Investigation of the Effects of Dimensional Inaccuracies on the First Natural Frequency of Cellular Lattice Structures

Amir Hosein Samimi, Mohammad Reza Karamooz-Ravari *, Reza Dehghani

Faculty of Mechanical and Materials Engineering
Kerman Graduate University of Advanced Technology, Iran
E-mail: amirhshs73@gmail.com, m.karamooz@kgut.ac.ir, r.dehghani@kgut.ac.ir
*Corresponding author

Received: 30 November 2021, Revised: 27 April 2022, Accepted: 30 April 2022

Abstract: Lattice structures have attracted a great deal of attention for being used in different industries due to unique properties such as high strength-to-weight ratio and high damping coefficient. These metamaterials might suffer from dimensional inaccuracies, i.e., variable strut's diameter, wavy struts, micropores, and deviation from the designed cross-sectional area, which arise from the fabrication process. These inaccuracies can drastically affect their mechanical response. In this paper, the effects of different dimensional inaccuracies, including variable struts' diameter, wavy struts, and material concentration at nodes, on the frequency response of different cellular lattice structures are studied. To do so, a finite element model is constructed using Timoshenko beam elements, and the natural frequencies are obtained for four different lattices. The obtained results show that, by increasing the average diameter, the natural frequency increases drastically, whereas by increasing the amount of variation in the struts' diameter and waviness the natural frequency decreases by a small amount. It is also observed that the lattice structures whose main deformation mechanism is axial loading are more sensitive to the change of average struts' diameter. In addition, the natural frequency increases as the concentration of material in the vicinity of the nodes increases. The effect of material concentration inaccuracy is more pronounced for the first lattice for which the number of struts meeting at one node is the smallest.

Keywords: Beam, Lattice Structures, Natural Frequency, Vibration

How to cite this paper: Amir Hosein Samimi, Mohammad Reza Karamooz-Ravari, and Reza Dehghani, "Investigation of the Effects of Dimensional Inaccuracies on the First Natural Frequency of Cellular Lattice Structures", Int J of Advanced Design and Manufacturing Technology, Vol. 15/No. 3, 2022, pp. 109-117. DOI: 10.30486/admt.2022.1946219.1324.

Biographical notes: Amir Hosein Samimi received his MSc degree in Mechanical Engineering from Kerman Graduate University of Technology, Kerman, Iran, in 2021. **Mohammad Reza Karamooz-Ravari** and **Reza Dehghani** received their PhD degrees in Mechanical Engineering from Isfahan University of Technology (IUT), Isfahan, Iran, in 2015 and 2010, respectively. They are currently associate professors at the Kerman Graduate University of Advanced Technology, Kerman, Iran. Their research interests include robotics, nonlinear control and vibrations.

1 INTRODUCTION

Cellular materials are a group of materials formed via the network connection of struts and plates in three-dimensional space. These materials have special properties, including high energy absorption, high strength-to-weight ratio, low heat transfer (thermal insulation), low relative density, sound absorption, and low weight [1-2]. These materials can be divided into two categories including lattice structures and porous materials; i.e., the former has regular, whereas the latter has an irregular structure. As another categorization, a cellular material is called close-cell if the boundary between each cell and other cells is detectable, and it is called open-cell if the inter-cell boundary is not detectable. Since lattice structures have a regular structure, their mechanical properties are largely controllable.

Due to their unique properties, these materials have vast applications in different industries such as medical, military, and aerospace [2-3]. Vibration of a mechanical system is a major factor leading to failure, which can have irreversible consequences and reduce its lifetime. In examining a system's vibrational response, the natural frequency is of utmost importance. The natural frequency of a system depends on the modulus of elasticity, material's density, and its geometry. Accordingly, in order to change frequency, the geometry or the material from which the part is fabricated should be changed. Still, in most cases, it is impossible to change geometry due to practical constraints and limitations.

Moreover, changing the material may not lead to optimal results when the material is a metal, because the elastic modulus-to-density ratio of most materials is almost identical. In this regard, the use of cellular materials, whose modulus of elasticity and density can be regulated and changed, is a good option. Also, when the human body is under the effect of a system's vibrations, it may sustain serious injuries in the joints and nervous and cardiovascular systems. Thus, reduction of the range of vibrations imposed on the riders in a vehicle can be of utmost importance [1]. Lattice structures are good choices for reducing the transferred vibrations, and thus their examination is crucial.

To assess the performance of lattice structures in vibrating systems, several experimental [5], [6], [9-11] and numerical [4], [7], [8] studies have been performed. DiTaranto studied the free vibrations of composite sandwich beams using the classic beam theory [4]. To do so, he assumed that the surface of the sandwich beam deforms based on the Euler–Bernoulli beam theory, whereas their core deforms only in shear. This model was used by researchers for a long time.

