Weight Optimization of Stainless Steel (SS304) Helical Spring

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Abstract
This study deals with the elaborate design optimization technique for helical compression spring with analytical method. Concentration is made on reducing weight of helical compression spring keeping the induced stresses within permissible limits. The spring is acted upon by compressive force so the spring gets compressed. The entitled work comprises, design of helical compression spring made from wire of solid circular section for a problem and optimizing the weight of solid wire spring by redesigning it with hollow circular section instead of solid circular section. After analytical design procedure the solid wire spring and optimized spring (i.e. spring made from hollow circular wire) are manufactured. After manufacturing of springs, analytical results are validated experimentally and in ANSYS.

Keywords: Compression spring, Weight Optimization, Stresses, Solid Circular Wire, Hollow Circular Wire, Experimental stress analysis, Solid edge, ANSYS.

1. INTRODUCTION
A spring is defined as an elastic machine element that deflects under the action of the load and returns to its original shape when load is removed. The various important functions of springs are to cushion, absorb or control energy due to either shock or vibration, to apply forces, to control motion, to measure forces, to store energy etc. In certain applications, springs are designed with a specific objective, such as minimum weight, minimum volume or maximum energy storage capacity. In such analysis, only one objective is considered at a time for a given application. The current study is concentrated on weight optimization of spring. In certain applications the weight of a helical spring is an important measure of quality. As the weight of the spring reduces the material required will also be less, ultimately, weight optimization lead to less material requirement and hence less material cost.

2. LITERATURE REVIEW
Most of the research activities emphasize on stress analysis, weight optimization of spring by varying design parameters for minimization of torsional and shear stresses experienced during loading. This includes the structural analysis, finite element analysis and optimization related to spring. Few important literatures are discussed further. R. S. Khurmi, J. K. Gupta [1], V. B. Bhandari [2] in their book of design

of machine elements present detail study of the spring. Spring chapter incorporates types of springs, material for helical springs, standard size of spring wire, terms used in compression springs, end connections for compression helical springs, end connections for tension helical springs, stresses in helical springs of circular wire, deflection of helical springs of circular wire, eccentric loading of springs, buckling of compression springs, surge in springs, energy stored in helical springs of circular wire, wire helical springs subjected to fatigue loading, helical torsion springs. R. S. Khurmi, J. K. Gupta

[1] in their book of strength of material gives the detail study of torsion of circular bars. From this book the study of solid shaft, hollow shaft and their comparison is referred. IS 7906-1 [4] lays down calculations for design of helical compression springs made from circular section wire and bar. Andrea Spaggiari, Igor Spinella, And Eugenio Dragoni [5] focused on the design of a large-scale linear SMA actuator conceived to maximize the stroke while limiting the overall size and the electric consumption. This result is achieved by adopting for the actuator a telescopic multi-stage architecture and using SMA helical springs with hollow cross section to power the stages. IS 4454-4 [6] covers stainless steels which are usually used in the cold drawn condition in the form of wire of circular cross-section up to 10 mm in diameter, for manufacture of springs and spring parts that are exposed to corrosive effects and sometimes to slightly increased temperatures. ASM Material Data Sheet [7], gives composition, physical, mechanical, electrical and thermal properties of SS 304 material. IS 7906-2 [8], covers cold coiled compression springs made from spring wires of up to 17 mm diameter. Also it covers testing procedure of cold coiled springs made from circular section wire and bar. R. C. Mc Wilson [9], describes the use of high speed motion photography and experimental strain measurements to describe the performance of helical compression-type suspension springs during the stopping motion of a hermetic refrigerator compressor. Igor Spinella, Eugenio Dragoni, Francesco Stortiero [10], contributes to enhancing the performances of SMA actuators by proposing a new SMA helical spring with a hollow section. The hollow spring is modeled, then it is constructed, and finally it is tested in compression to compare its performances with those of a spring

with a solid cross section of equal stiffness and strength. Emptied of the inefficient material from its center, the hollow spring features a lower mass (37% less) and an extremely lower cooling time (four times less) than its solid counterpart. These results demonstrate that helical springs with a hollow construction can be successfully exploited to build SMA actuators for higher operating frequencies and improved strokes. R. Sham Tickoo [11], covers the basics of FEA concepts, modeling and the analysis of engineering problems using ANSYS Workbench. It also covers structural and thermal analysis of model. Sangmesh Pattar

