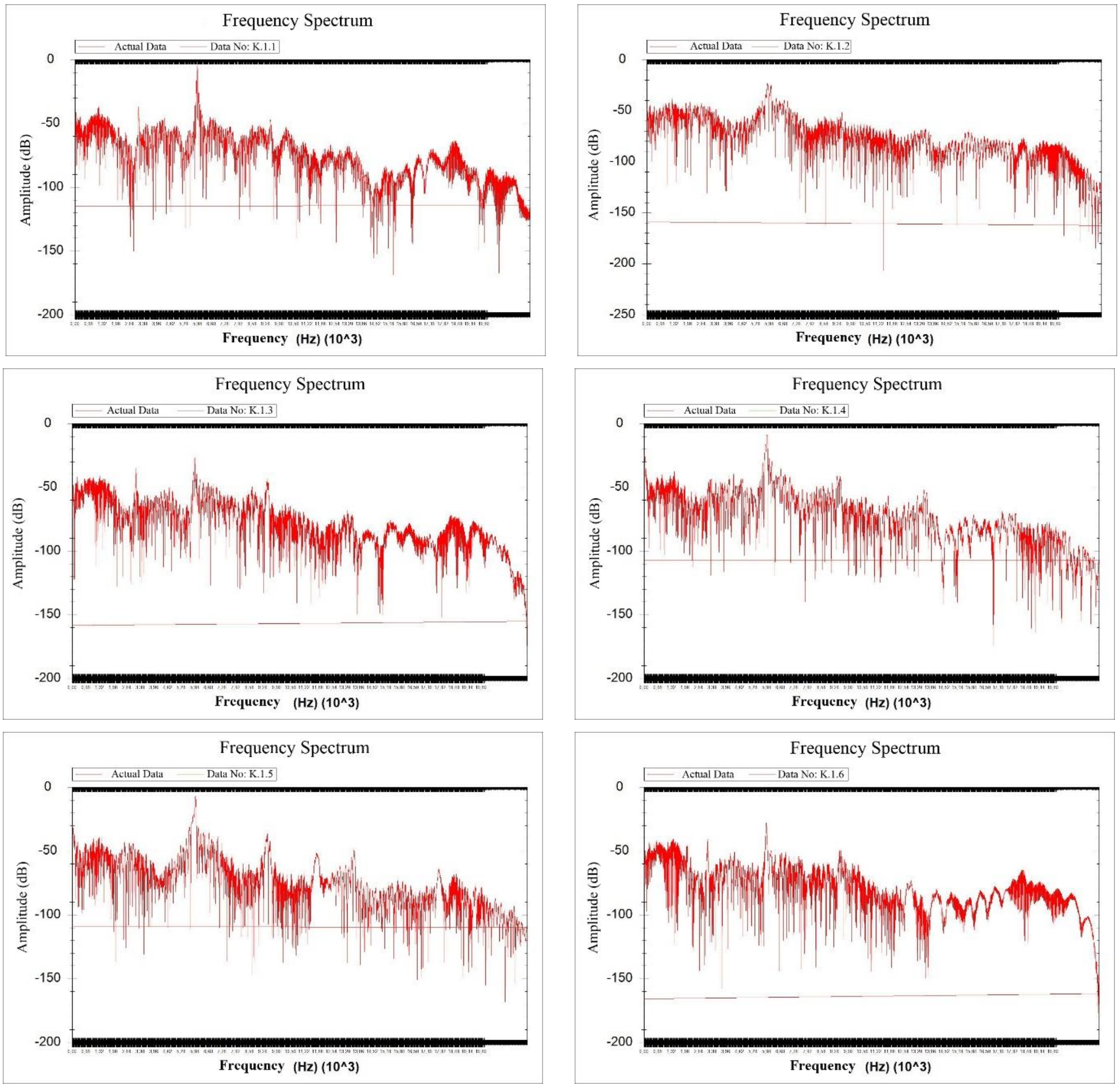

Fig. 4 Vibration Test Results of K.1 Samples

Samples coded K.1.2 through K.1.6, containing different ratios of matrix and reinforcement components, were prepared and subjected to vibration testing. The tests aimed to determine the first mode frequency of each structure, and the results were supported by graphical analyses (Fig. 4).

