Structural Design and Analysis of Hybrid Helical Compression Springs

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Abstract— A common problem in spring design is how to reduce the maximum stress experienced by helical compression spring and still sustain the given load-length prerequisite projected within the overall dimensions of length and diameter. But in practical situation available spring space in both along length and diameter will be fully utilized without any margin. In such cases, if maximum stress experienced by the spring results to be high then it will not be possible to review the specified requirements. The present work aims at offering a promising solution for such situation by proposing hybrid design of helical compression spring so as to achieve stress reduction to the desired attenuation. Detailed mathematical modeling is carried out which simplifies the design. Monograms will be furnished as an outcome of design using which amount of stress reduction anticipated for a given spring index of the single spring can be quickly quantified. Influence of spring index on maximum stress will be studied as part of this work. MATLAB Software is developed which embeds the formulation derived which can be used as a hand calculator which will be extremely useful for a spring designer to quickly estimate the design parameters. This software will also be helpful to carry out sensitivity analysis of the proposed design with in no time so as to achieve optimized configuration of the proposed hybrid spring.

Key words: Helical Compression Spring, Hybrid Configuration, MATLAB

I. Introduction

Springs are important mechanical members which are often used in machines to exert force, to provide flexibility, and to store or absorb energy. The spring of the suspension system plays an important role for a smooth and jerk free ride. Helical spring is the most popular type of springs.

The fundamental stress distribution, characteristic of helical coil springs and also presented an in depth discussion on the parameters influencing the quality of coil springs and also stated that the springs are to be designed for higher stresses with small dimensions[1]. Static analysis of typical helical compression spring configuration of two wheeler horn was described using NASTRAN solver and compared with analytical results[2]. The spring is analyzed for the fatigue loads and has been optimized for the selection of material, wire diameter, carbon percentage and other governing parameters[3].The spring is analyzed through analytical and finite element method to check the variation in the deformation value as well as maximum shear stress value and also observed that analytical results and finite element method results are within the acceptable range[4].The author has aimed to analyze the feasibility of adopting composite material for design of helical coil spring. Combination of springs with steel and composite material i.e Glass fiber epoxy resin is to be used in place of conventional spring steel. The cause of implementing combination of steel and composite material is the low stiffness of single composite spring, which limits its application to light vehicles [6]. After reviewing the literature is understood that the authors have not dealt with hybrid configuration, fw of them proposed change of material from metal to composite whose manufacturing feasibility is not up to the mark as of now and almost no paper has discussed about optimizing the design while meeting the overall space constraints.

II. Structural design of hybrid spring configuration

Spring designer very often encounters a problem while configuring the design with respect to maintaining a compromise between stress experienced by the spring and specified load vs length requirement with in dimensional constraints (Length and diameter).

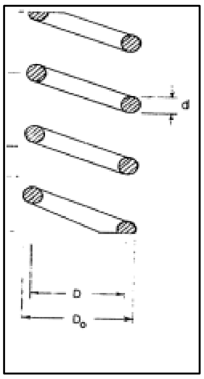

Fig. 1(a): Existing configuration

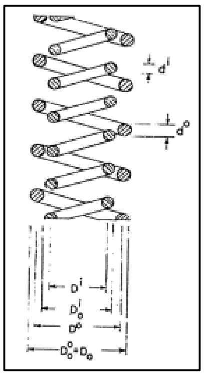

Fig. 2(b): Proposed hybrid configuration

In general spring designer entirely utilizes entire space in both along length and diameter. In such cases when maximum stress experienced by the existing spring reaches acceptable limits and if it is not possible to modify the specified requirement hybrid spring would be a promising solution to achieve reduction in stress. Existing and proposed configurations of helical compression spring are shown in Fig.1.

In the above figure

- D: Mean diameter of existing spring
- D_o: Outside diameter of existing spring
- D^i: Mean diameter of inner spring of hybrid configuration
- D_o^i: Outside diameter of inner spring of hybrid configuration
- D^o: Mean diameter of outer spring of hybrid configuration
- D_o^o: Outside diameter of outer spring of hybrid configuration
- d: Size of wire for existing spring
- d^i: Size of wire for inner spring of hybrid configuration
- d^o: Size of wire for outer spring of hybrid configuration

A. Design Inputs

Helical spring of suspension system used in Maruti Suzuki 800CC car is considered for the present work. Configuration details of existing spring are furnished below.

