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Determination of Resonance Frequency of Compressive Helical Spring to Avoid Failure: Finite Element Analysis Approach.

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ABSTRACT
The study, determination of resonance frequency of compressive helical spring to avoid failure using finite element analysis approach was successfully investigated. Compressive helical spring model was designed to retain opening diameter of 15 mm; wire diameter 2mm, spring height 50mm, pitch 5mm and maximum of 10 coils with assigned material being soft yellow Brass. Helical spring model was prepared with the aid of inventor and imported to; finite element analysis software where deflection or displacement was predicted. In addition, compressive force of 1500 N with fixed constraints was used to run the simulation. Furthermore, the maximum deflection was found to be 3.447 mm and the resonance frequency was evaluated to be $0.425\,Hz$ *with the natural frequency being 8.491 Hz under the stated conditions. These results indicated that the helical spring must be manufacture from a material whose natural frequency is 8.491 Hz if failure due to resonance must be avoided. The spring stiffness was also found to be* $435.16\,N/mm$ *at a spring index of 7.5. To avoid failure during operation, resonance frequency value must be less than the natural frequency value of spring material. The researchers made the following recommendations: Excessive spring deflection must be avoided to reduce stress within permissible limit, helical spring material must have higher natural frequency rather than resonance frequency, since failure due to resonance is predominant, etc.*

Keywords: *Resonance frequency, helical spring, deflection, finite element analysis, spring stiffness, constraints.*

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I. INTRODUCTION

Background to the Study

Blake (2022) opined that vibratory systems comprise means for storing potential energy (spring), means for storing kinetic energy (mass or inertia), and means by which the energy is gradually lost (damper). The vibration of a system involves the alternating transfer of energy between its potential and kinetic forms. In a damped system, some energy is dissipated at each cycle of vibration and must be replaced from an external source if a steady vibration is to be maintained.

Compressive helical spring is one of the most fundamental flexible mechanical elements used in several industrial applications like balances, brakes, vehicle suspensions and engine valves to satisfy functions like applying forces, storing or absorbing energy, providing mechanical systems with the flexibility and maintaining a force or a pressure. In addition, helical springs serve as the elastic member for most common types of vibration absorbers (Sreenivasulu, Yaswanth, Sukumar, Gouse Basha, ArunKumar, Heamanth & Krishna, 2019).

The possibility of resonance and excessive vibration (or surging) are reduced in helical springs because volute springs have a uniform pitch, more damping due to helical structure and an increasing natural period of vibration (instead of a constant period of vibration as in a cylindrical spring) as each helical closes. For design and selection of springs for practical purposes, deflection of the spring under axial load and maximum stresses induced are two major factors (Sreenivasulu et al., 2019).

Khurmi and Gupta (2012) stated that the frequency is the number of cycles described in one second. The frequency of free vibration is known as natural frequency. When the spring is under the influence of a periodic disturbing force, forced vibration occurs. If the frequency of the external force is same as that of the natural frequency of spring, resonance takes place and spring vibrates with maximum amplitude or deflection.

According to Crocker (as cited in Fiebig and Wrobel, 2017) the vibration amplitude of a mechanical system depends on the ratio of the driving force frequency and the natural frequency of the system. When the excitation force frequency is equal to the natural frequency of the object, the phenomenon of mechanical resonance occurs, and as a result maximum value can be observed in the vibration amplitude/deflection.

Finite element analysis approach here, is a process of simulating the behavior of the helical spring part under given conditions via software so that the effects of real world conditions could be quantify on the part.

It was observed that resonance results in very large deflections of the coils and as well as very high stresses. Under these conditions, it is just possible that the spring may fail. In order to avoid resonance, the natural frequency of the spring should be at least twenty times the resonance frequency (Khurmi and Gupta, 2012). Hence, the paper aimed at studying the determination of resonance frequency of compressive helical spring to avoid failure using finite element analysis approach.

Statement of the Problem

In order to avoid sudden failure of helical springs, according to Khurmi and Gupta, (2012) resonance results in very large deflections of the coils and as well as very high stresses. Under these conditions, it is just possible that the spring may fail. In order to avoid resonance, the natural frequency of the spring should be at least twenty times the resonance frequency.