Kim and Hwang studied the effect of deboning on the flexural strength, natural frequency, and frequency response of honeycomb sandwich structures with different lengths numerically and experimentally [5]. They found that as deboning increases, the natural frequency decreases. Lou et al. examined the free vibration of a stainless-steel sandwich structure with a pyramidal truss core under simply supported boundary conditions, and studied the effects of changing the length, diameter, and gravity angle of the truss's struts on the frequency response [6]. Xu and Qiu proposed a novel method and examined the free vibration of composite lattice truss core sandwich beams, and examined the effects of material and geometric parameters on natural frequency [7]. Niu et al. Studied the main frequency of cellular materials and, accordingly, proposed an optimal fabrication design for these materials under the influence of vibrations [8]. By studying two solid and almost-solid structures, Azmi et al. [9] investigated the effect of the strength of the part produced by the 3D printer on the vibration properties of the lattice structure. Their findings show that the higher the strength of the part, the higher the frequency becomes. Using a new approach, Andresen et al. [10] studied the effect of structural irregularities on the value of the first frequency of a structure without any change in weight or stiffness. This work was formed by simulating the desired model, numerically and experimentally. Braun et al. simulated a beam model and a solid model of a sandwich structure filled with BCC and BCCZ structures, and compared the natural frequencies of these two structures [11]. Using a new method, Monkova et al. investigated the effect of cell thickness on the damping properties of BCC lattice structure made of ABS plastic [12]. The obtained results show that the stiffness and frequency increase with increasing cell thickness. Wang et al. used 3D printing to fabricate cellular structures with variable density. They then optimized the internal topology of these structures in order to maximize the fundamental frequency [13].

Cellular lattice structures are mainly fabricated by additive manufacturing (AM) and suffer from some dimensional inaccuracies, i.e., variable strut's diameter, wavy struts, micropores, and deviation from the designed cross-sectional area. These inaccuracies can drastically affect their mechanical response [14]. To the best knowledge of the authors, the effects of these inaccuracies on the frequency response of cellular lattices have not been investigated. In this paper, a finite element model, based on Timoshenko beam elements, is developed to study the effects of struts variable cross-sectional area, struts' waviness, and material concentration at the vicinity of vertices on the natural frequencies of different cellular lattice structures.

2 FINITE ELEMENT MODELING

In this section, first, the proposed beam finite element model, for taking the dimensional inaccuracies into account, is briefly introduced. Then the utilized boundary conditions and frequency analysis approach are explained.

2.1. Geometrical Modelling

Figure 1 shows a schematic view of the unit cells corresponding to the lattice structures used for the current study, named as Model 1 to Model 4. These four structures are chosen because of the existence of diagonal, horizontal, and perpendicular struts which makes the examination of the effect of struts' orientation and deformation mechanisms possible.

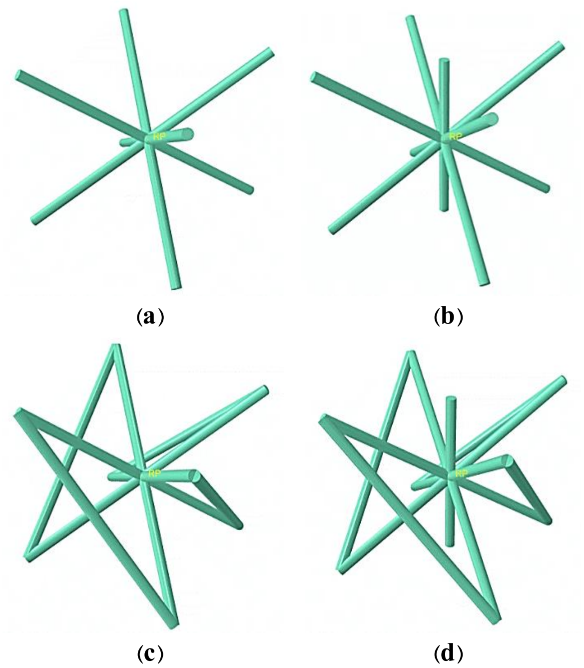


Fig. 1 A schematic representation of the unit cell corresponding to the lattice structure of: (a): Model 1, (b): Model 2, (c): Model 3, and (d): Model 4.

In order to construct the finite element model of the lattice structures, a Python program is developed as the input for Abaqus finite element package. The program gets the vertices of the lattice and their connections and constructs a wire frame of the lattice. As mentioned earlier, in this paper, three types of dimensional inaccuracies, including variable struts' diameter, wavy struts, and material concentration at the vicinity of vertices are taken into account. To do so, each strut is divided into *N* sections, each of which has a randomly assigned radius presented by "Eq. (1)", reflecting the variable struts' diameter.

$$R_i = R_{av} + \alpha_i R_{\mathrm{var}} \tag{1}$$

In which, R_i is the i-th section's radius, R_{av} is the struts' average diameter, α_i is a random real number between -1 and 1, and R_{var} is the maximum value of the struts' diameter variation.

To produce wavy struts, the nodes, connecting two sections of each strut, are moved to a random position within a circle with the radius of δ located in a plane passing through that node and with a normal of the original strut, as shown in "Fig. 2". Note that all the vertices located on the top and bottom faces of the lattices are remained at their initial position for the sake of applying boundary conditions. Figures 3(a) and (b) show the variable struts' diameter and wavy struts, respectively.

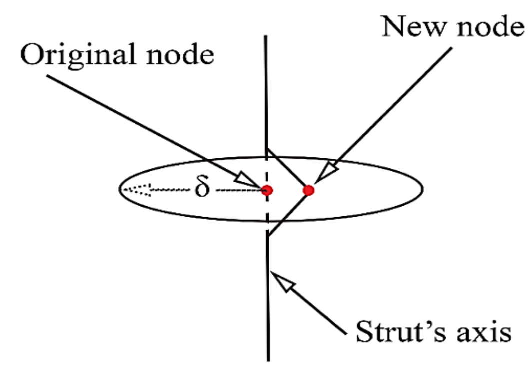


Fig. 2 Schematic representation of how the wavy strut inaccuracy is implemented in the model.

