Study Large Deformation Coil Spring Development For Robotics Submersible

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Abstract

In this work the present a theoretical study for the free vibration of cylindrical, conical and helical springs. Circular cross sections, and non-circular cross section, namely elliptical, are considered as well for the investigating of the frequency characteristics of the springs. The equations of motion are derived mathematically for springs with different geometries. The mode shapes are numerically implemented by using COMSOL 4.2 software package for three dimensional solid elements. The mode shapes configurations are determined by applying different force loads and boundary conditions for different number of spring turns. The results show that increasing the number of turns leads to decrease the spring stiffness and vice versa. Also decreasing turn number is a good strategy to distinguish between different mode shapes. Springs stiffness is directly proportional to coil diameter. It is also shown that the configuration of cylindrical- elliptical spring is prone to the applied force where the stiffness is lower among all other spring types with the same number of turns.

دراسة التشوهات الحاصلة في النوابض الحلزونية للغاطس الآلي

الخلاصة

يقدم هذا العمل دراسة نظرية للاهتزازات الحرة لانواع من النوابض كالحلزونية والاسطوانية والمستطيلة متساوية ومختلفة المقطع كالمخروطية .تم اشتقاق المعادلات الرياضية للنوابض ذات المقطع المتساوي رياضيا اما الدوال الشكلية للنوابض تم حسابها عن طريق برنامج متطور يسمى كومسول (4.2) لعنصر ثلاثي الابعاد ووضع قوى مختلفة تراوحت بين 50 الى 150 نيوتن وتثبيت طرف من النابض واظهرت النتائج ان زيادة عدد حلقات النوابض يؤدي الى قلة جساءة النابض والعكس بالعكس. كما انها طريقة جيدة للتفريق بين الدوال الشكلية كما ان هناك علاقة بين كل من جساءة النابض وقطر الملف ويعتبر النابض الاسطواني افضل من النوابض الاخرى عن تسليط الاحمال بجساءة اقل ولنفس عدد الحلقات .

KEY WORDS

Helical springs; non-cylindrical; free vibration

Notations

Έ, Ḡ ,ύ	= Young's modulus N/m^2 ,shear modulus N/m^2 , Poisson's ratio
ρ	= mass per unit volume of wire /kg/m^3
t	= time / s
t,n,b	= tangential, normal and binormal unit vector
χ, τ,h	= curvature ,tortuosity and step for unit angle of the helix
M_t ,M_n ,M_b	= torsional moment and bending moments, respectively
T_t ,T_n ,T_b	= axial force and shear forces , respectively
U_t , U_n , U_b	= Frenet components of displacement vector
Ω_t Ω_n Ω_b	= Frenet components of rotational vector
J or I_t	= torsional moment of inertia
A	= cross sectional area
d, D	= diameters of the circular cross- section and helix (R=D/2)
I_n , I_b	= moment of inertias of cross –section with respect to n,b axes
C_t, C_n, C_b	= the axial stiffness and the shearing stiffness's ,respectively
D_t D_n D_b	= the tensional stiffness and the flexural stiffness's respectively
p m	= external force and moment vector per unit length
S	= state vector

1. Introduction

Helical springs are commonly used in many engineering applications serving important mechanical tasks. The problem of helical springs is a classic mechanical problem that is subjected to many theoretical studies for decades. Performances of compressive springs working within dynamic envirments in mechanisms have become particularly important in recent years . Helical springs are amongst the most familiar engineering components and , as vital part of the automotive engine, they have been the subject of close scientific scrutiny . Cylindrical and non –cylindrical helical springs are common in many applications for wide variety of reasons, Figure (1) demonstrate the robotic fish design [7]. The number of paper present on the non–cylindrical coil springs is, yet, insufficient [3],[4],[5].The problem is described by six differential equations .These are second order equation with variable coefficients , with six unknown displacements. Three translations , and three rotations at every point along the member. A number of investigations were conducted in the field of vibration behavior of helical springs with constant cross section [6]. However, there is no paper published on the vibration analysis of the helical springs with variable cross section.