According to Crocker (as cited in Fiebig and Wrobel, 2017) the vibration amplitude of a mechanical system depends on the ratio of the driving force frequency and the natural frequency of the system. When the excitation force frequency is equal to the natural frequency of the object, the phenomenon of mechanical resonance occurs, and as a result maximum value can be observed in the vibration amplitude/deflection. It is on this note that the researchers aimed at studying the determination of resonance frequency of compressive helical spring to avoid failure using finite element analysis approach.

Purpose of the Study

The general purpose of the study is to determine the resonance frequency of compressive helical spring to avoid failure using finite element analysis approach.

Significance of the Study

The result of this study will be beneficial to industrial spring designers/production engineers in the following ways:

- Production engineers can improve helical spring safety; reduce operational noise and avoid sudden spring failure by choosing spring material whose natural frequency is greater than disturbing periodic force frequency.
- The knowledge of displacement or deflection can be used to improve the design life of helical springs by making appropriate provisions for expansion.

Scope of the Study

This research focused on determining the resonance frequency of compressive helical spring to avoid failure using finite element analysis approach. So, all efforts were directed towards the general objective. Deflection or displacement evaluations followed Finite Element Analysis. The researchers are members of Federal Polytechnic Nekede, within South East of Nigeria. Results may be subject to variations within other parts of the World.

II. Review of Related Literature

Blake (2022) studied basic vibration theory and he concluded that the vibratory systems comprise means for storing potential energy (spring), means for storing kinetic energy (mass or inertia), and means by which the energy is gradually lost (damper). The vibration of a system involves the alternating transfer of energy between its potential and kinetic forms. Sreenivasulu et al., (2019) experimented on modeling and analysis of helical springs using CATIA-V5R19 and ANSYS 16.0. They added that compressive helical spring is one of the most fundamental flexible mechanical elements used in several industrial applications. In addition, helical springs serve as the elastic member for most common types of vibration absorbers.

Khurmi and Gupta (2012) studied theory of machines, vibrations and stated that the frequency is the number of cycles described in one second. The frequency of free vibration is known as natural frequency. When the spring is under the influence of a periodic disturbing force, forced vibration occurs. If the frequency of the external force is same as that of the natural frequency of spring, resonance takes place and spring vibrates with maximum amplitude or deflection.

Fiebig and Wrobel (2017) conducted simulation and experiment on use of mechanical resonance in machine drive systems. Based on simulation and experimental investigations, the sequential extraction of energy from an oscillator in resonance has been described. Finally, the accumulation of energy at resonance and its use in a prototype of punching press machine and in the crankshaft system was presented. Khurmi and Gupta (2012) studied machine designs, springs and concluded that resonance results in very large deflections of the coils and as well as very high stresses. Under these conditions, it is just possible that the spring may fail. In order to avoid resonance, the natural frequency of the spring should be at least twenty times the resonance frequency.

III. Methodology

The researchers considered an open helical spring model with assigned material soft brass to increase fatigue, ductility and resilience as shown in **Figure 1.0.** The diameter of the open helical spring is 15 mm; wire diameter is 2mm, spring height is 50mm, pitch of 5mm with 10 coils or revolutions. The helical spring model was prepared with the aid of inventor software and imported to; Finite Element Analysis software where displacement were predicted. Helical spring model was subjected to compressive force of 1500 N with fixed constraints.

Design Analysis/Calculation

The stress components in an element are given as below.

$(\sigma_x)_n = \frac{E}{(1+v)(1-2v)}[(1-v)a_n + ve_n] \ldots\ldots(1)$ (as cited in Onyenobi etal., 2022)

$$(\sigma_y)_n = \frac{E}{(1+v)(1-2v)}[va_n + (1-v)e_n] \ldots\ldots(2)$$

$$(\tau_{xy})_n = \frac{E}{2(1+v)}(b_n + d_n) \ldots\ldots(3)$$

$$v = Poisson's\ ratio, E = modulus\ of\ elasticity$$

The displacement field is shown below.

$$a_n = \frac{\partial u_n}{\partial x} \ \ldots(4)$$

$$e_n = \frac{\partial v_n}{\partial y} \ \ldots(5)$$

$$b_n + d_n = \frac{\partial u_n}{\partial y} + \frac{\partial v_n}{\partial x} \ldots.(6)$$

$$v\ and\ u\ are\ velocity\ components\ of\ x\ and\ y$$

The principal strains are given below

$e_x = \frac{1}{E}\left[\sigma_x - \frac{1}{m}(\sigma_y + \sigma_z)\right] \ldots\ldots(7)$ (as cited in Onyenobi etal., 2022).

$$e_y = \frac{1}{E}\left[\sigma_y - \frac{1}{m}(\sigma_x + \sigma_z)\right] \ldots\ldots(7)$$

$$e_z = \frac{1}{E}\left[\sigma_z - \frac{1}{m}\left(\sigma_x + \sigma_y\right)\right] \ldots\ldots (8)$$

Von Mises Stress can be given as below.