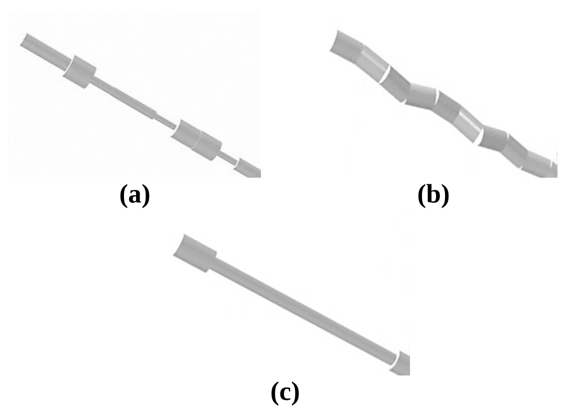
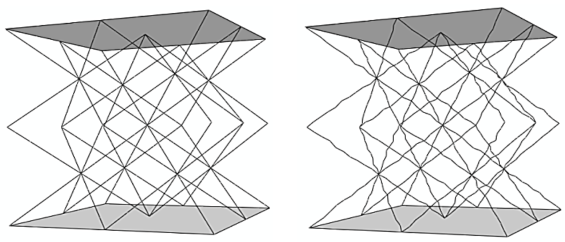


Fig. 3 A schematic view of the dimensional inaccuracies that are taken into account: (a): variable strut's diameter, (b): wavy strut, and (c): material concentration at the vicinity of vertices.

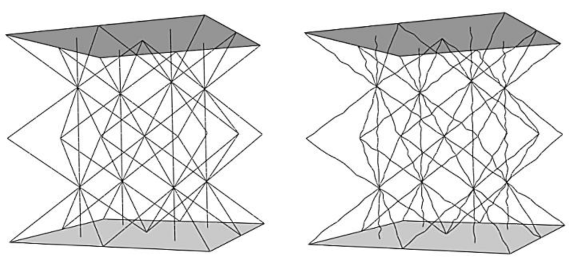
When a lattice structure is fabricated using additive manufacturing technology, some extra material is concentrated at the vertices, where more than two struts meet.

To take this inaccuracy into account, a sphere with the radius of 20 percent of struts' length and the center of each node is considered, and the radius of that portion of the strut, $Rrin$, which is located in this sphere, is considered to be 20 percent larger than the average radius of that strut. Figure 3(c) shows this type of dimensional inaccuracy. This approach was previously used by several authors providing good results [15-17].
The preliminary model's cell size and its struts' average diameter are considered to be 25 mm and 1.5 mm, respectively. Subsequently, a surface with a thickness of 2 mm is constructed and connected to the structure on the top and bottom faces. This plane is added in order to simulate the real structure found in the literature [18].



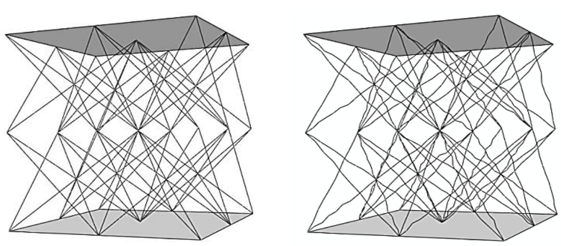
(a) **(b)**

Fig. 4 Schematic representation of the wavy strut inaccuracy applied to Model 1: (a): non-defected lattice, and (b): defected lattice.



(a) **(b)**

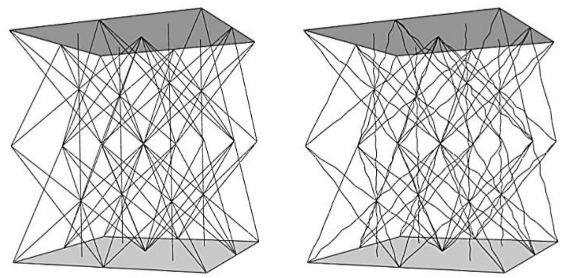
Fig. 5 Schematic representation of the wavy strut inaccuracy applied to Model 2: (a): non-defected lattice, and (b): defected lattice.



(a) **(b)**

Fig. 6 Schematic representation of the wavy strut inaccuracy applied to Model 3: (a): non-defected lattice, and (b): defected lattice.

Figures 4–7 show an overview of the accurate beam model and the corresponding beam model with wavy struts inaccuracy for Model 1 to Model 4 containing 2×2×2 unit cells.



(a) **(b)**

Fig. 7 A schematic representation of the wavy strut inaccuracy applied to Model 4: (a): non-defected lattice, and (b): defected lattice

2.2. Boundary Conditions

Since the main purpose of this paper is to examine the effect of dimensional inaccuracies on the value of natural frequency, only one boundary condition is assumed for all the studied structures. Here, it is supposed that the bottom face of the lattices is clamped, so that all translational and rotational degrees of freedom are constrained, i.e:

$$u_x = u_y = u_z = \theta_x = \theta_y = \theta_z = 0 \quad (2)$$

Where. u_i is the translational degree of freedom, θ_i is the rotational degree of freedom and i stands for x, y, and z directions.

