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Free Vibration Analysis of Composite Cylindrical Shell Reinforced with Silicon Nano-Particles: Analytical and FEM Approach

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Previous research presented the effect of nanomaterials on the mechanical properties of composite materials with various volume fraction effects; in addition, their research presented the effect of nanomaterials on the same mechanical characteristics for a composite plate structure, such as vibration and thermal buckling behavior. Therefore, since the use of shell structures is for large applications, it is necessary to investigate the modification of the vibration characteristics of its design with the effect of nanomaterials and study the influence of other reinforced nanoparticle types on its features. Therefore, in this work, silicon nanoparticles were selected to investigate their effect on the vibration behavior of a shell structure. As a result, this work included studying the vibration behavior by testing the shell structure with a vibration test machine. In addition, after manufacturing the composite material shell with various silicon volume fractions, the mechanical properties were evaluated. In addition, the finite element technique with the Ansys program was used to assess and compare the vibration behavior of the shell structure using the numerical technique. The comparison of the results gave an acceptable percentage error not exceeding 10.93%. Finally, the results evaluated showed that the modification with silicon nanomaterials gave very good results since the nanomaterials improved about 65% of the shell's mechanical properties and vibration characteristics.

Keywords: Shell Vibration, Silica Nano, Silica Shell Vibration, Composite Shell, and Nano Composite.

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Introduction

The composite materials investigation in previous years in different applications was due to the high strength to weight ratio; therefore, this investigation for composite materials being modified for mechanical properties for composite materials by reinforcement with different fibers, and then modified for composite by reinforcement with varying concentrations of powder, [1-3]. Then, the investigated different composite materials structures are as a beam, plate, and other facilities with various applications, such as the vibration of the plate with different parameters, [4-5], buckling for a plate with multiple parameters, [6-8], stress analysis for other structures, fatigue characterization with different applications, [9], and prosthetic and orthotics structures. Thus, due to the impartment for composite materials and application, then it was necessary to investigate the modification of the composite materials with reinforcement by nanoparticle materials since this modification with the composite materials leads to an increase in the material mechanical properties with a high value and with a low increasing for the weight of the material, [10-11]. Therefore, one application for composite materials was for a shell structure under vibration behavior due to impartment for shell structure. So, different nanomaterials can be used to modify the mechanical properties of materials. Then one of the impartment materials can be used with silica nanoparticle materials since these materials give high modifications and change the structure's dynamic behavior. Also, due to impartment for shell structure, then, work in this paper is to modify the dynamic behavior of shell structure by reinforcement with silica nanomaterials.

Therefore, many researchers studied the dynamic behavior of shell structure with different techniques and parameters effect, as mentioned below. A. A. Hamzah et al. [12] investigated the effect of thermal load on the dynamic characteristics of a cylindrical structure by using the finite element technique.

In 2019, a semi-analytical method was used by Fuzhen Pang et al. [13] to study the vibration characterization of composite laminated cylindrical and spherical shells. Then, in 2019, Haichao Li et al. [14] investigated free vibration analysis of combined spherical and cylindrical shells with non-uniform thickness based on the Ritz method using a semi-analytical solution. Also, in 2019, Zhaoye Qin et al. [15] studied analytically the dynamic model for vibration analysis of a cylindrical shell structure made of functionally graded materials with arbitrary boundary conditions. The Rayleigh-Ritz method was used, and the vibration response of a cylindrical shell based on geometric parameters, the volume fraction of carbon nanotubes, and boundary conditions were also evaluated. M. Azmi et al. [16] studied the effect of SiO_2 nanomaterials on the dynamic response by using an analytical model. Thus, this investigation included determining the dynamic behavior for the column with various nanomaterials amounts; in addition, this study involved the dynamic analysis for different supported columns. The column's dynamic behavior was calculated under the blast load applied. Xiao Li [17] examined the stability conditions of composite laminated nonlinear cylindrical shells under periodic axial loads and a hygrothermal environment. Using experimental, numerical, and analytical techniques, M. Zarei et al. In [18] investigated the vibrational characteristics of joined stiffened conical-cylindrical composite shells.