Although, there are some studies of the problems of free vibration of cylindrical coil spring [4], there have been only a few studies on the free vibration of helical springs with irregular shapes . Yildirim[5] investigated the free vibration frequencies of cylindrical springs by the transfer matrix method .Nagaya et al. [1] have determined the free vibration frequencies of non-cylindrical helical springs both experimentally and by the method of Myklestad. For this purpose, they have used the static element transfer matrix, where they derived the closed form solution with taking into account only the axial deformation for circular cross sections . Yildirim [1] used both the Myklestad method and the complementary functions methods , and presented the free vibration of non-cylindrical helical springs taking into account the effects of axial and shear deformation together with the rotary inertia . The free vibration problem of helical spring by the transfer matrix method .Yildirim employed the transfer matrix and the complementary functions to compute the eignvalues on non-cylindrical helical springs.The applications that use the helical and other types of springs are in continuous developments starting from the micro scale applications to huge civil engineering structures. The frequency characteristics of the helical springs can be implemented as a substitution for some continuous system applications. For instance, the robotics fish, is the interest of many researchers and companies around the globe. Due to highly need of such application, many models for robotics fish have been suggested in the last ten years. Some of these models are based on purely mechanical design , and some are based on using of smart materials. In general, the thrust mechanism stills the main challenge in the size and design of submersibles. Recently, it has been shown that the fluid-conveying pipes are a powerful technique for the thrust of submersibles .The mode of fluttering depends on the pressure inside the pipe , and it is found that higher pressure leads to fluttering with higher modes.

In this study we extend the work presented by Aren [7] who designed a robotics fish that works on the fluid inducing mechanism for the thrust force, he used relatively long hollow tail made of latex, see figure (1). The tail conveys water that is pumped from the head of the fish and flows through the latex tail and induces the tail to flutter and result in thrust force moves the fish forward. We investigate replacing of the long latex tail by a short helical spring that does the same function.the objective of the work is to replace the long latex tail by short coiled spring, than studying the igenfrequencies of the coiled spring under the effect of internal flow along the main axis,we investigate the effect of the internal pressure on the mode shapes for different types of coiled springs. Using of suitable type of coiled spring as a substitution for the latex tail of the submersible

Stream Flow

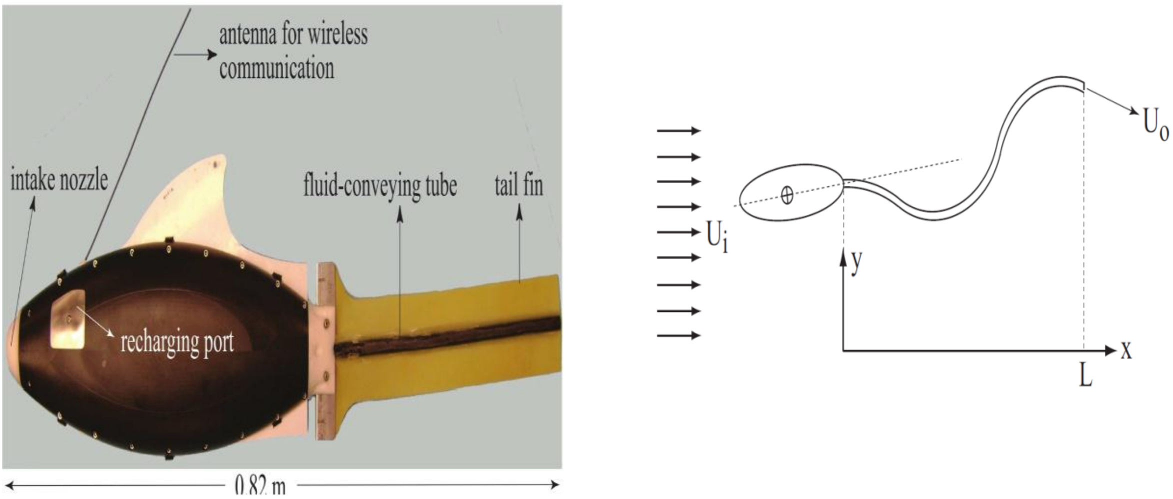


Figure (1). (a)The robotic fish design / (b)The free body diagram [7]