- Mean coil diameter, D = 100 mm
- Wire diameter, d = 11 mm
- Number of turns, n = 4
- Material: Oil tempered carbon steel
- Shear modulus, G = 31296 MPa
- Density, ρ = 7840 kg/m3
- Functional load, F_2 = 2150 N

B. Assumptions

Following design parameters are taken common for both existing and proposed configurations

- L_S: Solid length of spring
- K: Stiffness
- L_F: Free length of spring
- G: Shear modulus of spring material
- D_o: Outside diameter of spring ($D_o^o = D_o$)
  - No radial clearance exists between two layers of hybrid spring
  - Stress experienced by the outer spring would be same as that of internal spring

C. Analytical Method

Maximum shear stress experienced by the existing configuration can be expressed as
Where

$$K_s = 1 + \frac{1}{2C} \qquad (1a)$$

δ: Total deflection

$$\text{Spring index, } C = \frac{D}{d}$$

Functional load can be expressed as

$$\frac{F_2}{D^2} = \frac{G\delta}{8C^5 L_s} \qquad (2)$$

Where F_2: Functional load
D: Mean diameter of spring
From figure 1
Do = D + d

$$D_0 = D + \frac{D}{C} = D\left[1 + \frac{1}{C}\right] = D\left[\frac{C+1}{C}\right]$$

From which

$$D = D_0\left[\frac{C}{C+1}\right] \qquad (3)$$

Substituting equation 3 in equation 2

$$\frac{F_2}{D_o^2\left(\frac{C}{C+1}\right)^2} = \frac{G\delta}{8C^5 L_s}$$

$$\frac{F_2}{D_o^2} = \frac{G\delta}{8C^3 L_s (C+1)^2} \qquad (4)$$

Applying equation 4 for outer spring of hybrid design gives

$$\frac{F_2^{o}}{(D_o^{o})^2} = \frac{G\,\delta}{8\,C^{I^3}\,L_s\,(C^I+1)^2} \qquad (5)$$

Applying equation 1 for hybrid design gives

$$\sigma^{I}_{max} = \frac{K^{I}_{s}\,G\,\delta}{\pi\,C^{I^2}\,L_s} \qquad (6)$$

In which

$$K^{I}_{s} = 1 + \frac{1}{2C^{I}} \qquad (6a)$$

Applying equation 5 for internal spring of hybrid design gives

$$\frac{F_2^{I}}{(D_o^{I})^2} = \frac{G\,\delta}{8\,C^{I^3}\,L_s\,(C^I+1)^2} \qquad (7)$$

From figure 1

$$\frac{D_o^{\,i}}{D_o^{\,o}} = \frac{\left[\frac{C^I-1}{C^I}\right]}{\left[\frac{C^I+1}{C^I}\right]} = \left[\frac{C^I-1}{C^I+1}\right]$$

$$D_o^{\,I} = D_o^{\,o}\left[\frac{C^I-1}{C^I+1}\right] \qquad (8)$$

Substituting equation 8 in 7 gives

$$\frac{F_2^{I}}{(D_o^{o})^2} = \frac{G\,\delta}{8\,C^{I^3}\,L_s\,(C^I+1)^2}\left[\frac{C^I-1}{C^I+1}\right]^2 \qquad (9)$$

Equation 9 brings out the relation between final load of internal spring and outside diameter of outer spring.
Re writing equation 4 as

$$\frac{1}{C^3\,(C+1)^2} = \frac{F_2\,8\,L_s}{D_o^{\,2}\,G\delta} \qquad (10)$$

Re writing equation 5 as

$$\frac{1}{C^{I^3}\,(C^I+1)^2} = \frac{F_2^{o}\,8\,L_s}{(D_o^{o})^2\,G\delta} \qquad (11)$$

Re writing equation 9 as

$$\frac{1}{C^{I^3}\,(C^I+1)^2}\left[\frac{C^I-1}{C^I+1}\right]^2 = \frac{F_2^{I}\,8\,L_s}{(D_o^{o})^2\,G\delta} \qquad (12)$$

Adding equation 11 and 12 and simpling

$$\frac{1}{C^3\,(C+1)^2} = \frac{1}{C^{I^3}\,(C^I+1)^2}\left[1+\left(\frac{C^I-1}{C^I+1}\right)^2\right] \qquad (13)$$