Kwanghun Kim et al. [19] analyzed the natural frequencies and mode shapes of the coupled laminated composite elliptical-cylindrical-elliptical shells with elastic boundary conditions using the finite element method (FEM). Finally, Giuseppe Sciascia et al. [20] used a multi-domain Ritz method and FEM for investigating vibration characteristics and dynamic instability analysis of stiffness laminated composite shell structures.

A review of studies shows that many researches have been done on static and dynamic behavior for a shell structure with different reinforcement fibers and nanomaterials effect. But, they did not study the impact of Silica nanomaterials reinforcement on the composite shell structure. Therefore, the main aim of this paper is to investigate the effects of different volume fractions for Silica nanoparticle materials on the natural frequency and deformation of a composite shell structure, combined with the unidirectional fiber and epoxy resin materials. The present research includes an experimental technique used to manufacture a composite shell with nanoparticle materials and then a tensile test and vibration rig to calculate the composite material shell's mechanical properties and natural frequency with the nano effect. The numerical technique will be used to compare the natural frequency results for given agreement with the experimental results and determine the deformation of the shell structure with the nano effect.

I. Experimental Work

The experimental work included using a vibration rig with a vibration machine to measure the natural frequency of a cantilever shell cylinder with various nano silicon volume fractions. Where the experimental work was divided into three parts; firstly, manufacturing the shell cylinder samples with various nanomaterials volume fractions, using nano volume fractions from 0 to 2.5%, secondly, calculating the mechanical properties for the composite materials manufactured with the nanoparticle effect, and finally, calculating the vibration characterization (natural frequency) for the shell structure sample.

1.1. Manufacturing of Samples

The manufacturing of nanocomposite samples included two parts; firstly, samples for tensile test, as shown in Fig. 1, according to the ASTM stander (D3039/D03039M), [21], as shown in Fig. 2 (with sample width=15 mm, overall length = 250 mm, thickness =1 mm, tab length =56 mm, tab thickness =1.5 mm and tab bevel angle =7° or 90°), for fiber direction (0° and 90°), and secondly, the shell samples, as shown in Fig. 3, with dimensions (shell length$=30$ cm, shell diameter$=15$ cm, and shell thichness$=4$ mm). Nanosilica (purity = 99%, particle size = 10–30 nm, surface area = 30–60 m^2/gm), obtained from Skyspring Nanomaterials, Inc., is introduced into the matrix. All tensile and shell manufactured samples were made with different volume fractions for nano silicon materials as $(0,\ 0.5,\ 1,\ 1.5,\ 2,\ \text{and}\ 2.5\%)$. In addition, the reinforcement fiber used for manufacturing the composite materials was unidirectional glass fiber with (30%) reinforcement fiber volume fraction and (70%) decrease with nano additive) epoxy resin material. Then, the manufacturing of the composite material samples (tensile and shell samples) combined the epoxy resin material with the nano silicon materials to produce a composite matrix using an ultrasonic machine and then reinforced the composite matrix with a unidirectional glass fiber material.

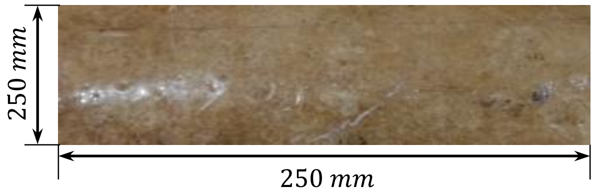


Fig. 1. Composite Tensile Sample.

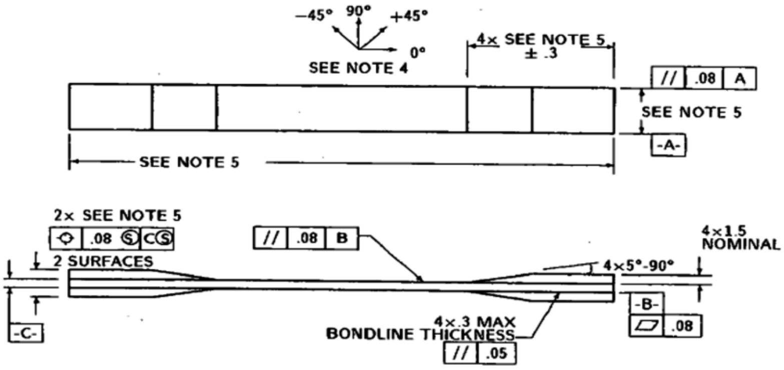


Fig. 2. ASTM (D3039/D03039M), Tensile Sample Drawing.