The vibration analysis conducted on composite samples coded K.1.1 through K.1.6 revealed that the first mode natural frequencies of the specimens ranged between 5837 Hz and 5994 Hz (Fig. 4). This narrow frequency band suggests a high degree of geometric and material consistency across the sample set, indicating successful manufacturing repeatability. Among the samples, K.1.5 exhibited the highest first mode frequency at 5994 Hz, implying superior stiffness characteristics, likely due to optimal dispersion and ratio of reinforcing nanoparticles. Conversely, sample K.1.2 presented the lowest frequency at 5837 Hz, which may be attributed to suboptimal matrix-reinforcement interaction or possible agglomeration of nanoparticles, such as CNTs or SiO_2, resulting in reduced rigidity. Given that the natural frequency is directly proportional to the square root of the stiffness-to-mass ratio, the observed variations highlight the sensitivity of dynamic behavior to even minor changes in composite composition. Most other samples, including K.1.1, K.1.3, K.1.4, and K.1.6, displayed frequencies within a close range of approximately 5926–5981 Hz, suggesting relatively stable vibrational performance and consistent mechanical integration of the matrix and reinforcement phases. These results support the hypothesis that nanoparticle-reinforced composites demonstrate optimal dynamic response when additive ratios are carefully controlled, with 1% CNT and 1.5% SiO_2 identified as likely optimal concentrations. The findings also underscore the importance of homogeneous dispersion and proper processing conditions in achieving desired mechanical and dynamic properties in nanocomposite systems.

Table 4 Analysis of samples K.1

Sample Code	K.1.1	K.1.2	K.1.3	K.1.4	K.1.5	K.1.6
First Mode Frequency (Hz)	5937 Hz	5837 Hz	5949 Hz	5981 Hz	5994 Hz	5926 Hz

The first natural frequency results obtained from the K.2 series composite samples indicate a significant variation in dynamic behavior across the set. While samples K.2.1 through K.2.4 exhibited relatively consistent frequencies ranging from 5830 Hz to 5892 Hz, samples K.2.5 and K.2.6 showed a substantial drop, with values of 3080 Hz and 4256 Hz, respectively (Fig. 5).The close proximity of the first four samples in terms of natural frequency suggests a uniform and effective integration of reinforcement materials within the matrix, likely resulting in comparable stiffness and mass properties. In contrast, the markedly lower frequencies observed in K.2.5 and K.2.6 point to a notable reduction in structural rigidity, potentially caused by inadequate reinforcement, poor nanoparticle dispersion, or defects within the composite structure. Such frequency drops may also be indicative of increased internal damping, voids, or agglomerated filler particles, all of which diminish the material's ability to resist vibrational energy. The deviation of K.2.5 from the general trend is particularly pronounced, with its frequency almost half that of the others, suggesting a critical flaw in composition or processing. These observations highlight the sensitivity of the composite's dynamic properties to material composition and microstructural quality. Therefore, careful control over fabrication parameters and nanoparticle distribution is essential to ensure consistent and reliable vibrational performance in nanocomposite systems.