[12] in his paper, analyzed the spring through analytical and finite element method to check the variation in the deformation value as well as maximum shear stress value. By the results of ANSYS it is observed that analytical results and finite element method results are within the acceptable range. Avakash Patel, V. A. Patel [13], used harmony search algorithm as optimization technique. The performance of algorithm is illustrated with optimization of helical spring using as front suspension spring of Maruti Suzuki 800 for minimum weight. Atish B. Dighewar [14] in his work deals with the elaborate design optimization technique of coil spring sets with genetic algorithm. Attention is focused on reducing the weight and stresses keeping into considerations the various critical points. Mehdi Bakhshesh, Majid Bakhshesh [15] in their research, steel helical spring related to light vehicle suspension system under the effect of a uniform loading has studied and finite element analysis is then compared with analytical solution. Afterwards, steel spring has been replaced by three different composite helical springs including E-glass/Epoxy,

Carbon/Epoxy and Kevlar/Epoxy. Spring weight, maximum stress and deflection have been compared with steel helical spring and factors of safety under the effect of applied loads have been calculated. It has been shown that spring optimization by material spring changing causes reduction of spring weight and maximum stress considerably. Many investigators have done vast research on design optimization of spring to avoid failure and enhance life. They have carried out analyses with different parameters such as material, boundary conditions and geometrical properties. They have also performed experimental, analytical and numerical analysis to optimize weight of spring and to find stresses. Weight of spring can be optimized by harmony search algorithm, genetic algorithm. Weight of spring can be optimized by using composite materials instead of steel. Thus there is more scope to work on optimization the weight of spring by designing it as if it is made from hollow wire/rod instead of solid wire. There is hardly any paper available that considers the weight optimization of spring by designing it from hollow circular wire/rod.

3. SCOPE OF THE WORK

In this work, dimensions of the springs made from solid as well as hollow circular wire of same material and for same problem are determined analytically. After determination of dimensions springs are manufactured. Once manufacturing is done springs are tested for deflection under given load, stiffness is calculated and stress is calculated experimentally. After experimentation of both springs 3D CAD models are developed. These 3D CAD models are then tested in ANSYS for stiffness and the stresses induced are determined. After tests, various parameters like weight, stiffness, stresses induced etc. are compared.

4. DESIGN EQUATIONS FOR HELICAL COMPRESSION SPRING MADE FROM SOLID CIRCULAR WIRE

Following design equations are referred to design solid wire spring [1][2]

$$\tau = K\frac{8WD}{\pi d^3} = K\frac{8WC}{\pi d^2}$$

$$D = Cd$$

$$\delta = \frac{8WC^3n}{dG}$$

$$n' = n + 2$$

$$k = \frac{W}{\delta}$$

$$L_S = n'd$$

$$L_F = n'.d + \delta_{max} + (n' - 1) \times 1$$

$$p = \frac{L_F}{n' - 1}$$

$$W_S = \rho \text{ X } \frac{\pi}{4} \text{ X } d^2 \text{X } \pi D n'$$

Where,

D = Mean diameter of the spring coil, d = Diameter of the spring wire,

n = Number of active coils,
G = Modulus of rigidity for the spring material, W = Axial load on the spring,
τ = Maximum shear stress induced in the wire, C = spring index = D/d,
p = Pitch of the coils, and
δ = Deflection of the spring, as a result of an axial load W. WS = Weight of solid wire spring.

