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Numerical Modal Analysis of Foams with Different Types and Configurations

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Anahtar Kelimeler

Kapalı hücreli aluminyum köpük
EPS dolgulu sentetik köpük
Titreşim analizi
Tabakalı hibrit köpük
Modal analiz
Mod şekli
Doğal frekans

Graphical/Tabular Abstract (Grafik Özet)

In this study, numerical modal analysis of foams with different types and configurations was carried out. / Bu çalışmada farklı tip ve konfigürasyonlara sahip köpüklerin nümerik modal analizi yürütülmüştür.

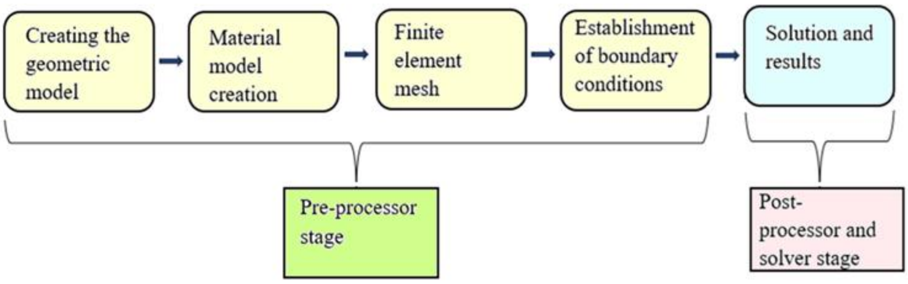

***Figure A:** Flow chart of design and analysis using ANSYS / **Şekil A:** ANSYS kullanılarak tasarım ve analizin akış şeması*

Highlights (Önemli noktalar)

- *The natural frequencies and mode shapes of foams with different types and configurations were investigated using the Finite Element Method under different boundary conditions. / Farklı tipte ve konfigürasyondaki köpüklerin doğal frekansları ve mod şekilleri, farklı sınır koşulları altında Sonlu Elemanlar Yöntemi kullanılarak araştırılmıştır.*
- *Changes in structural stiffness of the foams were analyzed depending on the volume fraction. / Köpüklerin yapısal sertliğindeki değişimler, hacim oranına bağlı olarak analiz edilmiştir.*
- *It provides guidance on optimum design conditions for researchers and engineers. / Araştırmacılar ve mühendisler için optimum tasarım koşulları hakkında yol gösterici bilgiler sağlamaktadır.*

***Aim (Amaç):** The vibration behavior of foams with different types and configurations was investigated, and it was revealed how the changes in natural frequencies, mode shapes and structural stiffness of these structures are affected by parameters such as material properties, boundary conditions and volume fraction. / Farklı tipte ve konfigürasyondaki köpüklerin titreşim davranışını incelenmiş ve bu yapıların doğal frekansları, mod şekilleri ve yapısal sertliklerindeki değişimlerin malzeme özellikleri, sınır koşulları ve hacim oranı gibi parametrelere bağlı olarak nasıl etkilendiği ortaya koyulmuştur.*

***Originality (Özgünlük):** It presents original findings that guide engineering designs by examining in detail the vibration behavior of foams under different boundary conditions in terms of volume fraction, natural frequencies and structural stiffness. / Farklı sınır koşulları altında köpüklerin titreşim davranışını hacim oranı, doğal frekanslar ve yapısal sertlik açısından detaylı bir şekilde inceleyerek mühendislik tasarımlarına rehberlik eden özgün bulgular sunmaktadır.*

***Results (Bulgular):** The effects of material configurations and volume fraction changes provided valuable information for the design of foams and optimum vibration performance to be used in engineering applications. These findings can provide guidance for preventing vibration-induced failures in engineering systems. / Malzeme konfigürasyonları ve hacim oranı değişimlerinin etkileri, köpüklerin tasarımı ve mühendislik uygulamalarında kullanılacak optimum titreşim performansı için değerli bilgiler sağlamıştır. Bu bulgular, mühendislik sistemlerinde titreşim kaynaklı arızaları önlemek için yol gösterici olabilir.*

***Conclusion (Sonuç):** Natural frequencies and mode shapes of foams under different boundary conditions were determined, and the effects of material application and boundary conditions on the vibration behavior were revealed. / Farklı sınır koşulları altında köpüklerin doğal frekansları ve mod şekilleri belirlenmiş, malzeme uygulamasının ve sınır koşullarının titreşim davranışına etkileri ortaya konulmuştur.*