$Von - mises\ stress = \sqrt{\sigma_x{}^2 - \sigma_x\sigma_y + \sigma_y{}^2} \ldots. (9)$

The torsional shear stress is given as below:

$$Shear\ stress, \tau = \frac{8\,W.D}{\pi d^3} \ldots. (10)$$

$$W = axial\ load\ on\ the\ spring$$

Direct shear stress due to load is given as below:

$$Shear\ stress = \frac{4\,W}{\pi d^2} \ldots (11)$$

Deflection of the coil spring can be calculated as shown below:

$$Deflection, \delta = \frac{8\,W \times D^3}{G \times d^4} \ldots. (12)$$

Energy stored in helical spring can be given as below:

$$U = \frac{\tau^2}{4\,K^2 \times G} \times V \ \ldots.(13)$$

$$V = volume\ of\ spring\ wire$$

$$K = Wahl's\ stress\ factor$$

Where $K = \frac{4C-1}{4C-4} + \frac{0.615}{C}$

According to Khurmi and Gupta (2012), the natural frequency of spring is given below.

$$f_n = \frac{0.4985}{\sqrt{\delta}} \quad \ldots.. (14)$$

$\delta = static\ deflection = 3.447\ mm\ or\ 0.003447\ m$ From **Fig.3**

$$f_n = \frac{0.4985}{\sqrt{0.003447}} = \frac{0.4985}{0.058711} = 8.491 \text{ Hz}$$

In order to avoid resonance, the natural frequency of the spring should be at least twenty times the resonance frequency.

$$Resonance\ Frequency = \frac{8.491}{20} = 0.425\ Hz$$

According to Khurmi and Gupta (2012) in machine design, the natural frequency of coil spring is given below.

$$f_n = \frac{d}{2\pi\, D^2 .n} \times \sqrt{\frac{6\,G.g}{\rho}} \quad \ldots. (15)$$

$d = wire\ diameter, D = mean\ diameter\ of\ spring, n = number\ of\ active\ turns, G = modulus\ of\ rigidity$

$\rho = density\ of\ material, g = acceleration\ due\ to\ gavity$

From **Table 2, we have**

$$f_n = \frac{2}{2\pi \times\ 15^2\ \times 8} \times \sqrt{\frac{6\ \times 41 \times 10^9 \times 9.81}{8514}}$$

$$f_n = 2.98\ Hz$$

In order to avoid resonance, the natural frequency of the spring should be at least twenty times the resonance frequency.

$$Resonance\ Frequency = \frac{2.98}{20} = 0.149\ Hz$$

The stiffness of the spring can be found as below:

$$Stiffness = \frac{load}{\delta} = \frac{1500}{3.447} = 435.16\ N/mm$$

IV. Results and Presentations

Meshing

Meshing was used to divide the helical spring model into section with nodes of 44735 and elements of 23808. Increasing the number of elements, means more computations and more mathematical formula for the element. Hence, the more precise the results would be. Mesh settings used is shown below. **See Figure 2.0.**

Table 1: ⊟Project Information

Part Number	COIL SPRING 2
Designer	EWURUM TENNISON
Cost	$66.00
Date Created	2/16/2023
Design Objective	Parametric Dimension
Study Type	Modal Analysis
Last Modification Date	2/16/2023, 3:24 AM
Number of Modes	8
Frequency Range	1 - 100
Compute Preloaded Modes	No
Enhanced Accuracy	Yes