5. DESIGN EQUATIONS FOR HELICAL COMPRESSION SPRING MADE FROM HOLLOW CIRCULAR WIRE

Following design equations are referred to design hollow wire spring [3][4][5]

$$\tau = K\frac{8WDd_o}{\pi(d_o^4 - d_i^4)}$$

$$D = Cd$$

$$\delta = \frac{8WD^3n}{(d_o^4 - d_i^4)G}$$

$$n' = n + 2$$

$$k = \frac{W}{\delta}$$

$$L_S = n'd_o$$

$$L_F = n'.d + \delta_{max} + (n' - 1) \times 1$$

$$p = \frac{L_F}{n' - 1}$$

$$W_H = \rho \text{ X } \frac{\pi}{4} \text{ X } (d_o^2 - d_i^2) \text{ X } \pi D n'$$

Where,
d_o = Outer diameter of the spring wire, d_i =Inner diameter of the spring wire, W_H = Weight of hollow wire spring.

6. PROBLEM STATEMENT

It is required to design a helical compression spring subjected to a maximum force of 600 N. The deflection of the spring corresponding to the maximum force should be approximately 30 mm. The spring index can be taken as 6. The spring is made of stainless steel (SS304) [6] [7] wire. The ultimate tensile strength and modulus of rigidity of the spring material are 505 MPa and 86000 MPa respectively. The permissible shear stress for the spring wire should be taken as 50 % of the ultimate tensile strength. Density of material is 8000 kg/m^3. Design the springs made from solid as well as hollow circular wire.

7. DESIGN OF SPRINGS

Using design equations solid as well as hollow wire springs are designed assuming both springs:

1. Are made from the same material
2. Have the same spring index
3. Have the same spring rate i.e. stiffness
4. Undergo the same maximum load

Table-1: Calculations result

Parameter	Solid Wire Spring	Hollow Wire Spring
Load applied (W) in N	600	600
Wire diameter in mm	d = 7	d_i = 3, d_o = 7
Mean coil diameter(D) mm	42	42
Maximum shear stress developed (τ) in N/mm^2	234.44	242.63
Number of active coils (n)	18	17
Total number of coils (n')	20	19
Deflection (δ) in mm	31	30.30
Stiffness (W/ δ) in N/mm	19.35	19.8
Solid length (L_S) in mm	140	133
Free length (L_F) in mm	190	181.3
Pitch of the coil (p) in mm	10	10.07
Weight of coil in kg	0.811	0.629
% Saving in material	22.44	

8. MANUFACTURING OF SPRINGS

Designed springs are then manufactured. Various steps in manufacturing of the springs are as follows:

1. Calculation of length of wire required.
2. Arbor/mandrel diameter and length calculation and preparing arbor/mandrel
3. Coiling of wire on Coiling Machine
4. Grinding
5. Stress Relieving and Heat Treating

Figure 1 shows photograph of solid wire spring and figure 2 shows the photograph of hollow wire spring.

Fig.1 Solid spring

Fig.2 Hollow spring

9. EXPERIMENTAL WORK

Experimental work has been conducted to validate the results obtained analytically. Experimental work is conducted on universal testing machine. In experimentation design load is applied gradually on solid and hollow wire springs to find deflection of spring, stiffness of spring and the stresses induced in the spring.

In the current experimental work static load testing [8] of spring has been carried out. This test is carried out in the normal direction of loading with the spring standing vertically. In each case before carrying out the static test the spring has been compressed 3 times in quick succession to the block length.

Table -2 shows the results of the compression test conducted on the both solid wire and hollow wire springs. Stress induced in the spring is calculated by using following equations. [9]

$$\tau = \frac{GdK\delta}{\pi D^2 n} \ldots\ldots\ldots\ldots\ldots \text{For solid wire spring}$$

$$\tau = \frac{Gd_oK\delta}{\pi D^2 n} \ldots\ldots\ldots\ldots\ldots \text{For hollow wire spring}$$

Table-2: Results of compression test

d Applied (N)	Deflection (mm)		Maximum Shear stress (τ) N/mm^2	
	Solid wire spring	**Hollow wire spring**	**Solid wire spring**	**Hollow wire spring**
50	2.65	2.75	18.01	19.68
100	5.00	4.88	34.03	34.95
150	7.85	8.11	53.45	58.09
200	10.42	9.71	70.90	69.56
250	13.23	12.69	90.03	90.92
300	14.78	15.08	100.59	108.01
350	17.41	17.95	118.52	128.60
400	19.75	20.20	134.45	144.74
450	22.73	23.44	154.69	167.92
500	25.51	25.00	173.63	179.12
550	27.92	27.64	190.03	198.02
600	30.15	29.85	205.22	213.86

Table 3 shows weights of the springs measured on electronic weighing machine.