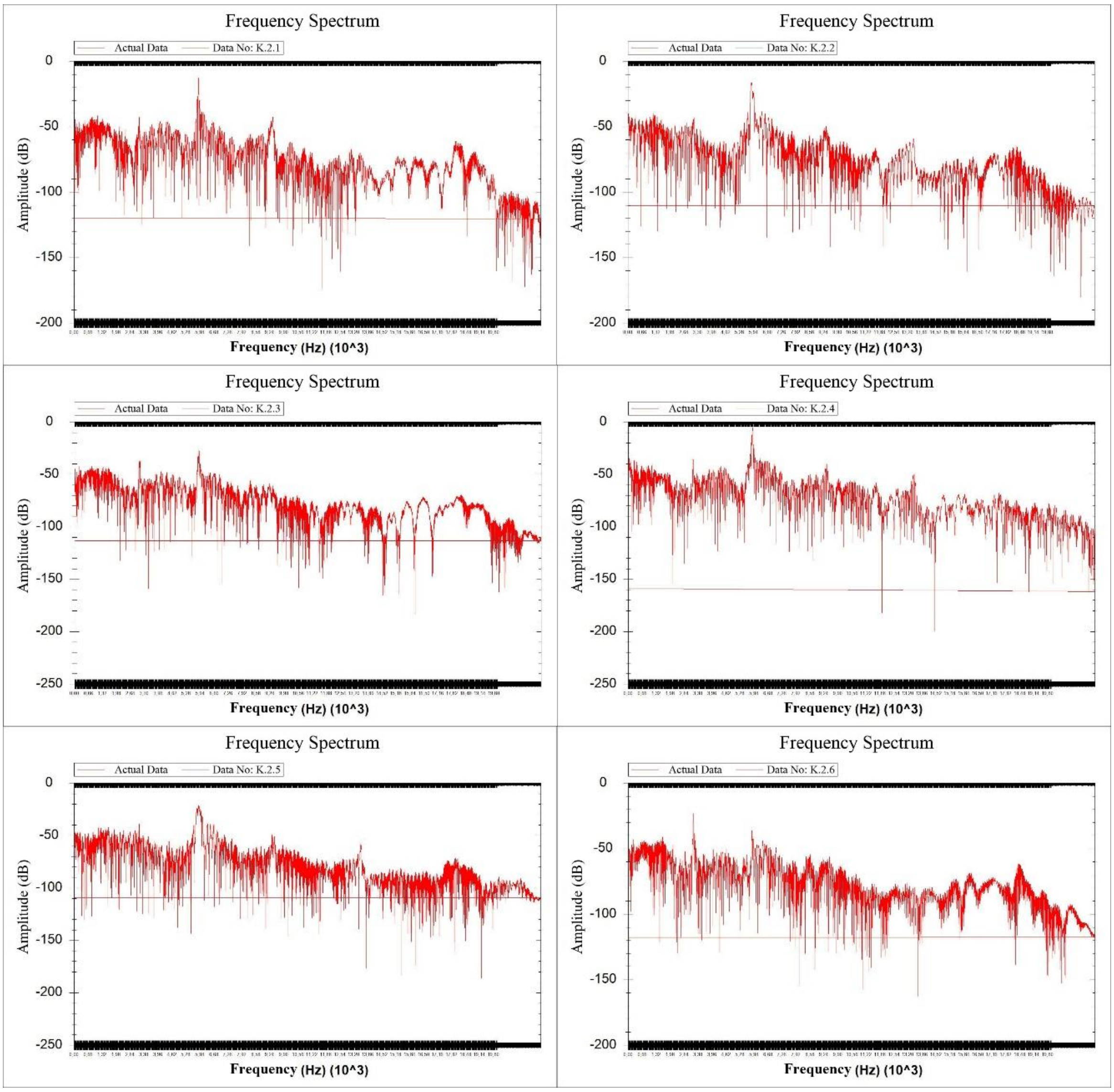

Fig.5 K.2. Vibration Test Results of Samples

Table 5 Analysis of sample K.2

Sample Code	K.2.1	K.2.2	K.2.3	K.2.4	K.2.5	K.2.6
First Mode Frequency (Hz)	5830 Hz	5892 Hz	5878 Hz	5876 Hz	3080 Hz	4256 Hz