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Abstract

Thanks to the perfect combination of mechanical properties such as high strength and rigidity, along with functional properties like thermo-acoustic insulation and vibration damping, foam structures are becoming increasingly attractive in engineering applications. While most research has focused on the mechanical properties of foams. On the other hand, understanding the vibration behavior of foams is vital since most failures in engineering applications are associated with violent vibrations. This research focused on the vibration analysis of foams with different types and configurations. In the context of vibration, modal analysis is a highly preferred method for fully understanding the structural behavior of materials. The Finite Element Method is commonly employed for numerical modal analysis to reveal the vibration characteristics of structures, including natural frequencies and corresponding mode shapes. With this objective, the natural frequencies and mode shapes of hybrid foams have been revealed under both clamped-free and free-free boundary conditions. The effects of material application and boundary conditions were investigated. The changes in the stiffness of the structure, occurring under different vibration modes of the system and depending on the volume fraction, have also been investigated. Since closed-cell aluminum foam and EPS-filled syntactic foam have different mechanical properties, the changes in the structural stiffness of the material are revealed as the volume fraction changes. For the second and third modes, there was no significant change in structural stiffness in the volume ratio ranges of 0-0.2 and 30-1000, while a decrease in structural stiffness was observed in the volume ratio range of 0.2 to 30. The findings and results obtained can provide valuable information to researchers and engineers for optimum design conditions.

Farklı Tip ve Konfigürasyonlara Sahip Köpüklerin Sayısal Modal Analizi

Makale Bilgisi

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Öz

Yüksek mukavemet ve sertlik gibi mekanik özelliklerin termo-akustik yalıtım ve titreşim sönümleme gibi işlevsel özelliklerle mükemmel birleşimi sayesinde, köpük yapıları mühendislik uygulamalarında giderek daha çekici hale geliyor. Çoğu araştırma köpüklerin mekanik özelliklerine odaklanmış olsa da köpüklerin titreşim davranışını anlamak hayati önem taşımaktadır, çünkü mühendislik uygulamalarındaki arızaların çoğu şiddetli titreşimlerle ilişkilidir. Bu araştırma, farklı tip ve konfigürasyonlardaki köpüklerin titreşim analizine odaklanmıştır. Titreşim bağlamında, modal analiz malzemelerin yapısal davranışını tam olarak anlamak için oldukça tercih edilen bir yöntemdir. Sonlu Elemanlar Yöntemi, doğal frekanslar ve karşılık gelen mod şekilleri dahil olmak üzere yapıların titreşim özelliklerini ortaya çıkarmak için sayısal modal analiz için yaygın olarak kullanılır. Bu amaçla, hibrit köpüklerin doğal frekansları ve mod şekilleri hem ankastre-serbest hem de serbest-serbest sınır koşulları altında ortaya çıkarılmıştır. Malzeme uygulamasının ve sınır koşullarının etkileri araştırılmıştır. Sistemin farklı titreşim modları altında ve hacim oranına bağlı olarak oluşan yapının sertliğindeki değişiklikler de araştırılmıştır. Kapalı hücreli alüminyum köpük ve EPS dolgulu sentetik köpük farklı mekanik özelliklere sahip olduğundan, malzemenin yapısal sertliğindeki değişimler hacim oranı değiştikçe ortaya çıkar. İkinci ve üçüncü modlar için, 0-0,2 ve 30-1000 hacim oranı aralıklarında yapısal sertlikte önemli bir değişim olmazken, 0,2 ile 30 hacim oranı aralığında yapısal sertlikte bir azalma gözlemlenmiştir. Elde edilen bulgular ve sonuçlar, araştırmacılara ve mühendislere optimum tasarım koşulları için değerli bilgiler sağlayabilir.

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1. INTRODUCTION (GİRİŞ)

Open and closed-cell foams are widely utilized in various industrial sectors, including marine, aerospace, construction, and automotive industries, due to their high strength-to-weight ratio and their ability to provide acoustic and vibration damping [1-2]. Generally, increasing the number of open cells in the structure enhances properties such as softness, flexibility, permeability, and absorption capacity. On the other hand, increasing the number of closed cells in the structure improves buoyancy, bending stiffness, compressive strength, and thermal insulation [3]. For these reasons, modal analysis of these materials is essential for understanding their dynamic behavior when exposed to external stimuli like acoustic or mechanical vibrations. Free vibration analysis provides valuable information on natural frequencies, mode shapes, and damping properties.