Table-3: Weight of springs

Type of spring	Weight in kg
Solid wire spring	0.820
Hollow wire spring	0.616

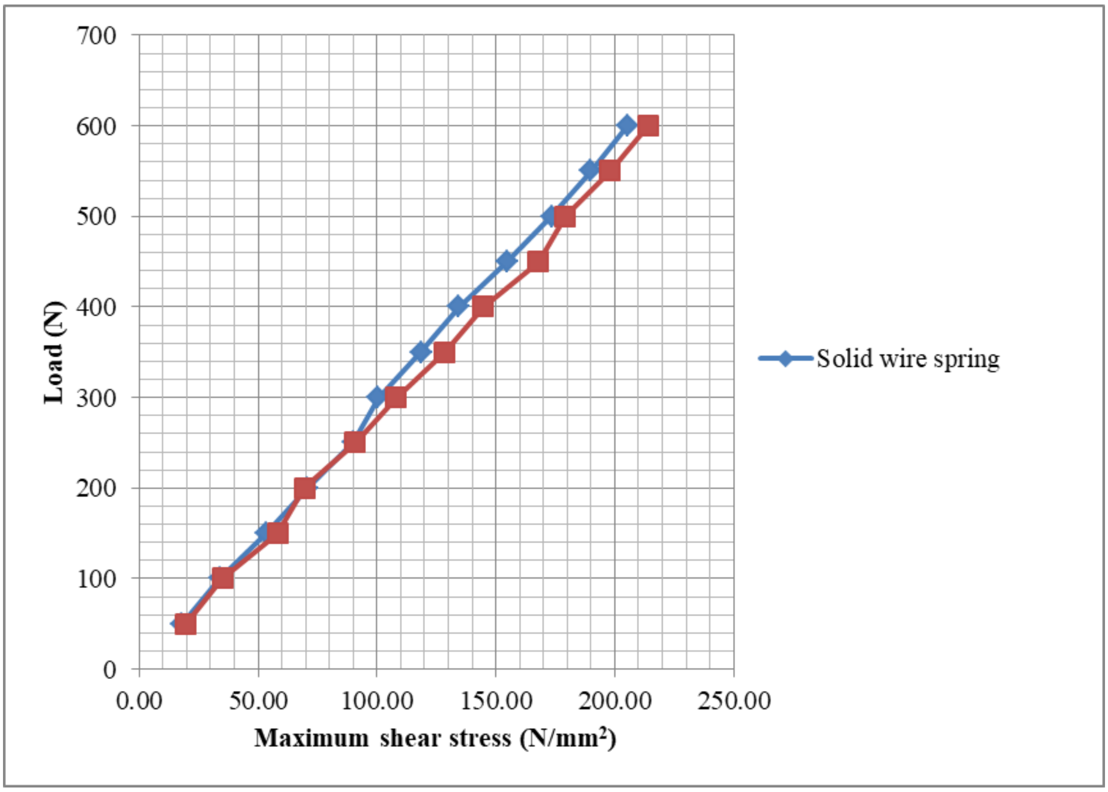

Chart-1 shows the graph of load applied vs maximum shear stress developed in springs.

Chart-1: Load applied vs maximum Shear stress

Chart-2 shows the graph of load applied vs deflection developed in springs. Experimentally stiffness of the solid wire spring is 19.90 and that for hollow wire spring is 20.10