Table 2: Mesh Settings and Material properties

Avg. Element Size (fraction of model diameter)		0.08
Min. Element Size (fraction of avg. size)		0.2
Grading Factor		1.5
Max. Turn Angle		60 deg
Create Curved Mesh Elements		Yes
Material		Brass, Soft Yellow, Welded
Density		8.5 g/cm^3
Mass		0.0251675 kg
Area		5932.21 mm^2
Volume		2960.88 mm^3
Center of Gravity		x=0 mm y=25 mm z=0 mm
Assigned Material Name		Brass, Soft Yellow, Welded
General	Mass Density	8.5 g/cm^3
	Yield Strength	103.4 MPa
	Ultimate Tensile Strength	275 MPa
Stress	Young's Modulus	109.6 GPa
	Poisson's Ratio	0.331 ul
	Shear Modulus	41.1721 GPa
Part Name(s)	COIL SPRING 2	

Table 3: Operating conditions, Compressive Force

Load Type	Force
Magnitude	1500.000 N
Vector X	92.139 N
Vector Y	-1497.153 N
Vector Z	6.660 N

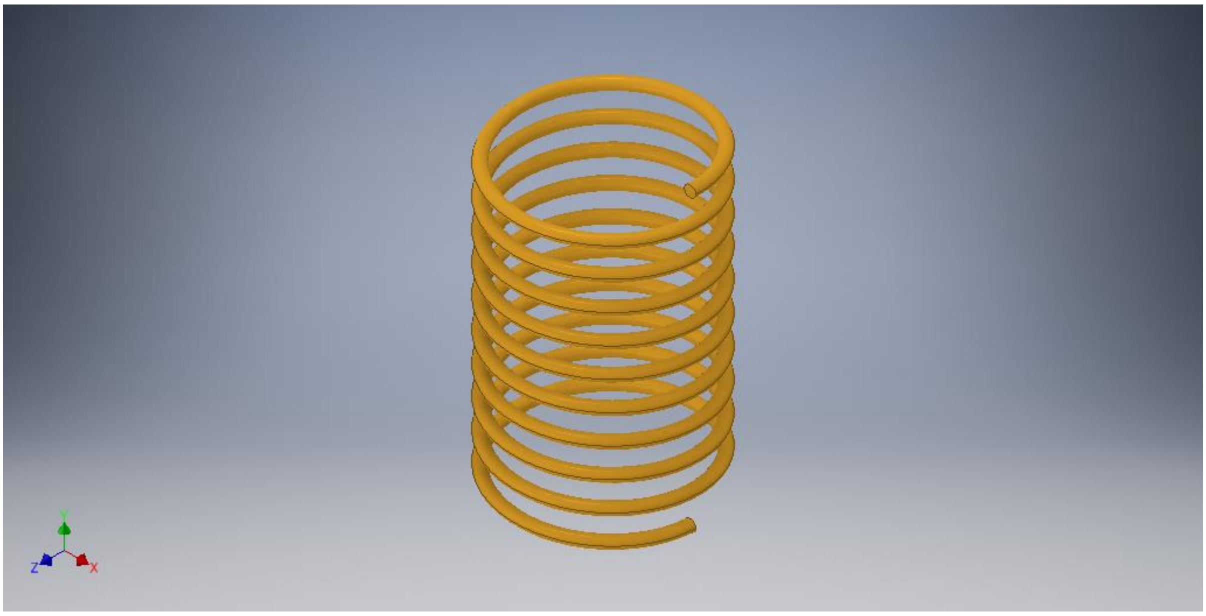