Syntactic foam is a closed-cell, lightweight composite material created by incorporating low-density hollow micro balloons into a matrix material [4-7]. The micro balloons used in syntactic foam production are made from various materials, including metals, ceramics, glass, polymers, and carbon. The matrix materials commonly used include silicones, phenolic resins, polyesters, polyurethanes, epoxy resins, and others [8-9]. The literature contains studies on the free vibration analysis of syntactic foams. Şansveren and Yaman examined how varying the volume fraction and density of carbon nanofibers and micro balloons affects the vibration behaviors of carbon nanofiber-reinforced syntactic foam. Their study investigated the natural frequencies and damping ratios through free vibration tests. The vibration test results indicated that the addition of carbon nanofibers increased the strength of the material but did not affect its damping characteristics [10]. Buddhacosa et al. developed epoxy syntactic foam by incorporating up to 23 wt% micro-sized elastomeric particles from recycled waste tires into syntactic foam (epoxy modified with 5 wt% hollow glass microspheres). They examined the vibration responses of the materials via laser Doppler vibrometry (LDV). They stated in their studies that the damping ratio increases as the weight ratio of elastomeric fillers is increased [11]. In their studies, Maraş and Yaman investigated the vibration properties of sandwich structures with syntactic foam cores using both numerical simulations and experimental methods. Initially, they derived the differential equations of sandwich syntactic foam beams using high-order shear deformation theory and then compared the natural frequencies with experimental results to validate the numerical model. They validated the numerical model by comparing it with experimental findings [12]. Rahmani et al. applied an advanced model based on high-order sandwich panel theory for analyzing the free vibrations of syntactic foam sandwich beams featuring a functionally graded flexible core. Through numerical analysis, they investigated how beam design characteristics affected natural frequencies [13]. In their study, Waddar et al. investigated the experimental free vibration characteristics of silane-treated cenosphere/epoxy syntactic foams under axial pressure. An increase in filler content led to a rise in the natural frequency of the syntactic foam composites. Superior performance (up to an 11.46% increase in natural frequencies) was recorded with the silane-modified cenosphere embedded in the epoxy matrix compared to the untreated ones [14]. In their study, Maraş et al. numerically examined the vibration properties of laminated syntactic foam beams under unclamped boundary conditions. First, they obtained numerical results using the Finite Element Method based on first-order shear deformation theory and compared them with ANSYS results. They stated that there was good agreement between numerical and experimental results [15].

Metal foam is a porous material composed of metal with gas-filled pores [16-17]. Metal foams come in two types distinguished according to their geometric structures: open-cell and closed-cell [18]. These foams are widely used in various fields. Metal foams possess high energy absorption ability and characteristics such as lightness, thermal insulation, and damping resistance [19-20]. Aluminum-based metal foams hold a significant place in engineering applications. Aluminum foams can absorb more energy than most other metals. This material type can substitute composite materials in applications requiring vibration damping [21]. In their article, Rozskos et al. investigated the static and dynamic analysis of geometric models of closed-cell and open-cell aluminum foams using the homogenization technique and finite element analysis. At lower frequencies, the results indicated that both models (homogenized and optimized homogenized beam) showed similar natural frequencies and mode shapes. However, at higher frequencies, the influence of geometric shapes and imperfections became more significant in the results [22]. In their study, Dahil et al. measured the damping ratios of three aluminum foam samples with varying pore densities and investigated the influence of pore density on damping characteristics using experimental modal analysis. They stated that pore density has an effect on the calculated damping ratios, with an increase in pore number correlating to higher damping values [23]. In their study, Wang et al. examined the free vibration characteristics of circular cylindrical metal foam shells under different boundary conditions. The results showed that the porosity coefficient notably influences the natural frequencies of metal foam shells [24]. Ma et al. used the time-averaged electronic speckle pattern interference (ESPI) method to investigate the vibration response of a cantilever beam made from closed-cell aluminum foam. In the experimental setup, they utilized the real-time subtraction ESPI method to study the vibration response of a cantilever beam made from closed-cell aluminum foam. Consistent with the results of the finite element method simulation, they stated that the vibration mode shapes observed via the ESPI method were in good agreement with the numerical predictions [25]. Lei et al. utilized modal analysis to explore the dynamic characteristics of closed-cell aluminum foam. They observed that the damping ratio exhibited an increasing trend with increasing porosity, decreasing natural frequency, and average pore size [26].

Syntactic foam and metal foam both play crucial roles in material-damping applications. Given their properties, metal and syntactic foams emerge as promising candidates for development of hybrid foams. Hybrid foam, as the name suggests, is created by combining various materials [27].

In this study, the modal behaviors of layered hybrid foams, consisting of closed-cell aluminum foam and EPS-filled syntactic foam, as well as their individual components, were investigated numerically. Foams with different types and configurations were modeled under both clamped-free and free-free boundary conditions to investigate the effect of boundary conditions on natural frequencies and mode shapes. Elastic properties of EPS-filled syntactic foams and closed-cell aluminum foam were determined by experimental methods. Modal analysis was performed using ANSYS commercial finite element software package where the foams were modeled as homogeneous materials. This comprehensive investigation aims to provide insights into the dynamic behavior of hybrid foams for potential applications in vibration sensitive environments.