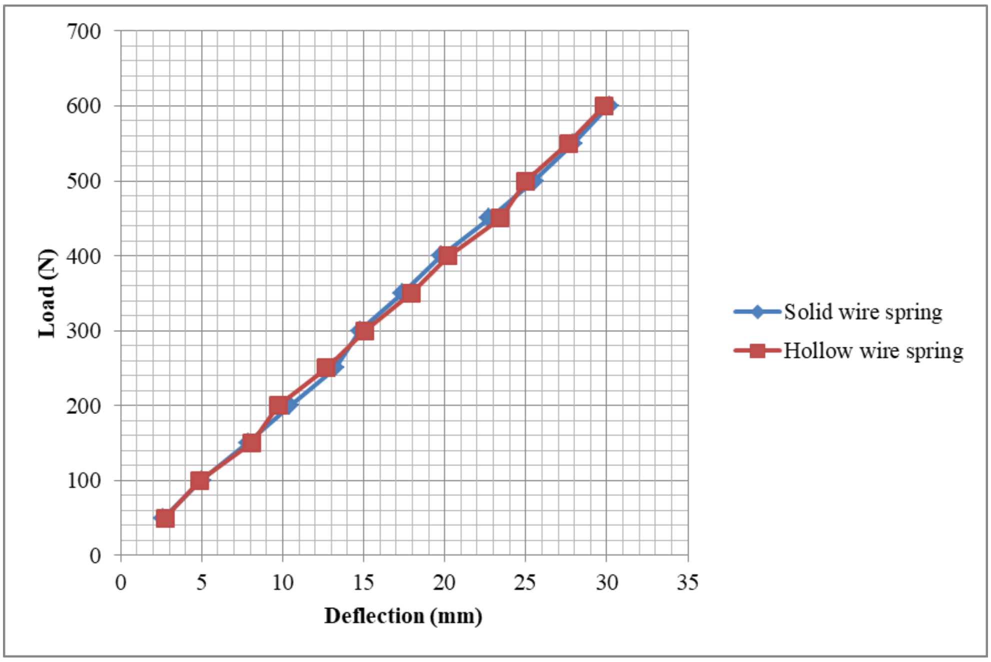

Chart-2: Load applied vs Deflection

10. FINITE ELEMENT ANALYSIS [10] [11]

The finite element analysis (FEA) is a computing technique that is used to obtain approximate solutions to boundary value problems. It uses a numerical method called finite element method (FEM). FEA

International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

involves the computer model of design that is loaded and analyzed for specific results, such as stress, deformation, natural frequencies, mode shapes, temperatures distributions, and so on. In the current dissertation work, FEA of spring is carried out in ANSYS which is a world's leading, widely distributed and popular commercial CAE package. Solid models (CAD) of springs are created in Solid Edge software. In order to create solid model in solid edge sketch, helical protrusion and helical cutout features are used. These solid models of springs are imported in ANSYS workbench. Static structural analysis of solid wire spring and hollow wire spring is carried out in ANSYS CAE software package.