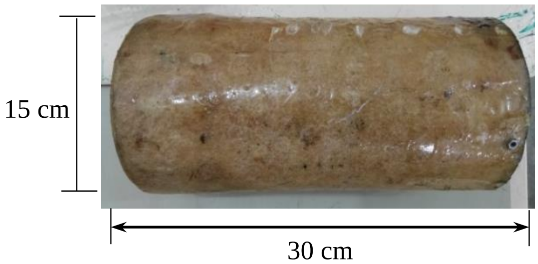


Fig. 3. Shell Composite Structure.

1.2. Mechanical Properties Testing

The mechanical properties testing included calculating the modulus of elasticity for composite materials with and without a nano parties effect. The tensile samples are presented in Fig. 1 to test five models for each volume fraction of nanoparticle effect and then calculate the average value for composite materials, as shown in Table 1. Also, the tensile test was done by using a universal tensile test machine. Therefore, the mechanical properties determined by the experimental work can be used as a numerical technique to obtain the mechanical behavior of the shell structure.

Table 1.

Mechanical Properties for Composite Materials with Different Silica Nanoparticle Volume Fractions

No.	Nano Volume Fraction (%)	Modulus of Elasticity E_1 (GPa)	Modulus of Elasticity E_2 (GPa)
1	0	12.6	3.3
2	0.5	13.3	4.1
3	1	15.9	5.6
4	1.5	17.5	7.3
5	2	18.9	9.2
6	2.5	21.4	11.1

1.3. Vibration Characterization Measurement

The vibration testing included using the vibration test rig shown in Fig. 4 to calculate the natural frequency for the shell structure, shown in Fig. 4, with various Nanoparticle volume fractions. The vibration test rig consists of the following parts: structure rig accelerometer, amplifier, oscilloscope, and impact hammer [22]. The natural frequency was calculated by impacting the shell sample using an impact hammer and then reading the voltage signal using (an oscilloscope). Then, the natural frequency was calculated using FFT, using the SIGVIEW program, as shown in Fig. 5.

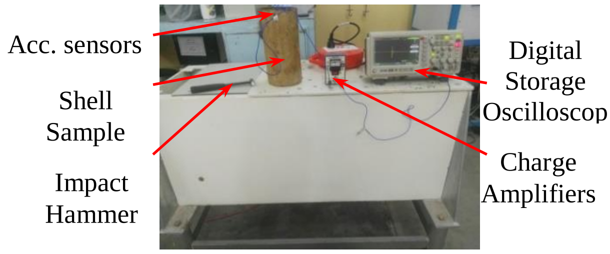
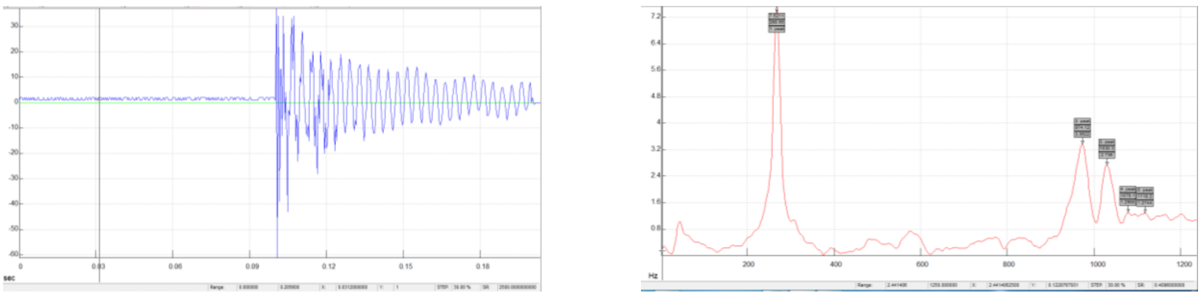


Fig. 4. Vibration test-rig.