2.3. Frequency analysis

In this paper, the subspace frequency analysis method is used, which is performed by specifying the number of requested modes, i.e., the first 2 modes of each structure are requested.

3 RESULT

In this section, first, a comparison is made between the beam model, solid models and the experimental results reported previously in the literature [18]. Then, in order to assess the effects of dimensional inaccuracies, the value of fundamental frequency of each structure is presented, considering different types of inaccuracies, and the obtained results are discussed.
All the lattices are supposed to be fabricated from LPBF Nylon-12. The physical properties that are required for the simulation of frequency response are presented in "Table 1" [18].

Table 1 Mechanical properties of polymer [18]

Parameter	Value	Unit
Elastic Modulus (E)	741	Mpa
Density (ρ)	1010	Kg/m^3
Poisson's Ratio (υ)	0.3	–

As mentioned in section 2.1, to introduce the dimensional inaccuracies into the beam finite element model, the struts are equally divided into N sections. Here, the value of the number of strut's sections, N, is supposed to be 10 for all the simulations. Then, each section is meshed using three-node Timoshenko beam elements, which is available as B32 in ABAQUS finite element package. A mesh sensitivity analysis is performed to be sure that an appropriate element size is chosen. To do so, as shown in "Fig. 8", considering the largest possible value for the initial guess of the size of elements, the element size is reduced by a factor of 0.5 until the amount of the change on the first natural frequency between two consecutive steps gets smaller than 10 percent. Using this approach, the mesh size of 1.5 mm is obtained and is utilized for all the simulations in this paper.

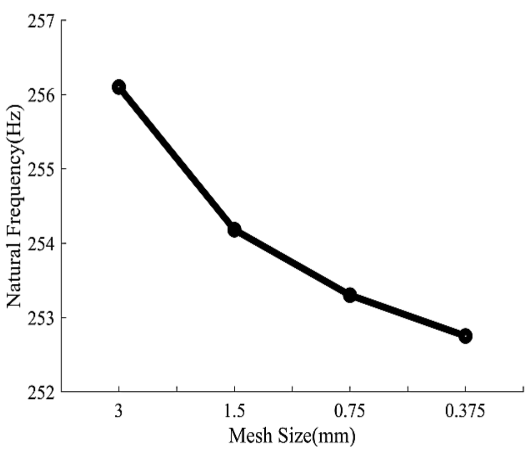


Fig. 8 Mesh sensitivity analysis for Model 1.

Due to the random nature of the proposed approach, the obtained results might be different from those obtained using the same geometric parameters. Accordingly, for each random model, the simulation is repeated 15 times and the average value of the fundamental frequency is reported.

3.1. Model Validation

In order to validate the utilized beam model, the first natural frequency obtained using the beam model is compared against that obtained using solid finite element model and the experimentally obtained one presented in the literature [18]. Note that the lattices are supposed to be completely perfect so that no inaccuracies are included. In addition, the solid finite element model of the lattices is meshed using 10-node quadratic tetrahedron elements, denoted as C3D10 in ABAQUS. After performing the mesh sensitivity analysis, the mesh size of 0.5 mm is obtained.

In "Table 2", the fundamental natural frequency obtained using the beam model is compared with that obtained using the solid model and the experimentally reported one.

Table 2 The first natural frequencies obtained using solid and beam finite element models

Model No.	Solid model (Hz)	Beam model (Hz) (error %)	Experimental Result (Hz) [16]
1	56	54.3(3.1%)	50
2	271.6	254.1(6.8%)	–
3	180	216.5(16.8%)	–
4	317.8	331.7(4.1%)	–

As can be seen, the prediction of the beam model is in a good agreement with the experimental one for Model 1, showing about 8.6 percent difference. The difference of the first natural frequency between solid and beam models is respectively 3.1, 6.8, 16.8, and 4.1 percent for Model 1, Model 2, Model 3, and Model 4. As can be seen, the discrepancy between the obtained results using beam and solid models is different for Model 1-4. This observation is associated with the main deformation mechanism of the lattices, which causes that the lattices' struts experience different loadings. Considering s as the number of struts, and v as the number of vertices, the Maxwell number can be formulated as [10]:

$$M = s - 3v + 6 \tag{3}$$

Using Equation (3), the Maxwell number of the lattices is respectively -13, -17, -9, -13. When the Maxwell number increases, the main deformation mechanism tends to axial one. As can be seen, the maximum discrepancy is associated with Model 3 whose Maxwell number is the highest. However, beside the Maxwell number, the deformation mechanism is related to the orientation of the struts which might change the deformation mechanism of the lattices, i.e., the second highest discrepancy is related to Model 2, which has vertical struts.

3.2. The Effects of Dimensional Inaccuracies on the Fundamental Natural Frequency

As mentioned earlier, when a cellular lattice structure, specially strut based ones, is fabricated using additive manufacturing technology, several dimensional inaccuracies might form during the process. These inaccuracies can drastically affect the mechanical response of the final lattice. These inaccuracies can be categorized into three major groups, including dimensional inaccuracies, surface inaccuracies and porosity [17]. In this paper, the former one is taken into account. To do so, the dimensional inaccuracies are introduced into the model and the obtained fundamental natural frequency is compared with the first natural frequency of the lattice with no inaccuracies. In this section, first, the effects of variation of struts' diameter are investigated. Then wavy struts inaccuracy is assessed. Finally, the effects of material concentration at the nodes are studied.