The first natural frequency measurements of the K.3 series composite samples revealed distinct variations in vibrational behavior. Sample K.3.1 exhibited a significantly higher frequency of 6873 Hz, standing out from the rest of the group, which ranged between 4232 Hz and 4356 Hz (Fig. 6). This considerable disparity suggests that K.3.1 possesses substantially greater stiffness or reduced mass relative to the other samples, indicating a possible difference in reinforcement ratio, dispersion quality, or material uniformity. In contrast, the remaining samples (K.3.2 through K.3.6) displayed closely clustered frequency values, pointing to similar mechanical and structural properties. The relatively narrow frequency range among these five samples suggests consistent fabrication parameters and material composition, although the overall frequency level is lower than that of K.3.1, implying comparatively reduced rigidity. The marked elevation in K.3.1's natural frequency may be attributed to an optimal reinforcement configuration or improved nanoparticle alignment within the matrix. Conversely, the lower frequencies observed in the other specimens could result from factors such as partial agglomeration, weaker matrix-filler bonding, or the presence of microstructural imperfections. These findings reinforce the importance of precise control over material formulation and processing techniques in ensuring reliable dynamic performance in advanced composite systems.

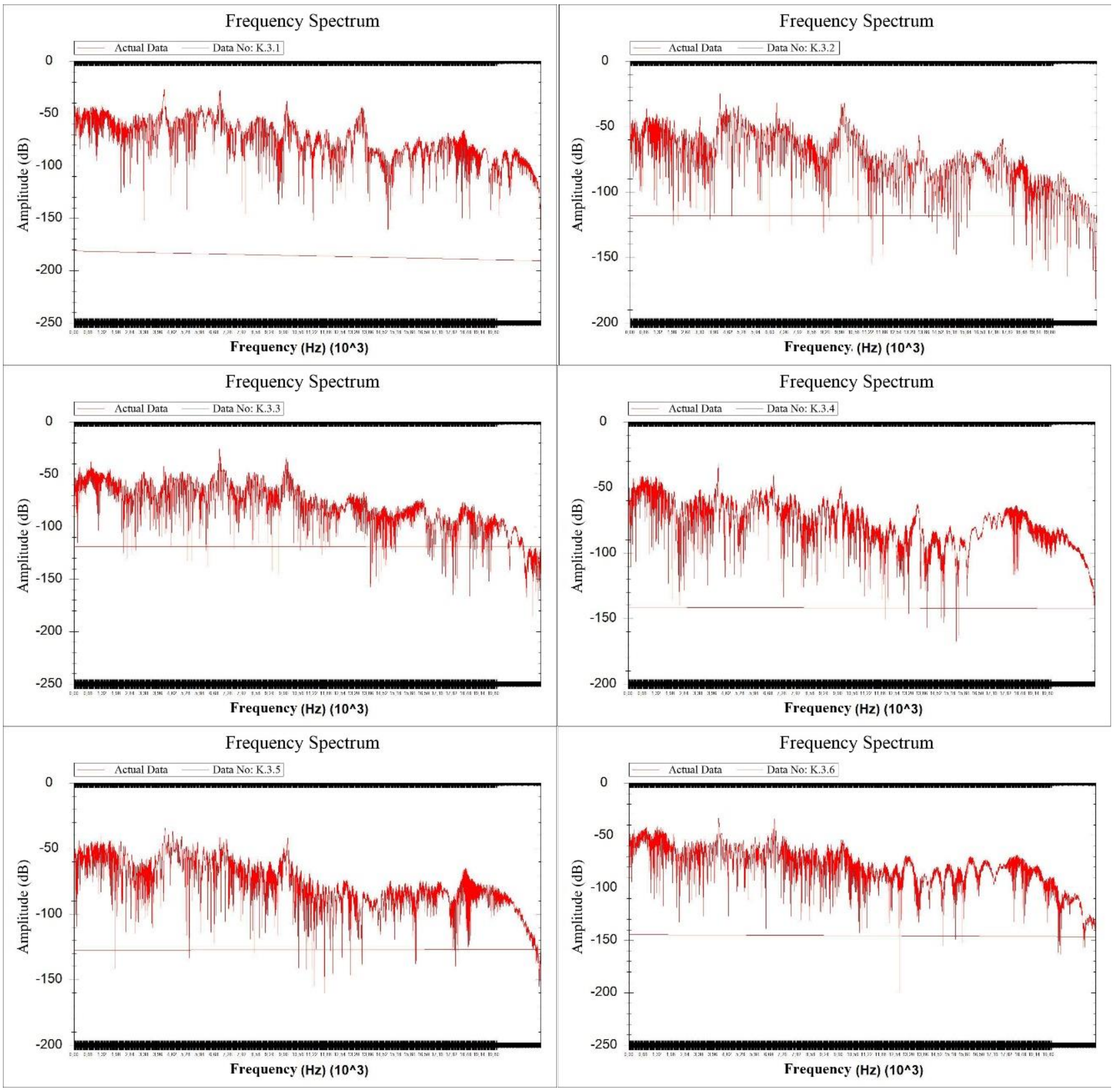

Fig.6 K.3 Vibration Test Results of Samples

Table 6 Analysis of sample K.2

Sample Code	K.3.1	K.3.2	K.3.3	K.3.4	K 3.5	K3.6
First Mode Frequency (Hz)	6873 Hz	4259 Hz	4307 Hz	4232 Hz	4327 Hz	4356 H