2. NUMERICAL STUDY (NÜMERİK ÇALIŞMA)

In this study, EPS-filled syntactic foams, closed-cell aluminum foam, and layered hybrid foams were subjected to free vibration analysis to determine their modal parameters. The 3D solid modeling of the foams, pre-processing, solving, and post-processing were performed using the ANSYS 18.1 Workbench package program. The methodology employed for foam design and analysis with the ANSYS package program is illustrated in Figure 1. During the pre-processing stage, the foam geometry, material properties, and boundary conditions were defined. In the post-processing stage, the results were graphically visualized, while in the solver stage, the frequencies were defined by modes. All produced foams were coded using a code system for easy reference. Table 1 lists the foam codes and their corresponding compositions.

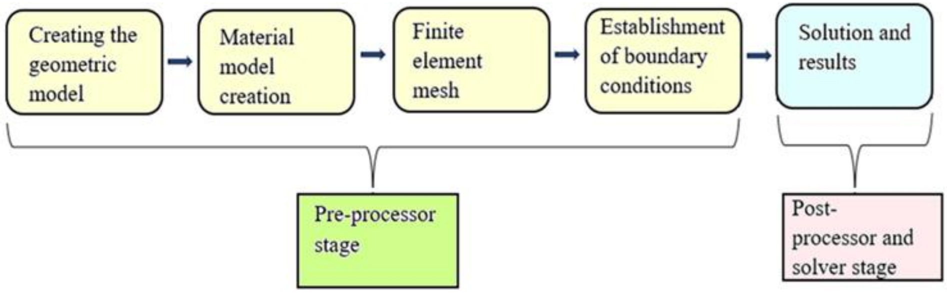

Figure 1. Flow chart of design and analysis using ANSYS (ANSYS kullanılarak tasarım ve analizin akış şeması)

Table 1. Designations of the foams used in this study (Bu çalışmada kullanılan köpüklerin tanımları)

Foam Code	Content
A_1	Closed-cell aluminum foam
H_1	20 mm aluminum foam / 10 mm syntactic foam with 10 kg/m^3 EPS density
H_2	20 mm aluminum foam / 10 mm syntactic foam with 18 kg/m^3 EPS density
H_3	20 mm aluminum foam / 10 mm syntactic foam with 30 kg/m^3 EPS density
H_4	10 mm aluminum foam / 20 mm syntactic foam with 10 kg/m^3 EPS density

H_5	10 mm aluminum foam / 20 mm syntactic foam with 18 kg/m^3 EPS density
H_6	10 mm aluminum foam / 20 mm syntactic foam with 30 kg/m^3 EPS density
S_1	Syntactic foam with 10 kg/m^3 EPS density
S_2	Syntactic foam with 18 kg/m^3 EPS density
S_3	Syntactic foam with 30 kg/m^3 EPS density

The dimensions of the foam materials were modeled as 100 x 30 x 30 mm. While modeling the layered hybrid foams, the adhesive material applied between the layers was excluded. The contact between the foams was modeled as perfectly bonded. This modeling serves the purpose of the adhesive layer. This approach ensured that the foams remained in full contact during the modal analysis. One of the most critical steps in the finite element method is the definition of material properties. Foam properties, including density, Young's modulus, and Poisson's ratio, were incorporated into the material library based on experimental data. The density of the foams was determined with the help of Archimedes' Principle. Young's modulus and Poisson's ratio of the foams were obtained from the compressive test carried out in the previous study [30]. To obtain the compressive stress-strain curves of the foams, 30 x 30 mm thick and 30 mm thick samples were prepared according to ASTM C365/C365 M, and a compressive load was applied to the samples at a rate of 0.5 mm/min under displacement control. The elastic properties of foams were determined based on the linear region of the stress-strain curve [31]. In this study, five tests were performed for each condition, and average values were taken into account. The foam material properties assigned at the pre-processing stage of the ANSYS simulation are presented in Table 2. Closed-cell aluminum foam and EPS-filled syntactic foam are generally considered nearly isotropic, showing small changes in mechanical properties along the three principal directions. Therefore, mechanical properties in the x, y, and z directions are assumed to be equal (linear elastic isotropic assumption).

Table 2. Mechanical properties of different foams
(Farklı köpüklerin mekanik özellikleri)

Property	Young's modulus	Poisson ratio	Density
Symbol	E	ν	ρ
Unit	MPa	-	g/cm^3
A_1	1726.0	0.33	0.400
S_1	756.00	0.30	0.469
S_2	687.70	0.30	0.479
S_3	687.71	0.30	0.487

The finite element model of the structure was created using Solid 186 which is a higher-order 3D 20-node solid element that exhibits quadratic displacement behavior. Following the creation of the 3D model, mesh generation, which is the most important part of the 'Model' section, was carried out. The process of converting geometric elements into finite elements is called meshing [28]. The meshed solid model is shown in Figure 2. Various configurations were tested during the meshing process to achieve an optimal mesh size, with the element size refined until result convergence was obtained. The final mesh structure consisted of 8281 nodes and 1728 solid elements.