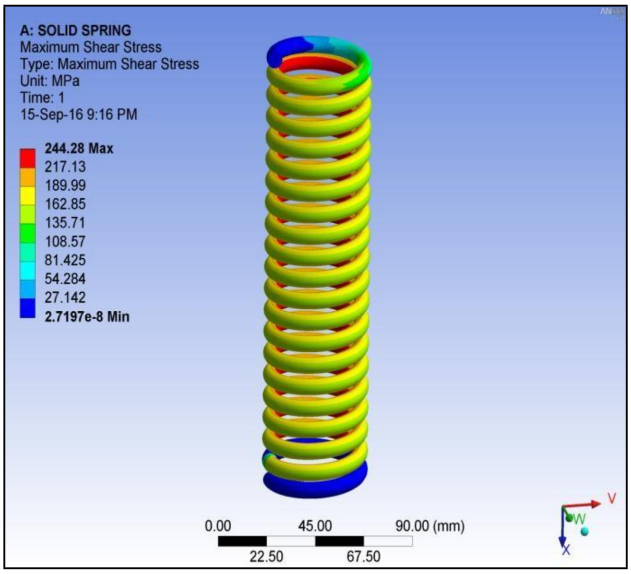

Fig -3: Maximum shear stress in solid wire spring

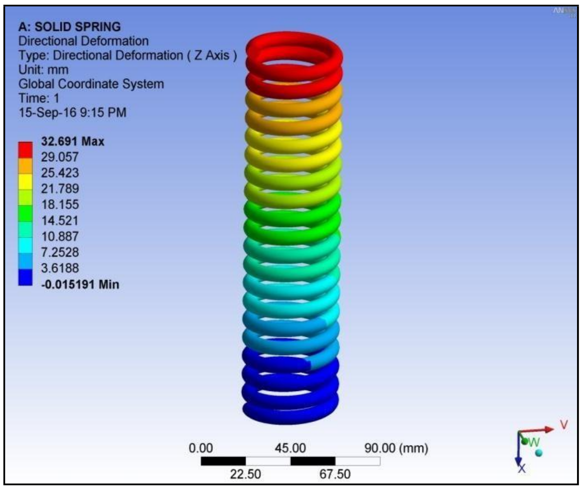

Fig -4: Deflection in solid wire spring

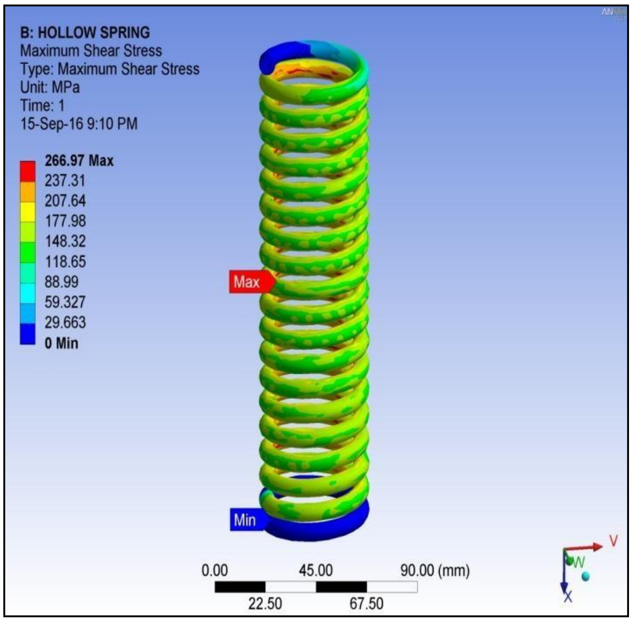

Fig -5: Maximum shear stress in hollow wire spring

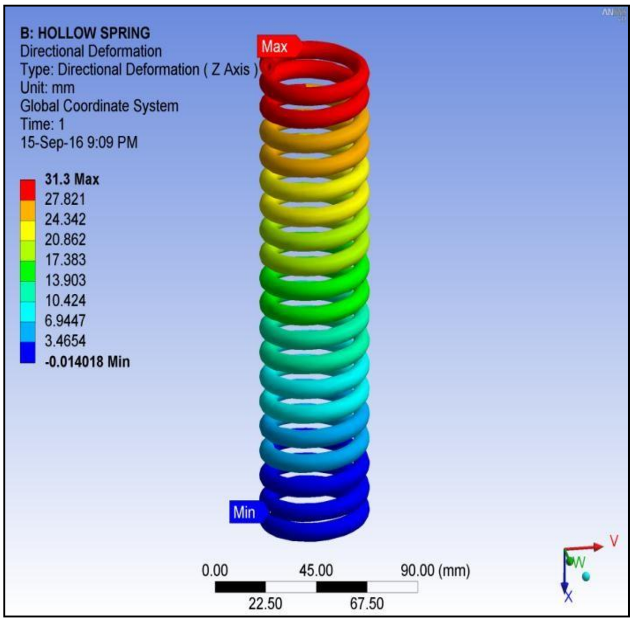

Fig -6: Deflection in hollow wire spring

Fig -3 shows the maximum shear stress and fig -4 shows deflection developed in solid wire spring. Fig -5 shows the maximum shear stress and fig -6 shows deflection developed in hollow wire spring. Table -4 shows output of static structural analysis of springs.