2. Free Vibration Formulation of cylindrical Coil Springs

The cylindrical helical coiled springs has the simplest mathematical model among the other types. The equation of motion for the 12-degree for free vibrations springs in (t, n ,b)[1,2]:-

$$\frac{\partial \mathrm{U}_t^{\circ}}{\partial s} = X\, \mathrm{U}_t^{n} + \frac{T_t^{\circ}}{C_t} \tag{1}$$

$$\frac{\partial \mathrm{U}_n^{\circ}}{\partial s} = X\, \mathrm{U}_t^{\circ} + \tau\, \mathrm{U}_b^{\circ} + \Omega_t^{\circ} + \mathrm{U}_n^{\circ}/C_n \tag{2}$$

$$\frac{\partial \mathrm{U}_b^{\circ}}{\partial s} = -\tau\, \mathrm{U}_n^{\circ} - \Omega_n^{\circ} + \frac{T_b^{\circ}}{C_b} \tag{3}$$

$$\frac{\partial \Omega_t^{\circ}}{\partial s} = X\, \Omega_n^{\circ} + \frac{M_t^{\circ}}{D_t} \tag{4}$$

$$\frac{\partial \Omega_n^{\circ}}{\partial s} = -X\, \Omega_t^{\circ} + \tau \Omega_n^{\circ} + \frac{M_n^{\circ}}{D_n} \tag{5}$$

$$\frac{\partial \Omega_b^{\circ}}{\partial s} = -\tau \Omega_n^{\circ} + \frac{M_b^{\circ}}{D_b} \tag{6}$$

$$\frac{\partial T_t^{\circ}}{\partial s} = X T_n^{\circ} - P_t^{\circ} + \rho A(\partial^2\, \mathrm{U}_t^{\circ}/\partial t^2) \tag{7}$$

$$\frac{\partial T_n^{\circ}}{\partial s} = -X T_t^{\circ} + \tau T_b^{\circ} - P_n^{\circ} + \rho A(\partial^2\, \mathrm{U}_n^{\circ}/\partial t^2) \tag{8}$$

$$\frac{\partial T_b^{\circ}}{\partial s} = -\tau T_n^{\circ} - P_b^{\circ} + \rho A(\partial^2\, \mathrm{U}_b^{\circ}/\partial t^2) \tag{9}$$

$$\frac{\partial M_t^{\circ}}{\partial s} = X M_n^{\circ} - m_t^{\circ} + \rho J(\partial^2 \Omega_t^{\circ}\ /\partial t^2) \tag{10}$$

$$\frac{\partial M_n^{\circ}}{\partial s} = T_b^{\circ} - X M_t^{\circ} + \tau M_t^{\circ} - m_n^{\circ} + \rho I_n(\partial^2 \Omega_n^{\circ}\ /\partial t^2) \tag{11}$$

$$\frac{\partial M_b^{\circ}}{\partial s} = T_n^{\circ} - \tau M_n^{\circ} - m_b^{\circ} + \rho I_b(\partial^2 \Omega_b^{\circ}\ /\partial t^2) \tag{12}$$

3. Modeling tools

COMSOL Multiphysics 4.2 simulation environment was used to make this analysis , COMSOL 4.2 is a complete problem-solving tool. MATLAB interface allowed somewhat straight forward modeling of a complex three dimensional helical geometry without resorting to CAD modeling .The analysis was also rather fast ,with meshing and analyzing taking less than 10 seconds .A three dimensional helix was created and meshed in COMSOL . eigenfrequency analysis was conducted to identify the first five vibrational modes along with their frequencies.