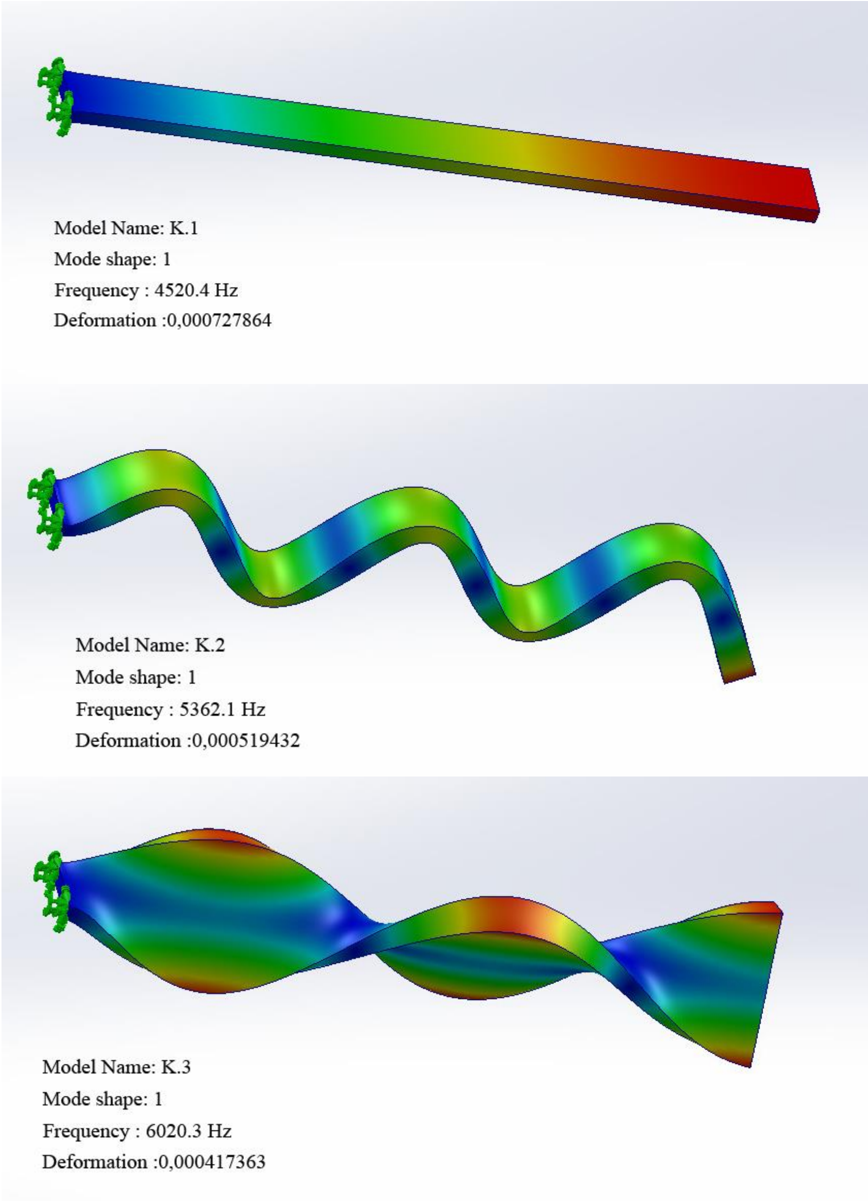

Fig.7 Modal analysis of layered composite materials

Modal analysis of layered composite materials of the samples is presented in Figure 7.

IV. DISCUSSION

Table 7 Comparison of Vibration Analysis Results: Experimental vs. Modal analysis with SolidWorks environment.

Sample Code	Experimental Frequency (Hz)	Numerical Frequency (Hz)	% Difference
K.1	5937,33	4520,4	23,8648
K.2	5135,33	5362,1	4.416
K.3	4725.67	6020,3	27,39

The comparison presented in Table 7 reveals notable discrepancies between the experimentally measured natural frequencies and those obtained from modal analysis in the SolidWorks simulation environment. Among the three sample groups, Sample K.2 exhibits the smallest deviation, with a percentage difference of only 4.42%, indicating a strong correlation between experimental and numerical results. This suggests that the material properties and boundary conditions in the SolidWorks model were appropriately defined for this configuration. In contrast, Samples K.1 and K.3 show significant discrepancies, with percentage errors of 23.86% and 27.39%, respectively. These differences may be attributed to several factors, including inaccuracies in the material property definitions—particularly the modulus of elasticity and density for the nanoparticle-reinforced composites—imprecise replication of experimental boundary conditions, and potential oversimplifications in the laminate layup modeling. Furthermore, the absence of damping in the numerical simulations could also contribute to the observed variances. These findings highlight the necessity of careful calibration of numerical models, especially when dealing with hybrid composite materials, to ensure reliable predictions of dynamic behavior.

V. CONCLUSION