II. Finite Element Technique

The numerical technique is an approximate solution for the engineering problem with accepted error, and it can be applied to the static and dynamic behavior of a structure with different boundary conditions [23-24]. A numerical technique used in this work comprised using finite element technique using Ansys program Version 15. The Ansys code needed first select the best element type required for the case applied, input the mechanical properties of the structure calculated from the experimental technique, mesh the structure by section for



(a) Vibration Signal

(b) FFT Signal

Fig. 5. Sigview Analysis of Signal Vibration.

the best number of elements, depending on the mesh generation technique, and finally calculating the required output for the problem [25-26]. So, the output of this work included calculating the natural frequency and deformation of the composite shell structure, supported as a cantilever, with different silica nanoparticle volume fractions. In addition, a comparison of the numerical natural frequency with the experimental results was made to obtain agreement for the results calculated.

Therefore, the best element can be used for the dynamic analysis of the shell structure is (Shell element with eight nodes and 5 degrees for each node), as shown in Fig. 6, where this element has the global displacement structure that can be listed as,

$$\{U\} = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} \qquad (1)$$

And the local displacement is,

$$\{q\}_i = \begin{Bmatrix} u \\ v \\ w \\ \alpha \\ \beta \end{Bmatrix}_i \quad \text{for } (i = 1, \dots, 8) \qquad (2)$$

Therefore, the global displacement can be calculated from the local displacement as:

$$\begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \sum_{i=1}^{8} N_i \begin{Bmatrix} u \\ v \\ w \end{Bmatrix}_i + \sum_{i=1}^{8} N_i \zeta \frac{h_i}{2} \mu_i \begin{Bmatrix} \alpha \\ \beta \end{Bmatrix}_i \qquad (3)$$

Where, N_i is the shape faction, and μ_i can be calculated from

$$\mu_i = \begin{bmatrix} -l_{2i} & l_{1i} \\ -m_{2i} & m_{1i} \\ -n_{2i} & n_{1i} \end{bmatrix} \qquad (4)$$

Then, displacement for shell element can be determined by using Eqs. 1 to 4 as:

$$\begin{Bmatrix} u_{,x} \\ u_{,y} \\ u_{,z} \\ v_{,x} \\ v_{,y} \\ v_{,z} \\ w_{,x} \\ w_{,y} \\ w_{,z} \end{Bmatrix} = \sum_{i=1}^{8} \begin{bmatrix} a_i & 0 & 0 & -d_i l_{2i} & d_i l_{1i} \\ b_i & 0 & 0 & -e_i l_{2i} & e_i l_{1i} \\ c_i & 0 & 0 & -g_i l_{2i} & g_i l_{1i} \\ 0 & a_i & 0 & -d_i m_{2i} & d_i m_{1i} \\ 0 & b_i & 0 & -e_i m_{2i} & e_i m_{1i} \\ 0 & c_i & 0 & -g_i m_{2i} & g_i m_{1i} \\ 0 & 0 & a_i & -d_i n_{2i} & d_i n_{1i} \\ 0 & 0 & b_i & -e_i n_{2i} & e_i n_{1i} \\ 0 & 0 & c_i & -g_i n_{2i} & g_i n_{1i} \end{bmatrix} \begin{Bmatrix} u \\ v \\ w \\ \alpha \\ \beta \end{Bmatrix}_i \qquad (5)$$

Where,

$$\begin{aligned} a_i &= J_{11} N_{i,\zeta} + J_{12} N_{i,\eta} \\ b_i &= J_{21} N_{i,\zeta} + J_{22} N_{i,\eta} \\ c_i &= J_{31} N_{i,\zeta} + J_{32} N_{i,\eta} \\ d_i &= \frac{h_i}{2} (a_i \zeta + J_{13} N_i) \\ e_i &= \frac{h_i}{2} (b_i \zeta + J_{23} N_i) \\ g_i &= \frac{h_i}{2} (c_i \zeta + J_{33} N_i) \end{aligned}$$