4. Case study analysis

A three dimensional helix was created in COMSOL4.2.to get deformation shape for different types of coiled springs. Figure (2) demonstrate different types of coiled springs , figures (3), (4) and (5) illustrate deformed and undeformations shapes for cylindrical, conical and elliptical springs for five mode shape .Table 1 records the results of COMSOL 4.2 when implemented for cylindrical, conical and elliptical springs .

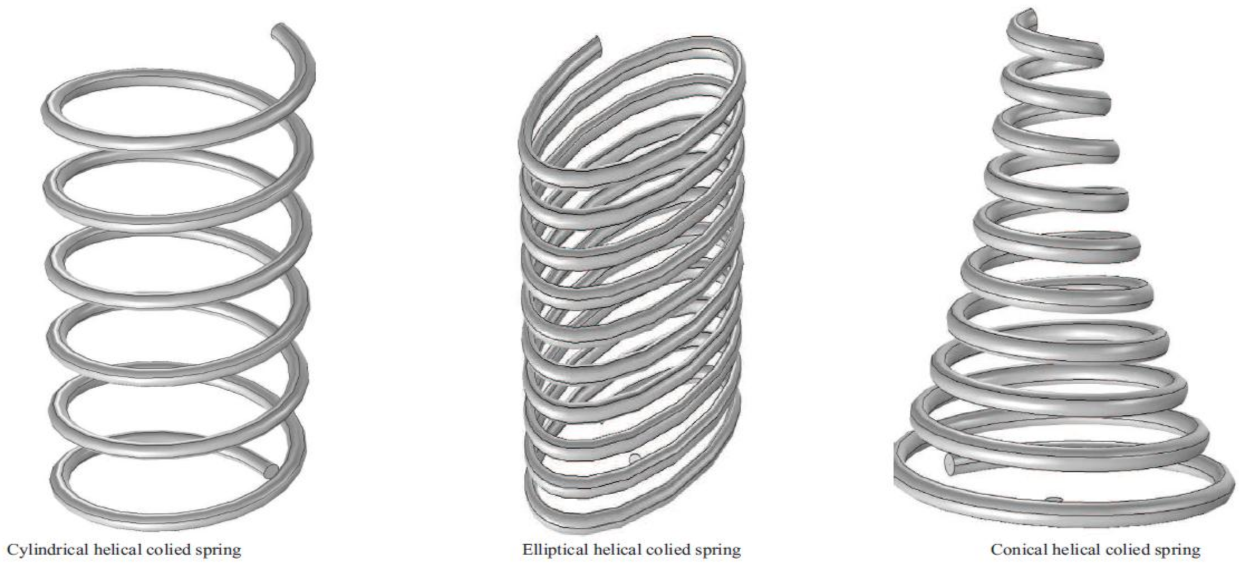


Figure (2).Different types of coiled springs

4.1. Cylindrical Spring analysis

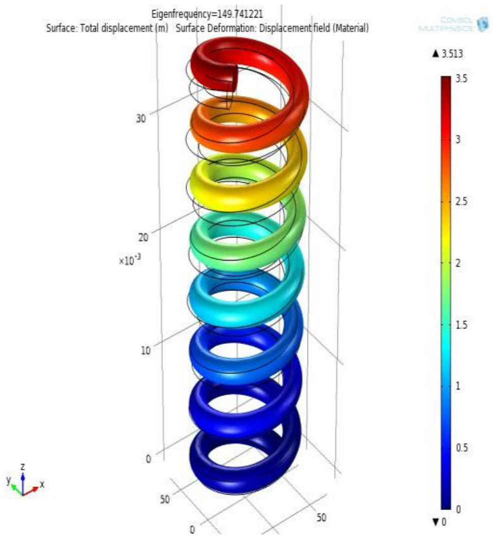
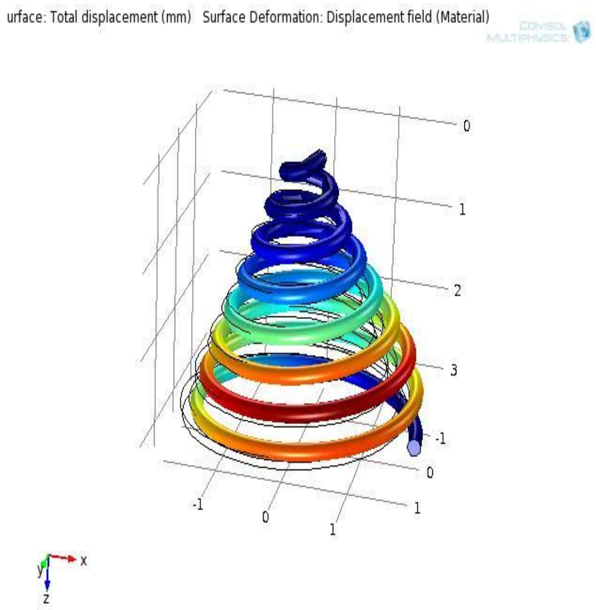