This study comprehensively explored the dynamic behavior of epoxy-based hybrid laminated composites reinforced with varying ratios of carbon nanotubes (CNT) and silicon dioxide (SiO_2) nanoparticles. Natural frequency measurements were conducted using the non-contact acoustic resonance method and validated through numerical modal analyses performed in the SolidWorks simulation environment. The comparison revealed significant variations between experimental and numerical results, particularly for the K.1, K.2, and K.3 sample series, with percentage differences ranging from 4.41% to 27.39%. These discrepancies were attributed to material anisotropy, potential nanoparticle agglomeration, fiber alignment irregularities, and deviations in actual versus modeled boundary conditions.

Among all samples, the K.1 series exhibited the most consistent and higher natural frequency values (average 5937.33 Hz), which suggests an optimal distribution of reinforcements and a stronger interfacial bond between the fiber and the matrix. In contrast, the K.2 and K.3 samples demonstrated considerable variation, with some specimens, such as K.2.5 and K.3.2, showing significantly lower frequencies, likely caused by microstructural inconsistencies or non-uniform nanoparticle dispersion.

The observation that K.3.1 achieved the highest frequency among all samples underlines the potential for high vibrational performance when nanoparticle content and fabrication conditions are meticulously optimized. Notably, the use of approximately 1% CNT and 1.5% SiO_2, combined with thorough vacuum degassing and controlled post-curing, was found to be effective in enhancing mechanical stiffness and damping capacity.

REFERENCES

[1]. Taş, H., & Soykök, İ. F. (2018). Tabakalı Hibrit Kompozit Profillerin Doğal Frekanslarının Sonlu Elemanlar Metodu ile Belirlenmesi. Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi, 20(60), 1045-1056.