3.2.1. Effects of Variable Struts' Diameter on The First Natural Frequency

It has been shown [19-21] that the struts' diameter of cellular lattice structures varies along their length, where the average value of the diameter is smaller and larger than the designed value for vertical and horizontal struts, respectively. Table 3 shows all the cases which are considered for studying the effects of struts' diameter variation. As can be seen, no inaccuracies are included in the first case. The designed struts' diameter is supposed to be 0.75 mm. However, due to experimental observations, in inaccurate models, the average value of struts' diameter is increased and decreased by 20 percent for diagonal and vertical struts, respectively. Note that the value of $Rrin$ is supposed to be equal to the value of the average radius, so that the effect of material concentration in the vicinity of nodes is not included.

Table 3 Different cases considered for studying the effects of variation in struts' diameter

Case No.	Rav (mm)	$Rvar$ (mm)	δ (mm)	Details
1	0.75	0	0	
2	0.75	0.15	0	
3	0.9	0	0	
4	0.9	0.18	0	Diagonal struts
	0.9	0	0	Other struts
5	0.9	0	0	Diagonal and horizontal struts
	0.9	0.18	0	Vertical struts
6	0.9	0	0	Diagonal and horizontal struts
	0.6	0.12	0	Vertical struts
7	0.9	0.18	0	Diagonal and horizontal struts
	0.6	0.12	0	Vertical struts

Figure 9 shows the fundamental natural frequency of the cases introduced in "Table 3" for all the lattice structures illustrated in "Fig. 2".