Then, by using the strain energy method and using Eq. 5, one can calculate the stiffness matrix as:

$$[K] = \int_{Vol.} [B]^T [D][B] dV \qquad (6)$$

Where,

$$[B]_i = \begin{bmatrix} a_i & 0 & 0 & -d_i l_{2i} & -d_i l_{1i} \\ 0 & b_i & 0 & -e_i m_{2i} & -e_i m_{1i} \\ 0 & 0 & c_i & -g_i n_{2i} & -g_i n_{1i} \\ b_i & a_i & 0 & -(e_i l_{2i} + d_i m_{2i}) & (e_i l_{1i} + d_i m_{1i}) \\ 0 & c_i & b_i & -(g_i m_{2i} + e_i n_{2i}) & (g_i m_{1i} + e_i n_{1i}) \\ c_i & 0 & a_i & -(d_i n_{2i} + g_i l_{2i}) & (d_i n_{1i} + g_i l_{1i}) \end{bmatrix}$$

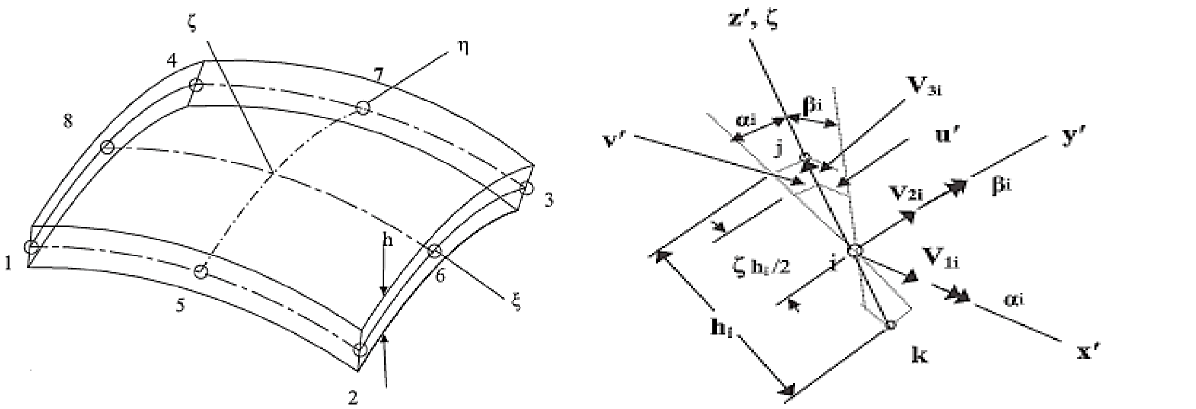
And, $[D]$ is the rigidity stiffness matrix.

Also, the mass matrix can be calculated as:

$$[M] = \int_V \rho [N]^T [N] dV \qquad (7)$$

After this, the natural frequency of the shell structure can be calculated by solution for the general equation for motion by eigenvalue technique as:

$$[M]\{\ddot{U}\} + [K]\{U\} = 0 \qquad (8)$$



(a) Shell element with 8-node (b) Nodal vector

Fig. 6. Element Type used for the Shell Structure

III. Results and Discussion

The present work results include investigating the modification of vibration characterizations for a shell structure using the effect of silica nanoparticle materials made of composite materials combined with resin and unidirectional glass fiber. This work included using experimental and numerical techniques to calculate the results required. Thus, the experimental results showed the effect of different volume fractions of nanoparticles on the natural frequency of the composite shell structure, supported as a cantilever, as shown in Fig. 7. Also, the numerical technique used comprised calculating the natural frequency of the shell tested in the experimental methods and then comparing the results calculated by the experimental measurements, as presented in Fig. 8. In

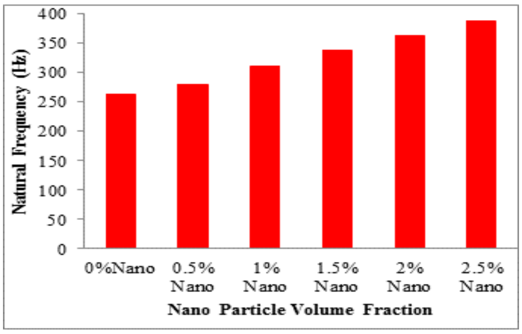


Fig. 7. Natural Frequency for Shell Cylinder with Different Nano Volume Fractions.