Figure (3). Cylindrical spring deformed & undeforormed.

4.2. Conical Spring analysis



Figure(4). Conical spring deformed & undeformed.

4.3. Elliptical Spring analysis

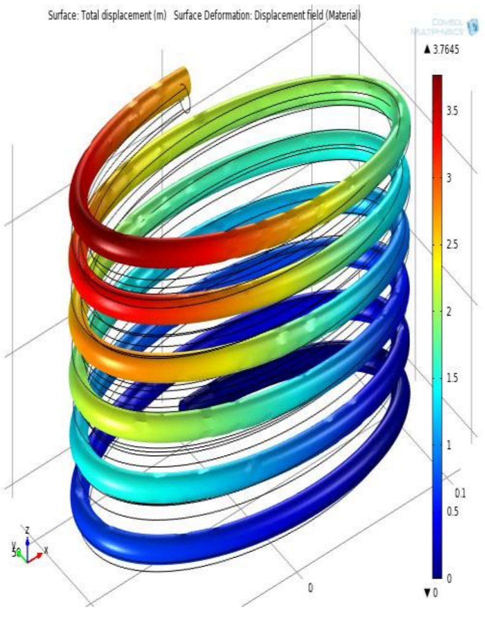


Figure (5).Cylindrical spring deformed & unreformed.

Table. (1). Application for spring steel AISI 4340 (n=6 ,E=2.0610^{11} N/m^2 V =0.3, d =0.005 m, a =0.001,α =0.00468 ,ρ =7900Kg/m^3).

Type	Mode1	Mode2	Mode3	Mode4	Mode5
Cylindrical/ PS	19.005	19.019	29.115	32.89	64.72
Yildirim[1]	36.52	36.544	150.627	165.616	201.82
Elliptical/ PS	23.646	25.587	31.500	32.888	53.765
Yildirim[1]	25.402	28.356	31.444	42.171	45.783
Conical/ PS	3.246	3.7.26	4.672	5.170	5.056
Yildirim[1]	3.200	3.121	4.556	5.443	5.508

PS=Present study

5. Results and Discussions

In this work, the equation of motion in helical spring was, derived from Timoshenko beam theory and Frenet formulae, after applying suitable boundary conditions by fixed one end. The software has been applied to the large deformation analysis of helical springs under axial loading. The Eigen frequency analysis was run across various values of the number of turns n, the wire diameter, and the helix diameter D.This paper presents theoretical analysis of vibration problem of coil springs of arbitrary shape by using COMSOL 4.2 .The results can be summarized five mode shape for cylindrical and elliptical springs as shown in figures (10,11) and table (2). For cylindrical spring . Figures (12,13) and table (3) for elliptical spring.