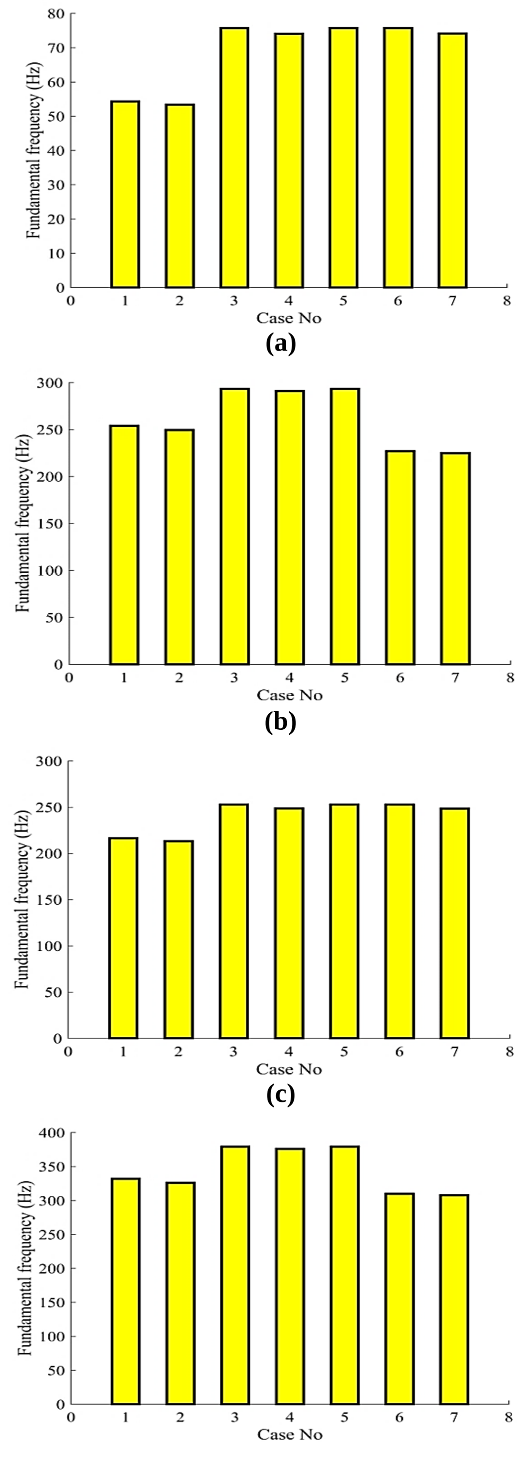


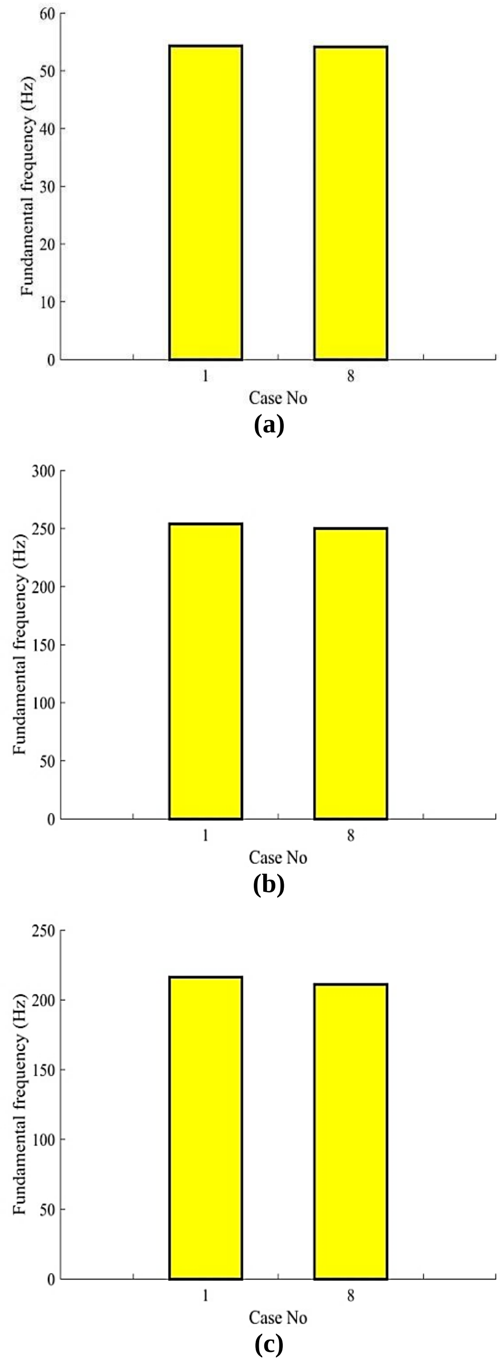
Fig. 9 Effects of variable struts' diameter on the first natural frequency for: (a): Model 1, (b): Model 2, (c): Model 3, and (d): Model 4.

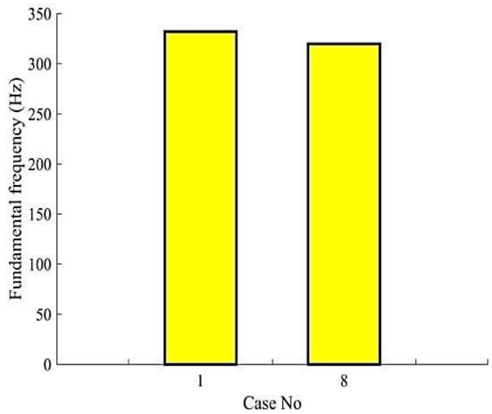
For Model 1, since all the struts are diagonal with the same orientation, cases 3, 5, and 6 as well as cases 4 and 7 are identical. Comparing the cases 1 and 3 shows that increasing the value of the average struts' diameter by a factor of 1.2, increases the value of fundamental frequency by a factor of 1.394, 1.154, 1.168, and 1.143 for Model 1 to Model 4, respectively. It means that the dimensional inaccuracies associated with the additive manufacturing technology can drastically affect the natural frequency of strut-based cellular lattice structures. However, these changes are more pronounced for the structures with the lower values of fundamental frequency which means that the stiffer the structure is the lower the effects of dimensional accuracies would be. A comparison between cases 3 and 6 for Model 2 and 4 supports this claim too. As can be seen, when the dimensional inaccuracy is applied on the horizontal struts, i.e., the average struts' diameter is decreased by a factor of 0.8, the fundamental frequency decreases 22.6 and 18.3 percent for Model 2 and Model 4, respectively. Again, this reduction is smaller for Model 4 in comparison with Model 2. When the struts' diameter variation inaccuracy is taken into account, i.e., cases 2, 4, and 5, the maximum change of the fundamental natural frequency is about 2.1 percent which is obtained by comparing cases 3 and 4 for Model 1. This observation shows that struts' diameter variation inaccuracy has a negligible effect on the natural frequency of the lattice structures.

As discussed in section 3.1, based on the Maxwell number, the main deformation mechanism of all the lattices presented in this paper is bending. However, for Model 2 and 4, the existence of vertical struts shifts the deformation mechanism toward axial loading. It means that Model 2 and 4 are stiffer than Model 1 and 3 so that the predicted natural frequency of the former lattices is higher than that of the latter ones. When the average strut diameter increases (decreases) the stiffness of the lattices increases (decreases). However, because of the axial loading as the main deformation mechanism, the increscent of stiffness for Models 2 and 4 is more pronounced than Models 1 and 3. Accordingly, the natural frequency of Models 2 and 4 is more sensitive to the change of average strut diameter than Models 1 and 3. When the struts' diameter variation is taken into account, the stiffness might decrease slightly. However, since the struts' diameter varies around the average diameter, the mass does not change pronouncedly. Therefore, the fundamental frequency of the lattices decreases slightly too.

3.2.2. Effects of Wavy Struts on First Natural Frequency

In order to investigate the effects of struts' waviness inaccuracy on the fundamental natural frequency of the discussed lattices, a value of 20 percent of the struts' radius is assigned to δ parameter. Accordingly, the utilized parameters are as $Rav = 0.75$ mm, $Rvar = 0$, and $\delta = 0.15$ mm. Considering this case as case 8, the results are compared to the fundamental frequency of case 1 and presented in "Fig. 10". As can be observed, the wavy strut inaccuracy does not have a pronounced effect on the natural frequency of the lattices. By applying the wavy struts inaccuracy, the natural frequency reduces by 0.2, 1.6, 2.4, and 1.9 percent for Model 1 to Model 4, respectively.