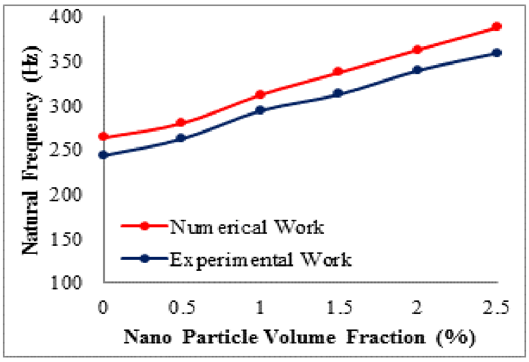
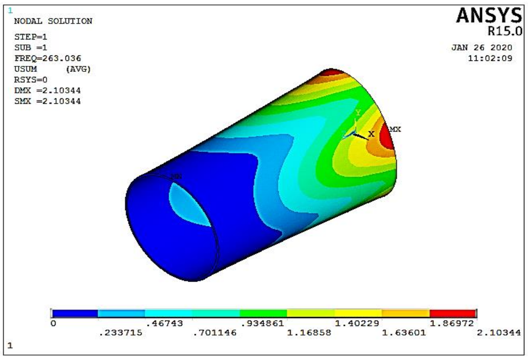
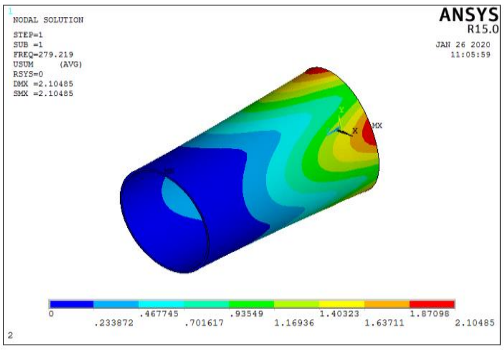


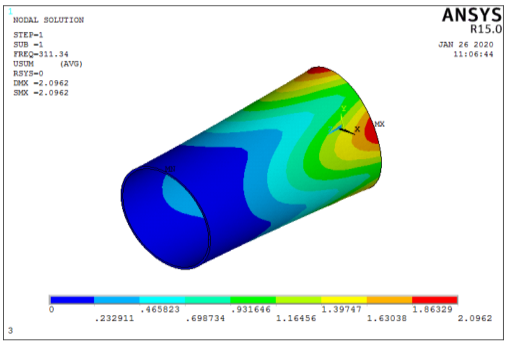
Fig. 8. Comparison between Experimental and Numerical Natural Frequency Results.



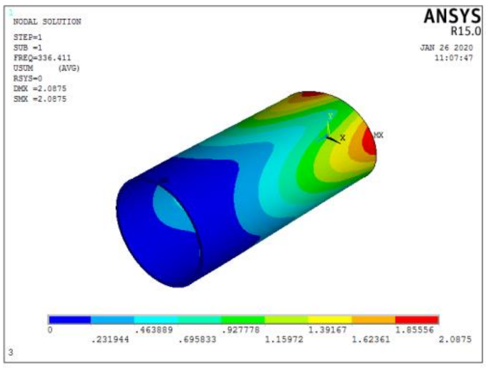
(a) 0% Nano Volume Fraction



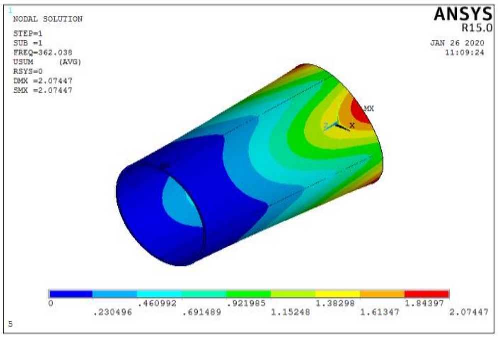
(b) 0.5% Nano Volume Fraction



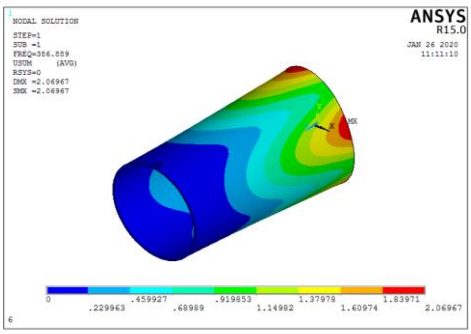
(c) 1% Nano Volume Fraction



(d) 1.5% Nano Volume Fraction



(e) 2% Nano Volume Fraction



(f) 2.5% Nano Volume Fraction

Fig. 9. Deformation for Shell Structure with Various Nanoparticle Reinforcement Volume Fractions.