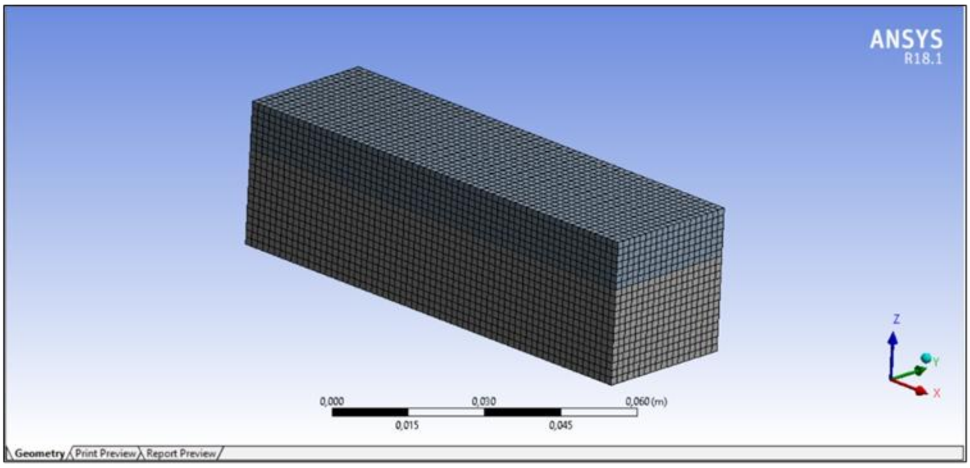

Figure 2. Finite element model of layered hybrid foam (Tabakalı hibrit köpüklerin sonlu eleman modeli)

Modal analysis was performed under two different boundary conditions:

Case 1: Free-Free Boundary Condition

In this condition, no support was applied to the end faces of the foam model. Modal analysis was performed for three modes under this configuration.

Case 2: Clamped-Free Boundary Condition

In this condition, one end surface of the foam model was fixed. Modal analysis was similarly performed for three modes under this configuration.

3. RESULTS (BULGULAR)

In this study, the effects of material application and boundary conditions were investigated numerically. The ANSYS software was used to perform vibration analysis on closed-cell aluminum foam, EPS-filled syntactic foams, and layered hybrid foams. To validate the finite element (FE) model, the FE results obtained for foams coded H_1, H_2, and H_3 under clamped-free boundary conditions were compared with the experimentally determined natural frequencies of these materials [31]. It can be seen from Table 3 that the FE model accurately predicts the vibration behavior of foams. The highest difference is in H_2 coded foam with 2.89%.

Table 3. Natural frequencies of H_1, H_2, and H_3 coded foams obtained from the FE model compare with experimental results (FE modelinden elde edilen H_1, H_2 ve H_3 kodlu köpüklerin doğal frekanslarının deneysel sonuçlarla karşılaştırılması)

First natural frequency (Hz)			
Sample	H_1	H_2	H_3
Experimental [31]	746.31	725.29	723.13
FEM (ANSYS)	765.85	746.91	744.51

Table 4 and Table 5 display the natural frequency values for the first three modes of numerically analyzed foams with various configurations. In addition to natural frequencies, mode shapes were also obtained during the numerical analysis to determine modal behavior. When Tables 4 and 5 are examined, the aluminum foam exhibits the highest natural frequency among all foam types. This indicates that the structure has high rigidity [29]. In contrast, EPS-filled syntactic foams demonstrate the lowest natural frequencies, reflecting their comparatively lower structural rigidity. As can be seen from Tables 4 and 5, the natural frequency of the EPS-filled syntactic foam is 583.42, 550.61, and 546.07 Hz under the clamped-free boundary conditions, and to 3110.4, 2935.5, and 2911.3 Hz under the free-free boundary conditions, respectively. This change can be explained using the frequency equation $f = (1/2\pi \sqrt{(k/m)})$. Here, f is the natural frequency; k is the stiffness; m is the mass. The increase in the mass leads to a decrease in the natural frequency by increasing the value of m. The increase in the density of the EPS material causes a decrease in the frequencies because the effect of increasing the mass is greater than the effect of increasing the stiffness [2, 10]. Layered hybrid foams exhibit a smaller decline in natural frequencies compared to their closed-cell aluminum foam counterparts.