5.1. Cylindrical Spring

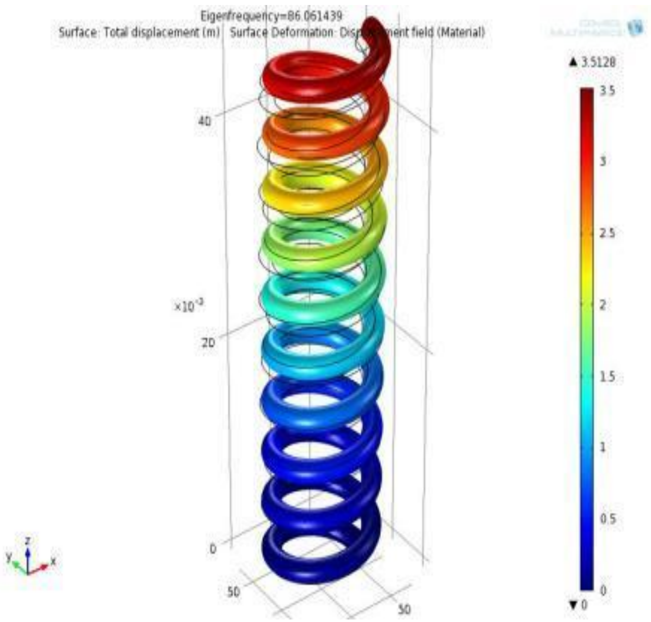
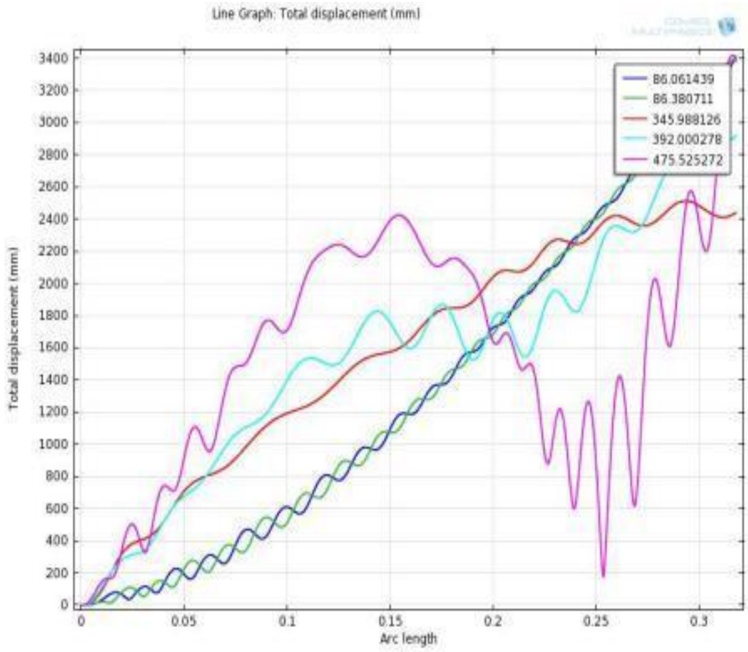