Table -4: Output of ANSYS

l Applied (N)	Deflection (mm)		Maximum Shear stress (τ) N/mm2	
	Solid wire spring	**Hollow wire spring**	**Solid wire spring**	**Hollow wire spring**
50	2.72	2.61	20.36	22.25
100	5.45	5.22	40.71	44.49

150	8.17	7.83	61.07	66.74
200	10.90	10.43	81.43	88.99

l Applied (N)	**Deflection (mm)**		**Maximum Shear stress (τ) N/mm^2**	
	Solid wire spring	**Hollow wire spring**	**Solid wire spring**	**Hollow wire spring**
250	13.62	13.04	101.78	111.24
300	16.35	15.65	122.14	133.48
350	19.07	18.26	142.49	155.73
400	21.79	20.87	162.85	177.98
450	24.52	23.48	183.21	200.23
500	27.24	26.08	203.56	222.47
550	29.97	28.69	223.92	244.72
600	32.69	31.30	244.28	266.97

Table -5 shows the weight of springs calculated from ANSYS. Chart -3 shows graph of load applied vs maximum shear stress developed in solid and hollow wire spring. Chart -4 shows graph of load applied vs deflection developed in solid and hollow wire spring.

Table -5: Weight of springs

Type of spring	**Weight in kg**
Solid wire spring	0.81263
Hollow wire spring	0.63020