Table 4. Frequency values obtained as a result of numerical analyses of all foams under clamped-free boundary conditions (Tüm köpüklerin ankastre-serbest sınır koşulları altında nümerik analizleri sonucunda elde edilen frekans değerleri)

Clamped-Free Boundary Condition			
Natural Frequency (Hz)			
Sample	1st Mode	2nd Mode	3rd Mode
A_1	956.70	956.70	2939.2
H_1	765.85	833.21	2456.4
H_2	746.91	822.53	2406.3
H_3	744.51	819.86	2397.7
H_4	710.68	711.40	2151.2
H_5	685.28	689.41	2070.4
H_6	681.26	685.29	2059.2
S_1	583.42	583.42	1816.6
S_2	550.61	550.61	1714.4
S_3	546.07	546.07	1700.3

Table 5. Frequency values obtained as a result of numerical analyses of all foams under free-free boundary conditions (Tüm köpüklerin serbest-serbest sınır koşulları altında nümerik analizleri sonucunda elde edilen frekans değerleri)

Free-Free Boundary Condition			
Natural Frequency (Hz)			
Sample	1st Mode	2nd Mode	3rd Mode
A_1	5067.2	5067.2	5829.8
H_1	4044.3	4403.5	4866.5
H_2	3936.6	4340.6	4760.9
H_3	3921.4	4325.3	4743.0
H_4	3716.1	3761.2	4249.3
H_5	3565.6	3641.3	4082.7
H_6	3543.6	3618.8	4061.2
S_1	3110.4	3110.4	3614.5
S_2	2935.5	2935.5	3411.2
S_3	2911.3	2911.3	3383.1

Tables 4 and 5 also highlight the changes in frequency based on the boundary conditions. In the transition from clamped-free to free-free boundary conditions, the increase in the frequencies of the first and second modes, which were initially excited, rose up to fivefold, while the increase in the frequency of the third mode, excited later, was approximately twofold. When the tables are examined, it is observed that there is a difference only in the frequencies of the first and second bending modes of the hybrid foams. The reason for this difference is attributed to the change in the bending stiffness caused by the variation in the cross-sectional profiles. The change observed in frequencies due to variations in the thicknesses of the structures forming the hybrid foam provides design engineers with enhanced flexibility in preventing structural damage during vibration control.

Vibration modes for all foam configurations were analysed under clamped-free and free-free boundary conditions. Figure 4 illustrates the first three mode shapes for the layered hybrid foam (H_6) under clamped-free conditions, while Figure 5 presents the corresponding mode shapes for free-free boundary conditions. The modal analysis of H_6 reveals that the first two modes are translational, whereas the third mode is torsional. These results indicate that bending vibration modes are excited earlier than torsional or longitudinal vibration modes.

Under clamped-free boundary conditions, the first three natural frequencies of H_6 are 681.26 Hz, 685.29 Hz, and 2059.2 Hz, respectively. The proximity of the first two frequencies suggests similar stiffness in the foam's two transverse directions, as their values are identical.

Additionally, the third natural frequency is approximately three times higher than the first, indicating distinct torsional behaviour. Furthermore, the mode shapes observed across all foam configurations were found to be consistent.

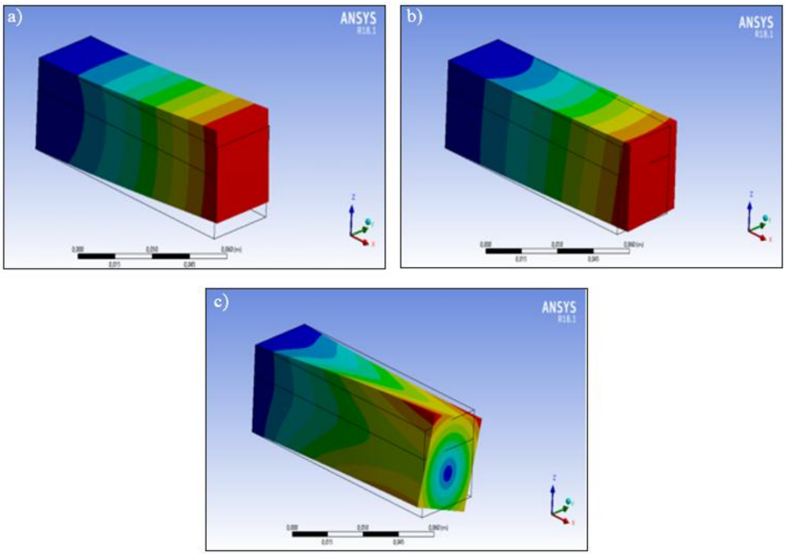

Figure 3. a) 1st mode b) 2nd mode c) 3rd mode of H_6 coded layered hybrid foam under clamped-free boundary condition (Ankastre-serbest sınır koşulu altında H_6 kodlu tabakalı hibrit köpüğün a) 1. mod b) 2. mod c) 3. modu)