Figure (6). Deformed& unreformed of cylindrical spring

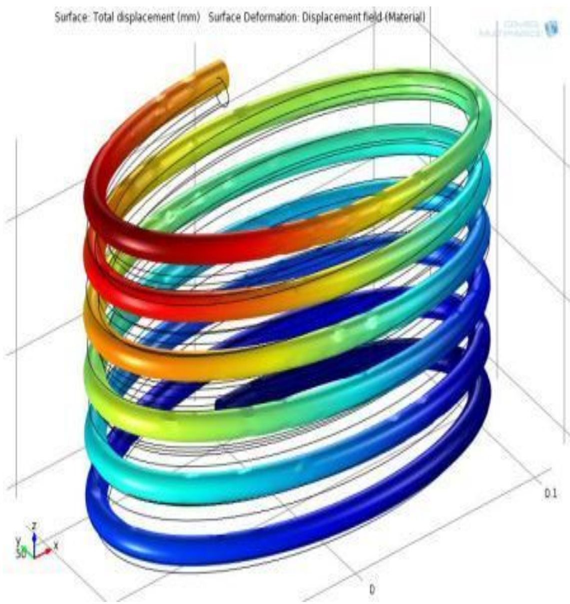


Figure(7). Fifth mode shape of spring fixed one end

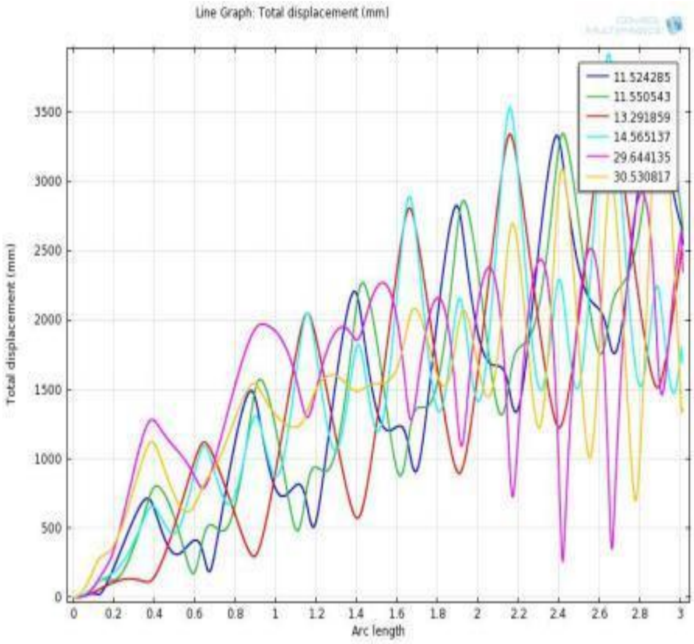
Table (2). Example for a cylindrical spring free vibrations, second with body load =50-150 N, Eigenfrequency for(5) mode shape number of turns =6.

Load	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
X=y=z=0	459.304	509.359	526.678	532.339	906.888
Y=0	107.84	108.153	238.845	268.833	474.070

5.2. Elliptical Spring



Figure(8). Deformed & undeformed of elliptical spring fixed one end



Figure(9). Fifth Vibration mode shape of elliptical springs fixed one end

Table (3). Example of an elliptical spring with out load , second with body load, Eigenfrequency for (5) mode shape number of turns =6 .

Load	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Y=0	11.524	13.294	14.565	29.644	30.538
X=y=z=0	25.402	28.356	31.444	42.171	45.783

6- Conclusions

The following notes can be extracted from the research results :-

1. Increasing spring turns number (n) will decreases spring stiffness and all resonant.
2. Decreasing spring turn number (n) is a good way to achieve separation between five mode and others.
3. Increasing diameter of the spring wire (d) will increas spring stiffness and increasing all resonant frequencies.
4. Springs having the same material and geometrical properties for elliptical type is more rigid than others types.
5. Some natural Frequencies are very close to each other for the elliptical type as illustrated in figures (14 ,15 ,16) below , which explore the effect of vibrational mode frequencies on spring number of turns(n) for constant pitch angle.
6. Figure (13) shows comparison of vibrational mode frequencies for Conical spring between this study and Yildrim