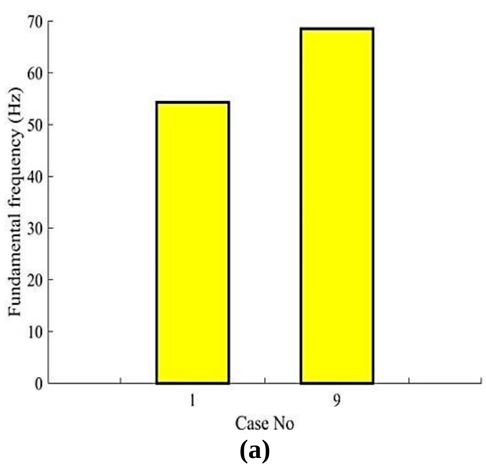
(d)

Fig. 10 Effect of wavy struts on the first natural frequency for: (a): Model 1, (b): Model 2, (c): Model 3, and (d): Model 4.

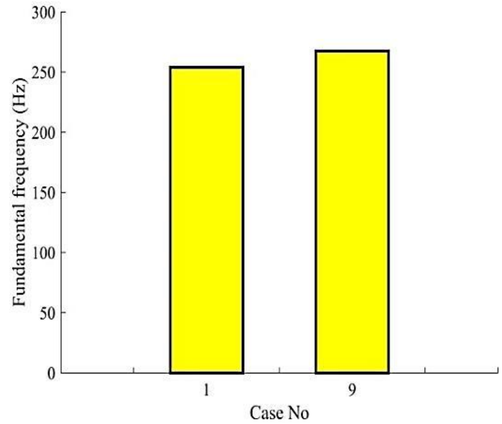
3.2.3. Effect of Material Concentration in The Vicinity of Nodes

To investigate the effects of material concentration in the vicinity of nodes on the fundamental frequency of the discussed lattices, $Rrin$ is increased 20 percent (case 9) and the obtained results are compared with the first case. Accordingly, the geometrical parameters used for the simulations are $Rrin = 0.9$ mm, $Rav = 0.75$ mm, $Rvar = 0$ mm and $\delta = 0.0$ mm. As shown in "Fig. 11", as the amount of Rrin increases, the fundamental natural frequency increases.

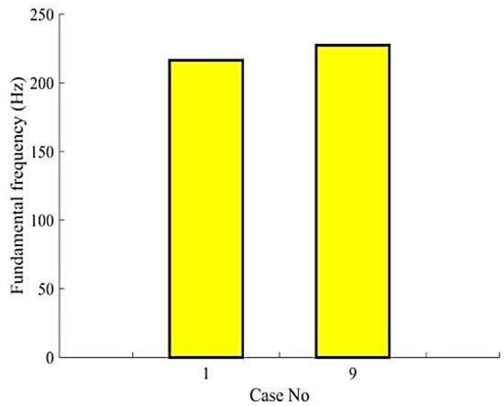
This increase is about 26 percent for Model 1, about 5 percent for Models 2 and 3, and about 4 percent for Model 4. It can be seen; the effect of this inaccuracy is more pronounced for Model 1. The reason behind this observation is that as the number of struts meeting at one node decreases, the stiffness of the lattice as well as the natural frequency increases more rapidly by material concentration.



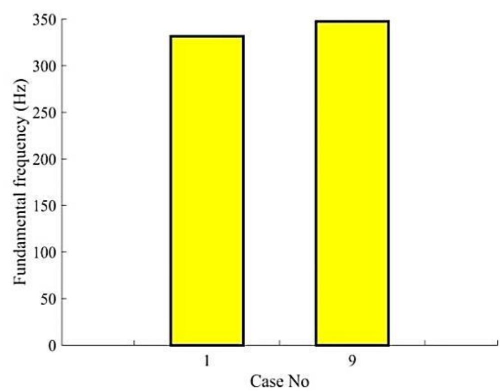
(a)



(b)



(c)



(d)

Fig. 11 Effect of material concentration in the vicinity of nodes on the first natural frequency for: (a): Model 1, (b): Model 2, (c): Model 3, and (d): Model 4.

4 CONCLUSIONS

This paper deals with the effects of dimensional inaccuracies, associated with additive manufacturing fabrication approach, on the natural frequency of different lattice structures. To do so, a beam finite element model is constructed and three types of inaccuracies, including variable struts' diameter, wavy struts, and material concentration at nodes, are taken into account. The obtained results showed that the natural frequency increases by increasing the average struts' diameter. In addition, the effects of average struts' diameter are more pronounced for the stiffer lattices. It is also observed that struts' diameter variation and wavy struts inaccuracies have negligible effect on the natural frequency of all the studied lattices structures. However, the effects of material concentration at the vicinity of nodes are noticeable for the first lattice for which the struts meeting at one node is the smallest.

REFERENCES

[1] Ashby, M. F., Evans, T., Fleck, N. A., Hutchinson, J. W., Wadley, H. N. G., and Gibson, L. J., Metal Foams: A Design Guide, Butterworth-Heinemann, Oxford, UK, Chaps. 4, 5, 2000.

[2] Banhart, J., Manufacturing Routes for Metallic Foams, Jom, Vol. 52, No. 12, 2000, pp. 22-27, DOI:10.1007/s11837-000-0062-8.

[3] Meisel, N. A., Williams, C. B., and Druschitz, A., Lightweight Metal Cellular Structures Via Indirect 3D Printing and Casting, Proceedings of The International Solid Freeform Fabrication Symposium, Austin, United States, 2012, pp. 162-176.

[4] Di Taranto, R. A., Theory of Vibratory Bending for Elastic and Viscoelastic Layered Finite-Length Beams, Appl. Mech, Vol. 32, No. 4, 1965, pp. 881-886, DOI:10.1115/1.3627330.