Fig. 1: Open Helical Spring Model

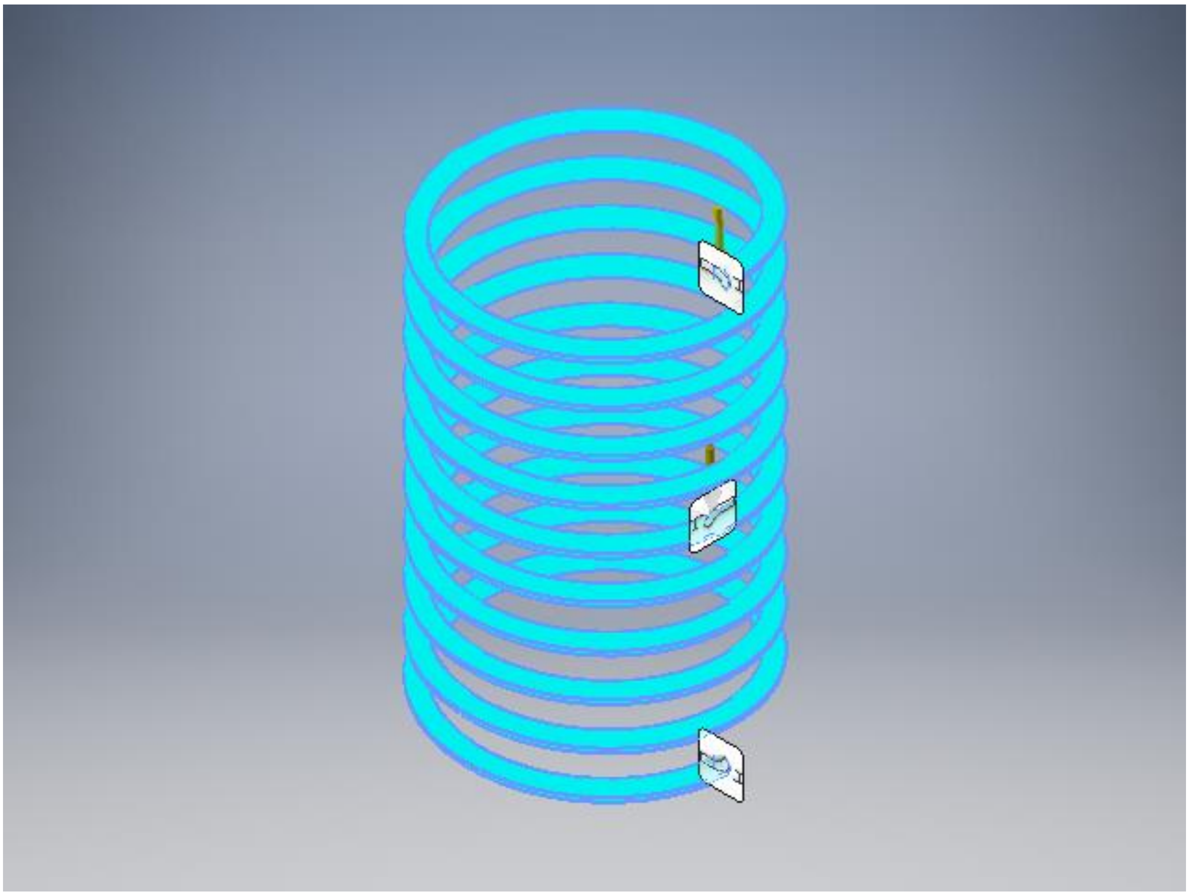

Fig.2: Load and Constraints on Spring Model

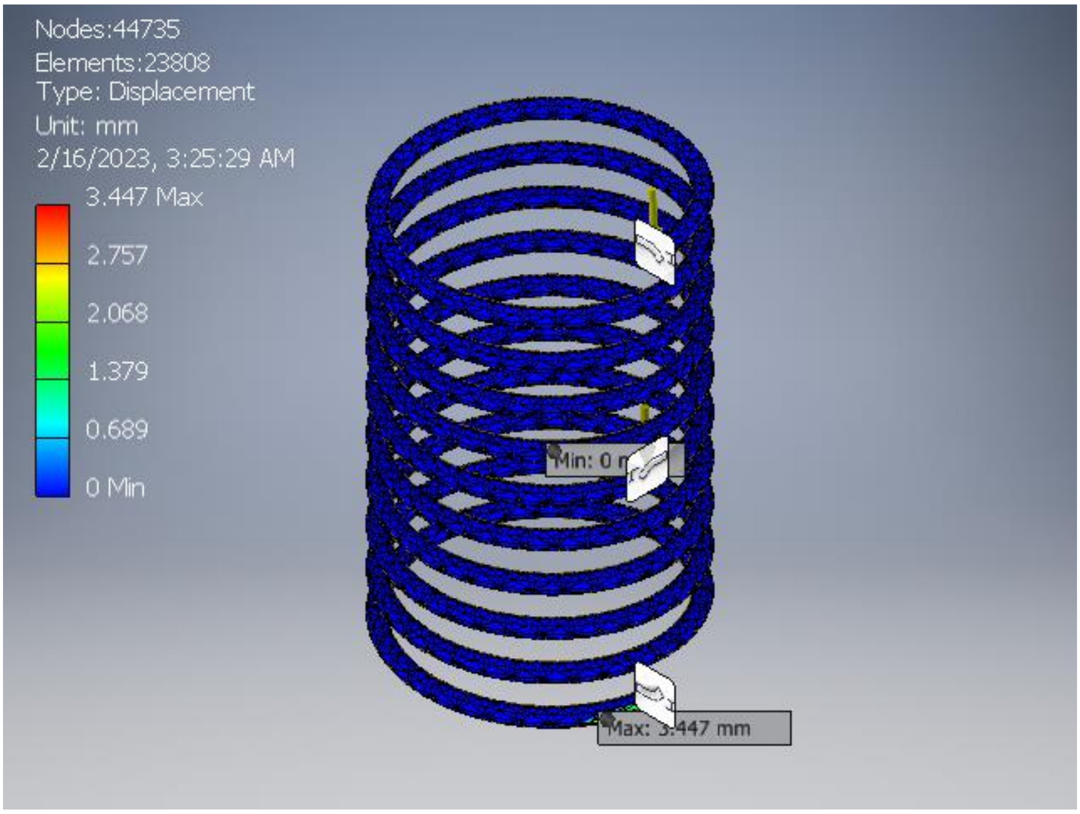

Fig.3: Displacement on Spring Model
⊟F1 547955.94 Hz Frequency

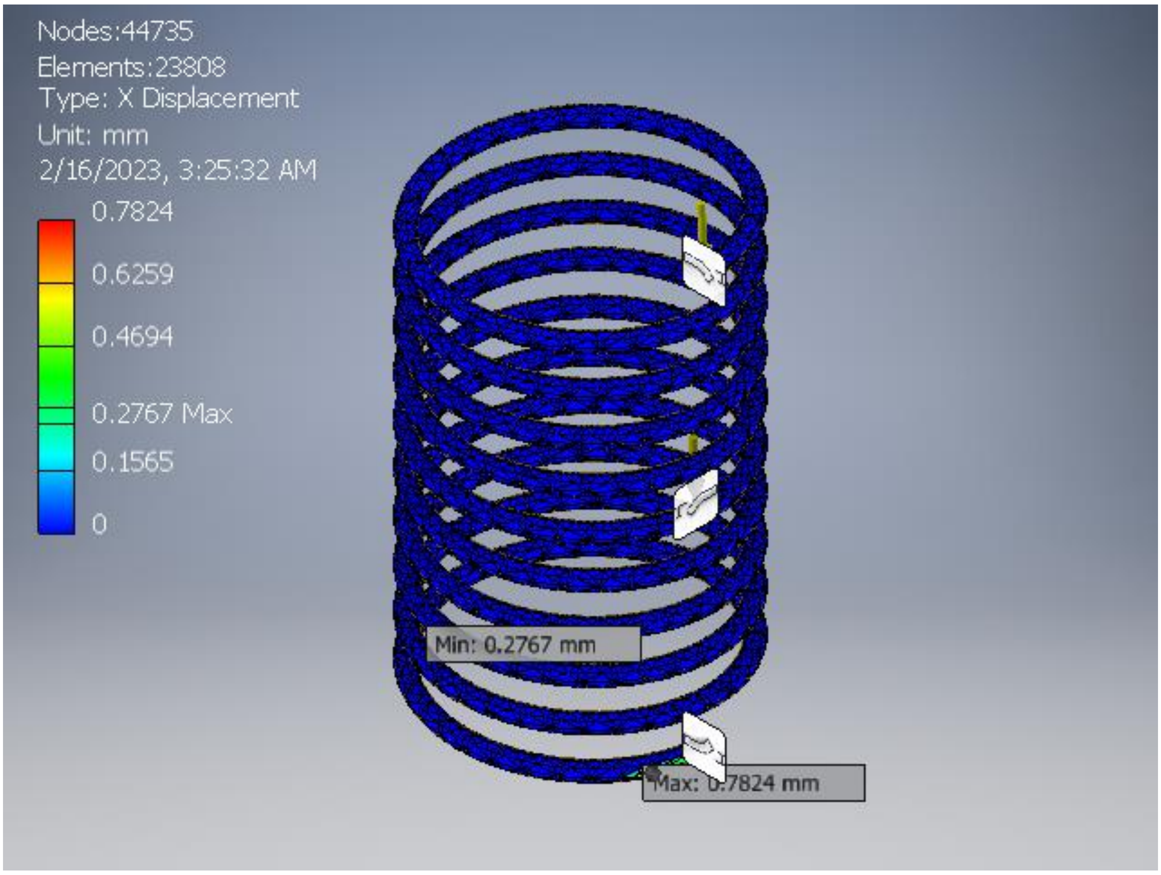

Fig.4: Displacement on Spring Model
⊟F1 547955.94 Hz Frequency

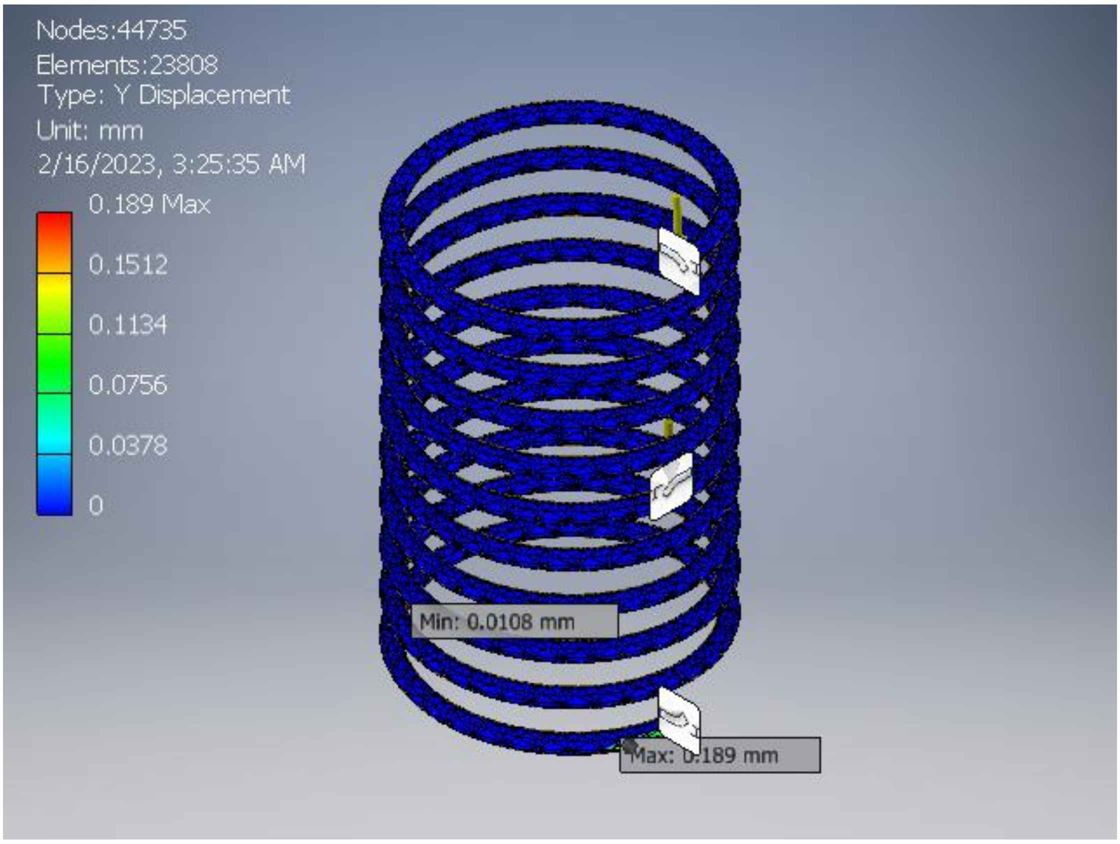

Fig.5: Displacement on Spring Model
⊟F1 547955.94 Hz Frequency

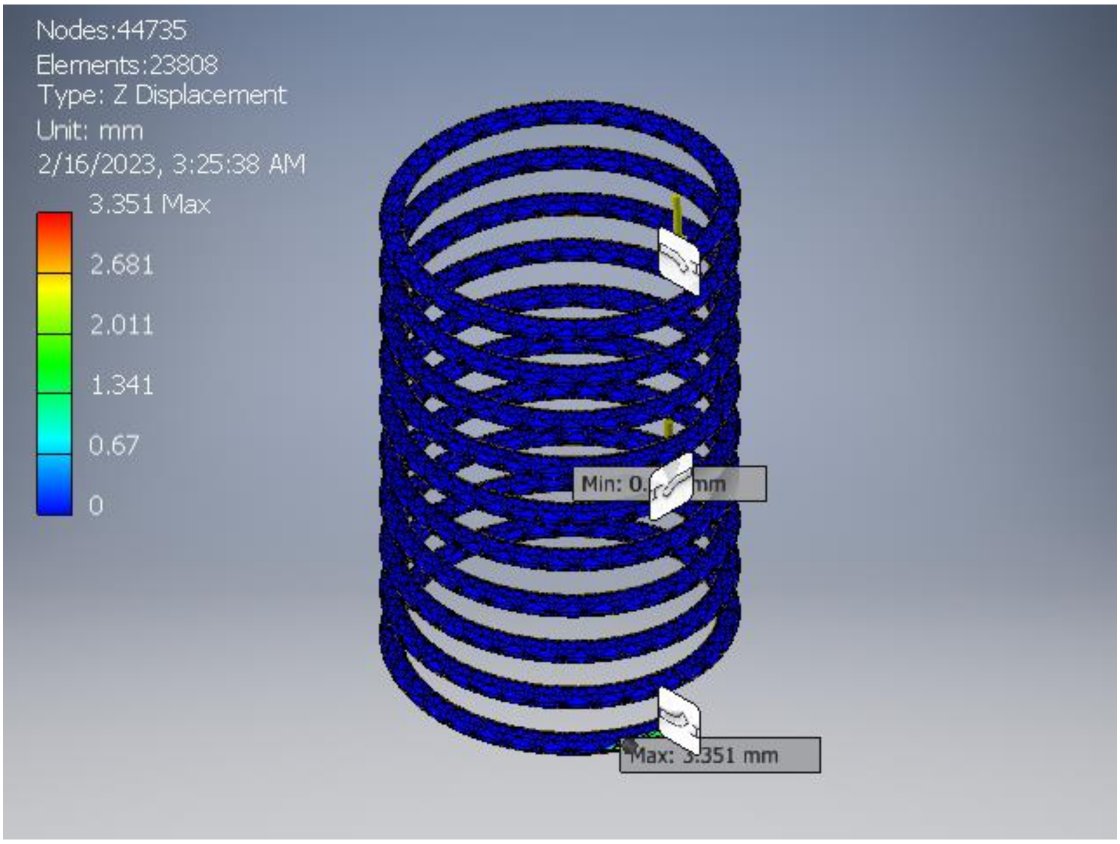

Fig.6: Displacement on Spring Model
⊟F1 547955.94 Hz Frequency

V. Discussion

Resonance frequency of compressive helical spring was investigated using finite element analysis approach. The diameter of the open helical spring is 15 mm; wire diameter is 2mm, spring height is 50mm, pitch of 5mm, 10 coils