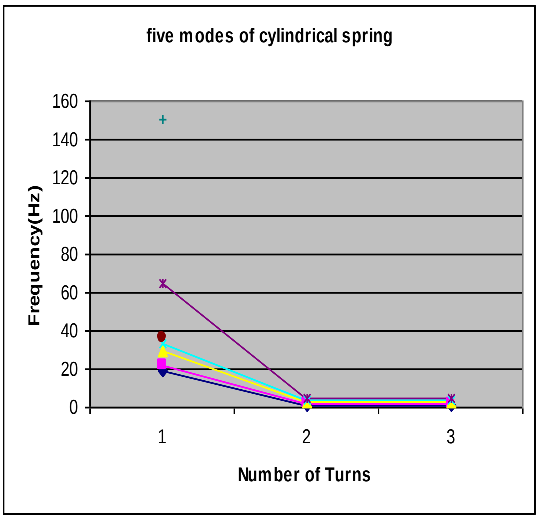
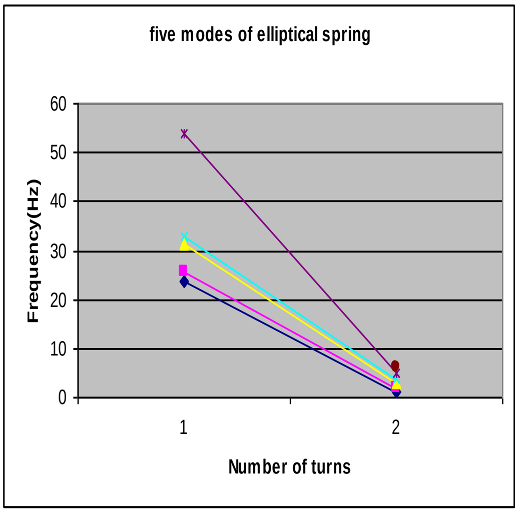
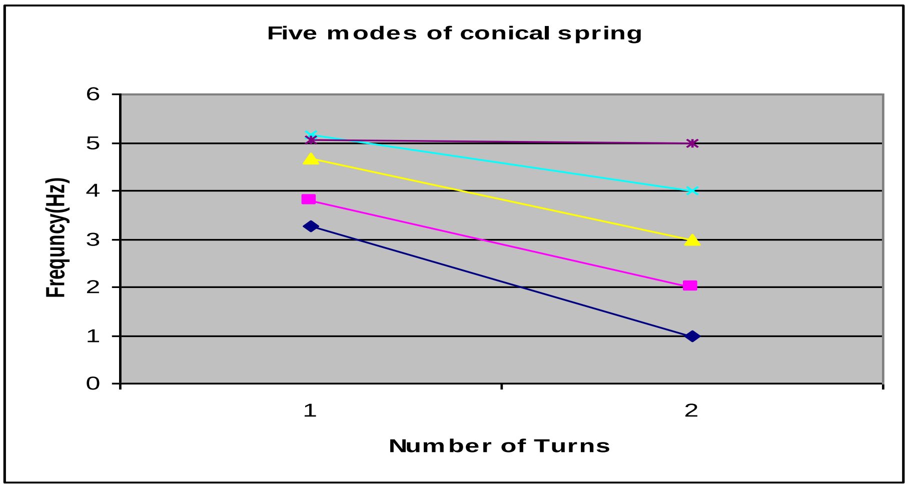


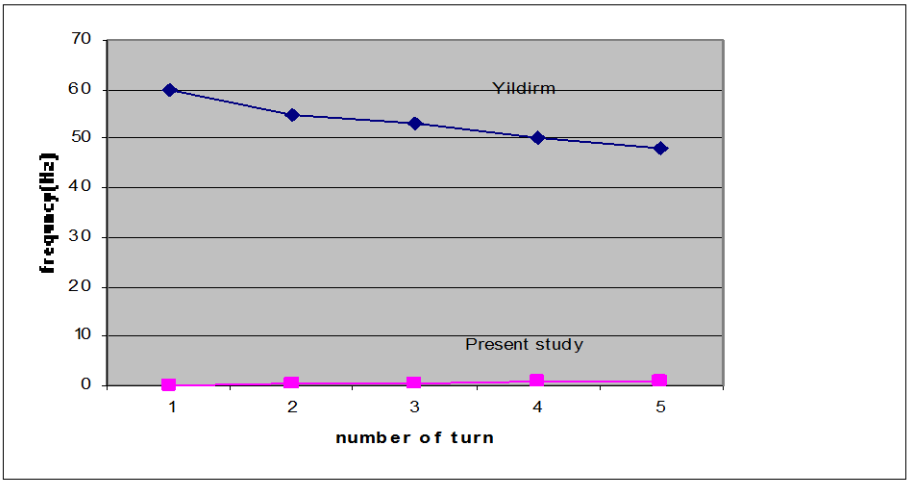
Figure.(10).Vibration mode frequencies on number of turns =6 of cylindrical spring



Figure(11).Vibration mode frequencies on number of turns=6 of elliptical spring



Figure(12).Vibrational mode frequencies on number of turns=6



Figure(13) comparison of vibrational Mode frequncies for Conical springs between this study and Yildrim.

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