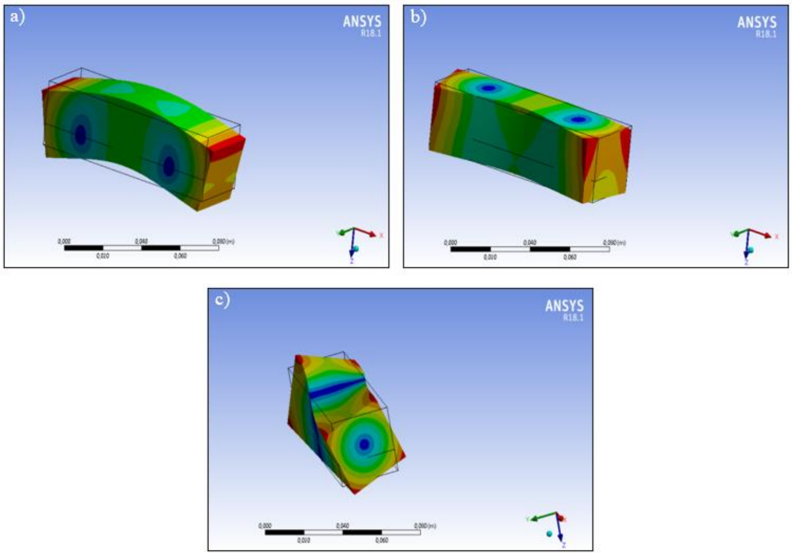

Figure 4. a) 1st mode b) 2nd mode c) 3rd mode of H_6 coded layered hybrid foam under free-free boundary condition (Serbest-serbest sınır koşulu altında H_6 kodlu tabakalı hibrit köpüğün a) 1. mod b) 2. mod c) 3. modu)

The relationship between structural stiffness and volume ratio is a critical factor in engineering applications. A precise understanding of this relationship is essential for accurately predicting and controlling structural vibration behavior. For this reason, the variations in structural stiffness as a function of the volume fraction of layered hybrid foam for the first three vibration modes under clamped-free boundary conditions are presented in Figure 6. Equation (1) is utilized to calculate Structural stiffness (EI) values for different vibration modes.

$$\omega_n = (\beta l)^2 \sqrt{\frac{EI}{\rho A l^4}}. \tag{1}$$

Where, ω_n: Natural frequency of the system. β: A geometric constant of the solution. l: Length of the beam. E: Young's modulus of the material. I: Moment of inertia. ρ: Density of the material. A: Section area. Among the parameters in the graph, V_s represents the volume of EPS-filled syntactic foam, V_{AL} represents the volume of closed-cell aluminum foam, and V_s/V_{AL} represents the volume ratio of syntactic foam and aluminum foam components of the layered hybrid foam.

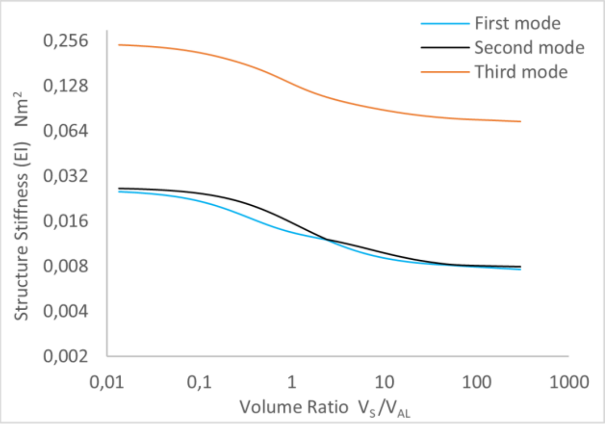

Figure 5. Structural stiffness variation of layered hybrid foam with respect to volumetric ratio and vibration modes under clamped-free boundary conditions (Ankastre-serbest sınır koşulları altında tabakalı hibrit köpüğün hacim oranı ve titreşim modlarına göre yapısal sertlik değişimi)

Figures 7a and 7b show how the first natural frequency of the layered hybrid foam varies in relation to the second and third natural frequencies under clamped-free boundary conditions.