addition, the numerical technique also included calculating the deformation of the shell structure, with the effect of nanoparticle reinforcement, as in Fig. 9.

Then, from the figures presented, it can be seen that the natural frequency for the shell structure increased with the high values by reinforcing the composite materials using silica nanoparticle materials. In addition, due to increasing the natural frequency, it was found that the deformation stress of the shell decreased with increasing the volume fraction of nanoparticles. As demonstrated in the results recorded in Table 1, the increase in the dynamic response of the shell was caused by the rise in the effective mechanical properties values of the composite materials of the shell structure owing to reinforcement with nanoparticle materials.

Conclusions

In this work, experimental techniques were presented to show the effect of the silica nanoparticle materials on the natural frequency of shell structure. In addition, numerical work was introduced to obtain the agreement for the experimental work by comparing the numerical results of the natural frequency with the experimental results evaluated. Thus, from the current work, the following important conclusions can be drawn:

The experimental work was a perfect technique that can be used to manufacture the composite materials and the shell structure and determine the mechanical properties of the composite materials and the vibration behavior of composite shell structure, with various nano volume fraction effects.

The comparison between experimental and numerical results for natural frequency gave a good accepting error with a maximum discrepancy that did not exceed (10.93%).

The addition of silica nanoparticle materials improves the mechanical properties (strength and modulus of elasticity) of the entire composite material structure. A nanomaterial-reinforced composite shell structure exhibits extremely high dynamic modifications. A higher nanomaterial volume fraction increases the natural frequency of shell structures.

Due to the modified mechanical properties and dynamic behavior of the composite materials with the reinforcement by silica nanoparticles, the deformation of the shell structure was decreased by increasing the nanoparticle materials.

In future work, it is recommended to examine how nanoparticle sizes and types affect the mechanical performance of cylinders reinforced with nanoparticles.

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Muhannad Al-Waily – Prof. Dr. (Applied Mechanics);
Sadeq H. Bakhy **–** Prof. Dr. (Applied Mechanics).

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Аналіз вільних коливань композитної циліндричної оболонки, армованої кремнієвими наночастинками: аналітичне та FEM наближення

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Попередні дослідження показали вплив наноматеріалів на механічні властивості композитних матеріалів з ефектами різних фракцій по об’єму; крім того, дослідження продемонстрували вплив наноматеріалів на такі механічні характеристики композитної пластинчастої структури, як коливання та термічна поведінка. Таким чином, механічні властивості та поведінка модифікуються на високі значення за рахунок зміцнення з низькою кількістю для наноматеріалів, яка не перевищує приблизно (3%). Завдання дослідження є встановлення модифікації вібраційних характеристик конструкції з ефектом наноматеріалів і вивчення впливу інших типів армованих наночастинок на характеристики. Наночастинки кремнію обрані для дослідження їх впливу на вібраційну поведінку оболонкової структури. Таким чином, робота включала використання експериментальної методики випробування конструкції оболонки за допомогою вібромашини для вивчення вібраційної поведінки. Після виготовлення оболонки з композитного матеріалу із різними об’ємними частками наночастинок кремнію оцінювали механічні властивості. Використовуючи чисельну техніку, зокрема, метод скінченних елементів за допомогою середовища Ansys, виконано оцінку вібраційної поведінки конструкції оболонки та здійснено порівняння результатів. Порівняння дало прийнятну відсоткову похибку, що не перевищує 10,93%. Оцінені результати показали, що модифікація кремнієвими наноматеріалами дала дуже хороші результати, оскільки наноматеріали покращили приблизно 65% механічних властивостей оболонки та вібраційні характеристики.