[2]. Ay E., Barış E., Çal T., Çetin S. T. 2019. Calculation of the modulus of elasticity with using natural frequency formula and updated finite element analysis of automotive rear lamp lens. International Journal of Automotive Science and Technology, 3(2),

[3]. Katmer, M. C., Akkurt, A., & Kocakulak, T. (2022). Determination and Investigation of Natural Frequency Values of A Composite Cover with Rib Design Added. *Dokuz Eylül Üniversitesi Mühendislik Fakültesi Fen ve Mühendislik Dergisi*, *24*(71), 679-687.

[4]. Günyar, A., Öztürk, H., Sabuncu, M. 2012. Kompozit Eğri Çubukların Doğal Frekans ve Burkulma Yükü Analizi, DEÜ Mühendislik Fakültesi Mühendislik Bilimleri Dergisi, Cilt. 14, Sayı. 42, s. 33-42.

[5]. Mota, G.M., Sollero, P., Batista, E.L., Albuquerque, A.L. 2008. Modal Analysis Technique for Anisotropic Composite Laminates, ICCES, Cilt. 7, Sayı. 2, s. 95-100.

[6]. Kwon. Y.W., Plessas, S.D. 2014. Numerical Modal Analysis of Composite Structures Coupled with Water, Composite Structures, s. 325-335.

[7]. Dongare, M.P., Deshmukh, S. 2012. Static and Modal Analysis of Composite Drive Shaft and Development of Regression Equations, International Journal of Engineering Research and Technology, Cilt. 1, Sayı. 10, s. 2-6.

[8]. Pingulkar, P., Suresha, B. 2016. Free Vibration Analysis of Laminated Composite Plates Using Finite Element Method, Polymers and Polymer Composites, Cilt. 24, Sayı. 10, s. 529-538.

[9]. Jalali, M. B., & Doğan, A. (2023). FARKLI SINIR ŞARTLARI VE FARKLI TABAKLANMA AÇILARI İÇİN TABAKALI KOMPOZİT BALPETEĞİ SANDVİÇ PLAĞIN SERBEST TİTREŞİM FREKANSLARININ KARŞILAŞTIRILMASI. Uludağ Üniversitesi Mühendislik Fakültesi Dergisi, 28(1), 293-306. https://doi.org/10.17482/uumfd.1150777

[10]. Çalışkan, M. B. (2021). KNT ve SiO2 nanopartikül ile modifiye edilmiş karbon-cam elyaf/epoksi kompozit plakaların mekanik özelliklerinin incelenmesi (master's thesis, Necmettin Erbakan Üniversitesi (Türkiye)).

[11]. Gürsoy, H. (2011). Kompozit malzemelerin mekanik ve modal özelliklerinin titreşim analizi ile belirlenmesi (Master's thesis, Fen Bilimleri Enstitüsü).

[12]. Cao, L., Yang, Q., & Liu, X. (2023). Structural Stability Analysis of Underwater High-Speed Moving Vehicles Based on Nonlinear Beam Theory. Aerospace, 10(11), 916. https://doi.org/10.3390/aerospace10110916

[13]. Erdoğan, İ., Kısa, M., Özen, M., Demircan, G., et al. (2023). Cam Elyaf Takviyeli Epoksi Nanokompozitlerin Dinamik Davranışlarının İncelenmesi. Harran Üniversitesi Mühendislik Dergisi, 8(2), 78-90. https://doi.org/10.46578/humder.1161116

[14]. Siemens. (2020). Non-destructive component testing by acoustic resonance analysis. Siemens Support. https://support.sw.siemens.com/de-DE/okba/KB000044608_EN_US/Non-Destructive-Component-Testing-by-Acoustic-Resonance-Analysis/index.html

[15]. Rao, S. S. (2019). Vibration of continuous systems. John Wiley & Sons.