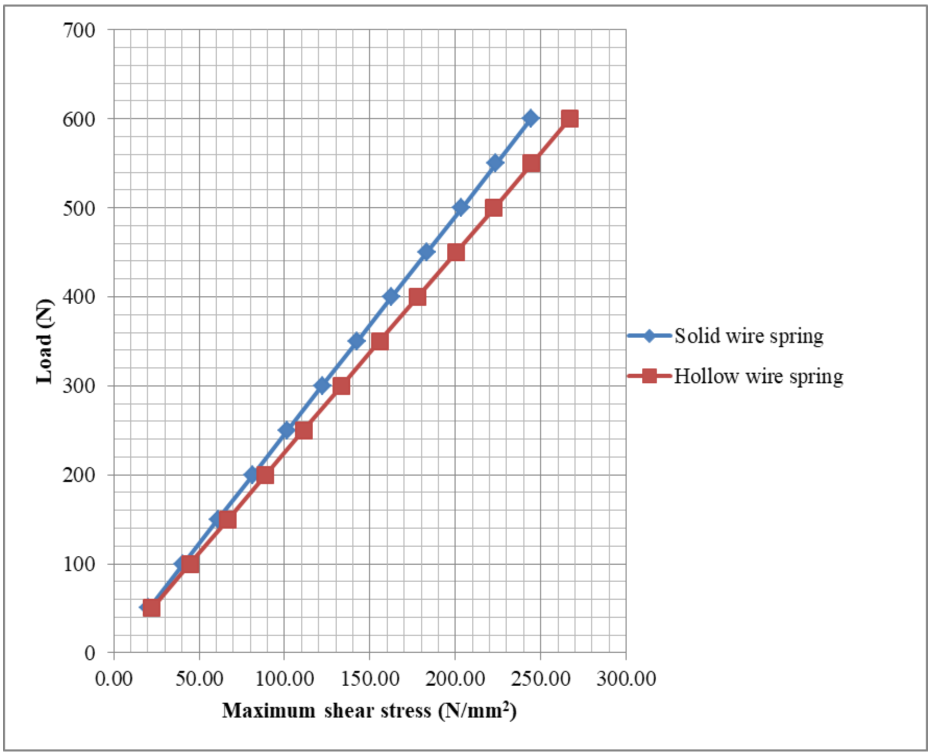

Chart -3: Load applied vs Maximum shear stress

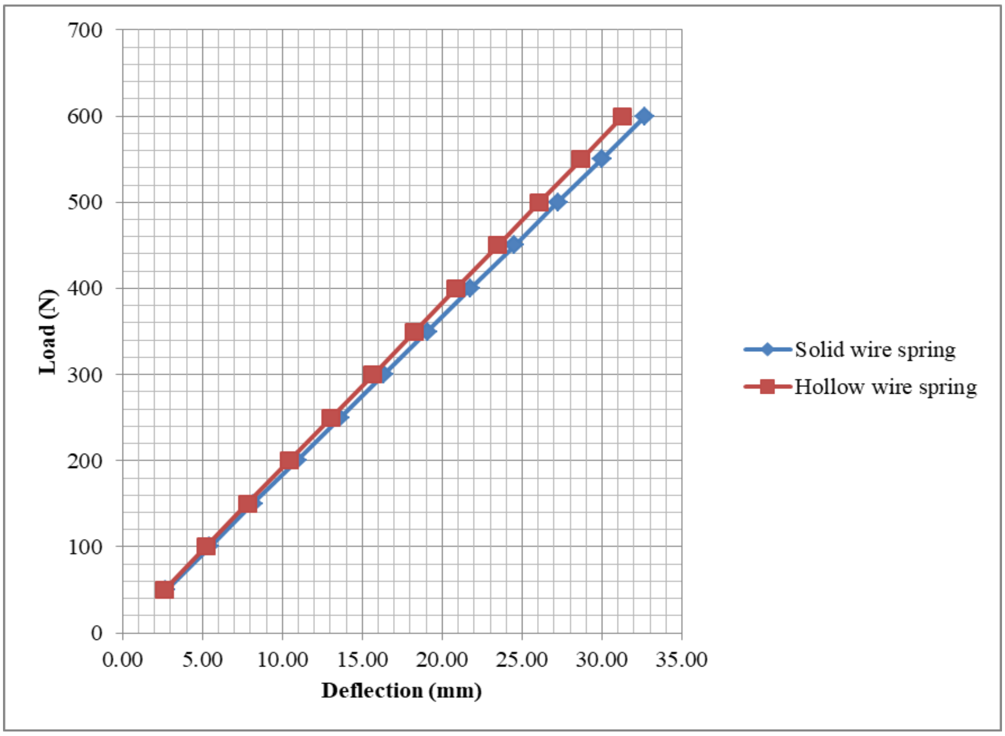

Chart -4: Load applied vs Deflection

In ANSYS stiffness of the solid wire spring is 18.40 and that for hollow wire spring is 19.16

11. COMPARISON OF RESULTS

From table 2, 3 and Chart 1, 3 it is observed that maximum shear developed in hollow wire spring is little more than maximum shear stress in solid wire spring but it is within permissible limit of 252.5 N/mm^2. In case of hollow wire spring analysis by ANSYS maximum shear stress is more than permissible limit but variation less than 15% is acceptable. Hence hollow wire spring design is safe. From table 2, 4 and Chart 2, 4 it is observed that maximum deflection occurred in hollow wire spring and solid wire spring is approximately equal under the action of same applied load. One more important thing is variation in maximum deflection evaluated by different method. It is seen that variation in maximum deflection evaluated by different methods is acceptable. The variation less than 15% is acceptable. It is observed that stiffness of hollow wire spring and solid wire spring is approximately equal under the action of same applied load. From above observations it is seen that saving in material is 22.44 % analytically as well as by ANSYS and it is 24.87 % in actual when measured on electronic weighing machine.

12. CAUSES OF DIFFERENCE IN RESULT OBTAINED BY VARIOUS METHODS

The analytical, experimental and ANSYS result shows the variation in results obtained. The difference in result should be due to following reasons.

1. Difference in loading condition causes variation in stress, deflection.
2. Slight variations in dimensions of springs cause variation in deflection and stress.
3. Variations in chemical composition and mechanical properties in actual from assumed causes variation in stress, deflection.
4. The physical weight of springs varies slightly from weight calculated by software or analytically. Due to presence of contaminations, pores in actual component or variation in density of material the weight

varies from weight calculated by software.

13. CONCLUSION

The study carried out in this work mainly concerned with the weight optimization of helical compression spring. Initially a solid wire spring is designed for given application and then in order to minimize or optimize the weight of spring it is redesigned with hollow circular cross section of wire keeping the same material, same spring index, same spring rate.

Making the spring wire hollow we can achieve the all properties that a solid wire spring can have with benefit of reducing the weight of spring. As seen in this study weight reduced is 22.44 % analytically as well as by ANSYS and is 24.87 % physically. Thus material cost is reduced by the same amount.

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