[5] Kim, H. Y., Hwang, W., Effect of Debonding on Natural Frequencies and Frequency Response Functions of Honeycomb Sandwich Beams, Composite Structures, Vol. 55, No. 1, 2002, pp. 51-62, DOI:10.1016/S0263-8223(01)00136-2.

[6] Lou, J., Ma, L., and Wu, L. Z., Free Vibration Analysis of Simply Supported Sandwich Beams With Lattice Truss Core, Materials Science and Engineering: B, Vol. 177, No. 19, 2012, pp. 1712-1716, DOI:10.1016/j.mseb.2012.02.003.

[7] Xu, M., Qiu, Z., Free Vibration Analysis and Optimization of Composite Lattice Truss Core Sandwich Beams with Interval Parameters, Composite Structures, Vol. 106, 2013, pp. 85-95, DOI:10.1016/j.compstruct.2013.05.048.

[8] Niu, B., Yan, J., and Cheng, G., Optimum Structure with Homogeneous Optimum Cellular Material for Maximum Fundamental Frequency, Structural and Multidisciplinary Optimization, Vol. 39, No. 2, 2009, pp. 115-132.

[9] Azmi, M. S., Ismail, R., Hasan, R., Alkahari, M. R., and Tokoroyama, T., Vibration Analysis of FDM Printed Lattice Structure Bar, Proceedings of SAKURA Symposium on Mechanical Science and Engineering, Nagoya, Japan, September, 2017, pp. 33-35.

[10] Andresen, S., Bäger, A., and Hamm, C., Eigenfrequency Maximisation by Using Irregular Lattice Structures, Journal of Sound and Vibration, Vol. 465, 2020, 115027.

[11] Braun, M., Ivanez, I., and Aranda-Ruiz, J., Numerical Analysis of The Dynamic Frequency Responses of Damaged Micro-Lattice Core Sandwich Plates, The Journal of Strain Analysis for Engineering Design, Vol. 55, No. 1-2, 2020, pp. 31-41, DOI: 10.1177/0309324719890958.

[12] Monkova, K., Vasina, M., Zaludek, M., Monka, P. P., and Tkac, J., Mechanical Vibration Damping and Compression Properties of a Lattice Structure, Materials, Vol. 14, No. 6, 2021, 1502, DOI: 10.3390/ma14061502.

[13] Wang, X., Zhang, P., Ludwick, S., Belski, E., and To, A. C., Natural Frequency Optimization of 3D Printed Variable-Density Honeycomb Structure Via a Homogenization-Based Approach, Additive Manufacturing, Vol. 20, 2018, pp. 189-198, DOI: 10.1016/j.addma.2017.10.001.

[14] Ravari, M. K., Kadkhodaei, M., Badrossamay, M., and Rezaei, R., Numerical Investigation on Mechanical Properties of Cellular Lattice Structures Fabricated by Fused Deposition Modeling, International Journal of Mechanical Sciences, Vol. 88, 2014, pp. 154-161, DOI:10.1016/j.ijmecsci.2014.08.009.

[15] Ravari, M. K., Kadkhodaei, M., A Computationally Efficient Modeling Approach for Predicting Mechanical Behavior of Cellular Lattice Structures, Journal of Materials Engineering and Performance, Vol. 24, No. 1, 2015, pp. 245-252, DOI:10.1007/s11665-014-1281-4.

[16] Zhou, J., Shrotriya, P., and Soboyejo, W. O., On the Deformation of Aluminum Lattice Block Structures: From Struts to Structures, Mechanics of Materials, Vol. 36, No. 8, 2004, pp. 723-737, DOI:10.1016/j.mechmat.2003.08.007.

[17] Galarreta, S. R., Jeffers, J. R., and Ghouse, S., A Validated Finite Element Analysis Procedure for Porous Structures, Materials & Design, Vol. 189, 2020, 108546, DOI:10.1016/j.matdes.2020.108546.

[18] Syam, W. P., Jianwei, W., Zhao, B., Maskery, I., Elmadih, W., and Leach, R., Design and Analysis of Strut-Based Lattice Structures for Vibration Isolation, Precision Engineering, Vol. 52, 2018, pp. 494-506, DOI:10.1016/j.precisioneng.2017.09.010.

[19] Echeta, I., Feng, X., Dutton, B., Leach, R., and Piano, S., Review of Defects in Lattice Structures Manufactured by Powder Bed Fusion, The International Journal of Advanced Manufacturing Technology, Vol. 106, No. 5, 2020, pp. 2649-2668, DOI:10.1007/s00170-019-04753-4.

[20] Arabnejad, S., Johnston, R. B., Pura, J. A., Singh, B., Tanzer, M., and Pasini, D., High-Strength Porous Biomaterials for Bone Replacement: A Strategy to Assess the Interplay Between Cell Morphology, Mechanical Properties, Bone Ingrowth and Manufacturing Constraints, Acta biomaterialia, Vol. 30, 2016, pp. 345-356.

[21] Cuadrado, A., Yánez, A., Martel, O., Deviaene, S., and Monopoli, D., Influence of Load Orientation and of Types of Loads on The Mechanical Properties of Porous Ti6Al4V Biomaterials, Materials & Design, Vol. 135, 2017, pp. 309-318, DOI:10.1016/j.matdes.2017.09.045.