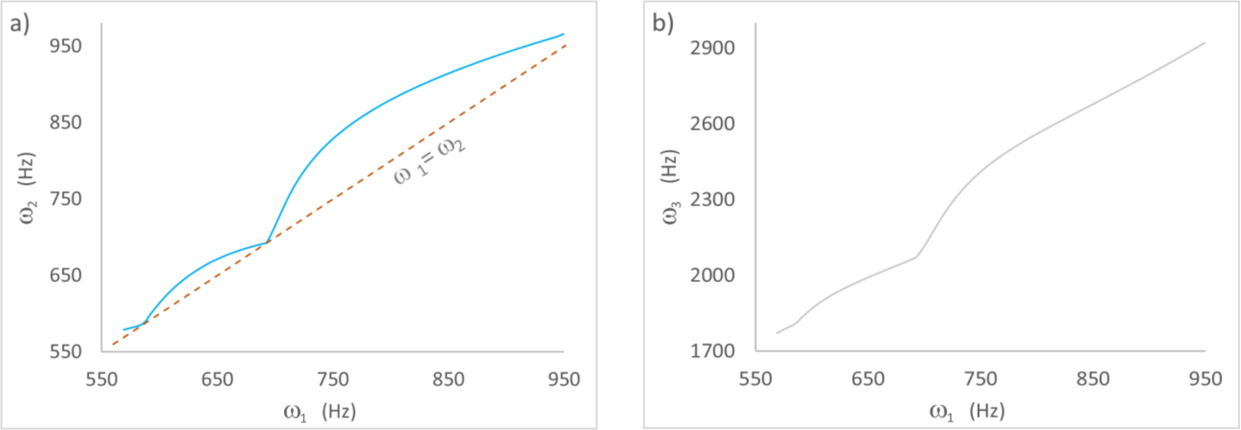

Figure 6. Variation of natural frequencies under clamped-free boundary conditions (Ankastre-serbest sınır koşulları altında doğal frekansların değişimi)

Figures 7a and 7b clearly illustrate the variation in natural frequencies by revealing the relationships between the first and second natural frequencies, as well as the first and third natural frequencies, respectively, of the hybrid structure. These figures demonstrate that the relationships between two natural frequencies vary in a nonlinear manner. The red dashed line added to the first graph represents the points at which the first and second natural frequencies are equal ($\omega_1 = \omega_2$). The curve indicates that, in the 800–900 Hz range, while the first natural frequency increases, the second natural frequency exhibits a tendency for more rapid growth, only to subsequently decrease, aligning the two frequencies at 692 Hz. In this region, there is a risk of concurrent resonances emerging in designs. Following the point of equality, it is observed that as the first natural frequency continues to increase, the second natural frequency shows a rapid, nonlinear rise. These occurrences are critically significant for the dynamic stability of the structure. Another notable aspect of the graph is the abrupt changes in slope in certain regions. Upon examining Figure 7b, a similar trend is observed. The most prominent difference in this graph appears in the variation of ω_1 within the 600–700 Hz range, where an approximately linear relationship is established between ω_1 and ω_2.

In conclusion, understanding the relationship between the natural frequencies of the hybrid system is essential for assessing the dynamic behavior of structures. The findings obtained from the graph should be considered in system design and stability analysis within engineering applications. Optimizing natural frequencies plays a crucial role in enhancing the safety and performance of structures.

4. CONCLUSIONS (SONUÇLAR)

Numerical investigations were conducted to study the free vibration behaviors of foams with different types and configurations under both clamped-free and free-free boundary conditions. The study analyzed how foam configuration and boundary conditions influence natural frequencies and mode shapes. The natural frequencies of layered hybrid foams were compared with those of closed-cell aluminum foam. It was observed that the frequency of layered aluminum foams was lower than that of closed-cell aluminum foam. For the same foams with a change in the boundary conditions, the natural frequency increased several folds. According to the experimental results reported in the previous study [31], it was determined that the differences between the numerical solutions we obtained from ANSYS, and the experimental natural frequencies varied from 0.41% to approximately 5%. The reason for this difference is attributed to errors during the production, adhesion, and measurement of the samples, as well as errors in the calculations. However, the calculation error rate can be further reduced by making changes to various parameters, such as the material properties and the mesh structure of the model created in ANSYS. In addition, the structural stiffness changes of the layered hybrid foam according to the volumetric ratio and vibration modes and how the first natural frequencies change with the second and third natural frequencies were investigated under clamped-free boundary conditions.

The findings of this study provided important data on optimum design conditions by determining structural stiffness changes depending on the volume ratio and vibration modes of layered hybrid foam structures. In particular, the combination of closed-cell aluminum foam and EPS-filled syntactic foam provided a suitable balance between lightness and durability according to structural performance requirements. Increasing the aluminum ratio in applications requiring high stiffness and preferring syntactic foam in cases where flexibility is required stands out as an effective approach to improving the performance and stability of the structure. This study has provided important information about dynamic stability and resonance risk by revealing that the relationships between the natural frequencies of hybrid foam structures change in a nonlinear manner. Sudden slope changes and frequency equality points observed in certain frequency ranges play a critical role in determining resonance risk. Optimizing the natural frequencies of hybrid structures increases the safety and performance of structures and enables the development of more robust and stable designs in engineering applications.

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Not Applicable.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Kübra Çağla ÇIBIKÇI*:** She conducted the experiments, analyzed the results and performed the writing process.

Deneyleri yapmış, sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

***Mustafa YAMAN*:** He conducted analyzed the results.

Sonuçları analiz etmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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