with assigned material being soft yellow Brass. The helical spring model was prepared with the aid of inventor software and imported to; finite element analysis software where deflection or displacement was predicted. Spring model was subjected to compressive force of 1500 N with fixed constraints. See **Fig. 2.**

Furthermore, according to **Fig. 3**, the maximum deflection was found to be 3.447 mm and from equation (4), the resonance frequency was evaluated to be $0.425\ Hz$ with the natural frequency being 8.491 Hz under the stated conditions. According to Khurmi and Gupta (2012), these results suggested that the helical spring must be manufacture from a material whose natural frequency is 8.491 Hz if failure due to resonance must be avoided. The spring stiffness was also found to be $435.16\ N/mm$ with spring index of 7.5. Fig 4 to Fig 6, showed the displacements of spring along X, Y and Z axes.

VI. Conclusion

According to the results, the value of resonance frequency of compressive helical spring model was found to be $0.425\ Hz$ as per the given condition. To avoid failure during operation, its value must be less than the natural frequency value.

Recommendations

The following recommendations are suggested based on the study:

1) Excessive spring deflection must be avoided to reduce stress within permissible limit.

2) Helical spring material must have higher natural frequency rather than resonance frequency, since failure due to resonance is predominant.

3) This research can also be done in future using different spring designs such as cone shape, leaf shape, torsion spring, and other advanced software for generalization.

Limitation of the Study

In the course of carrying out this research, determination of Resonance frequency of compressive helical spring to avoid failure using finite element analysis approach, the researchers encountered many hindrances which might cause deviations from actual results. Some of the hindrances includes: design difficulties, cost of design data analysis, lack of electricity, etc.

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Disclosure of conflict of interest

This research article is original and the corresponding author hereby confirms that all of the other authors have read and approved the manuscript with no ethical issues and with declaration of no conflict of interest.

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