While migrating from existing configuration to hybrid configuration it would be necessary to estimate C^I from C. Using equation 13 to do so would be a complex task.
Hence equation 13 has been rearranged as follows.

$$X\,(C^I)^7 + 4\,X\,(C^I)^6 + 9\,X\,(C^I)^5 + 4\,X\,(C^I)^4 + X\,(C^I)^3 - 2\,(C^I)^2 - 2 = 0 \qquad (13a)$$

Where

$$X = \frac{1}{C^3\,(C+1)^2} \qquad (13b)$$

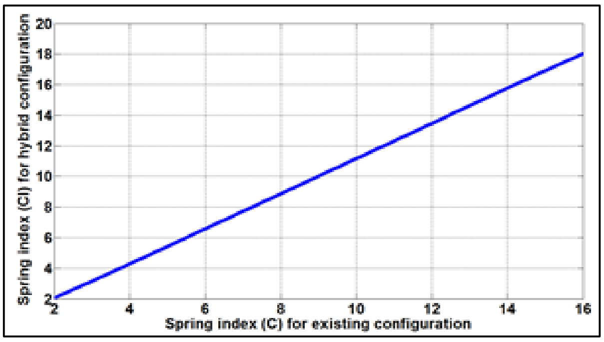

Fig. 2: Monogram for evaluating spring index for hybrid configuration

Values of 'X' for 'C' ranging from 2 to 16 are generated embedding equation 13b in MATLAB. Further separate MATLAB code is written to find out C^I for each value of X using 13a. From these values a polynomial along with its coefficients are evaluated as given below.

$$C^I = -6.78\times10^{-6}\,C^5 + 3\times10^{-4}\,C^4 - 5.1\times10^{-3}\,C^3 + 4.2\times10^{-2}\,C^2 + 9.78\times10^{-1}\,C - 3.7\times10^{-2} \qquad (13c)$$

This polynomial will be extremely useful to find out value of C^I for any value of C. Further a monogram has been generated from the above equation which would be helpful for the spring designer in arriving at hybrid configuration and the same is given in figure 2.

$$\frac{\sigma_{max}}{\sigma^{i}_{max}} = \frac{K_s}{K^I_s}\frac{C^{I^2}}{C^2} \qquad (14)$$

$$\%\ reductioninstress = \frac{\sigma_{max} - \sigma^{I}_{max}}{\sigma_{max}} = 1 - \frac{\sigma^{I}_{max}}{\sigma_{max}} = 1 - \frac{K^I_s}{K_s}\frac{C^2}{C^{I^2}} \qquad (15)$$

Equation 15 has been plotted in figure 3 to evaluate percentage reduction in stress with hybrid configuration as a function of spring index for existing configuration.

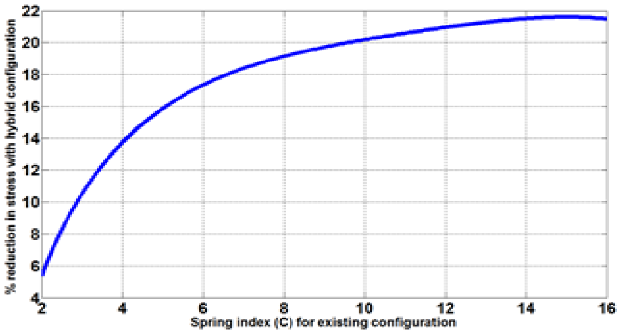

Fig. 3: Variation of reduction in stress with spring index for hybrid configuration

From figure 3 the following observations are drawn

- Even when there are low index values, consideration should be given to hybrid springs as it is possible to obtain 10% stress attenuation in this range.
- In the most widely used ranges (i.e. c = 5 to 9) stress attenuation of 18 % is possible with proposed hybrid configuration

Further additional relations necessary for sizing of hybrid configuration are evaluated as follows.

Applying equation 3 for outer layer of hybrid configuration gives

$$D^o = D^o_o\left[\frac{C^I}{C^I+1}\right] \qquad (16)$$

Dividing equation 16 by equation 3 gives

$$\frac{D^o}{D} = \frac{D^o_o\left[\frac{C^I}{C^I+1}\right]}{D_o\left[\frac{C}{C+1}\right]}$$

$$D^o = D\left(\frac{D^o_o\left[\frac{C^I}{C^I+1}\right]}{D_o\left[\frac{C}{C+1}\right]}\right) = D\left[\frac{C+1}{C^I+1}\right]\frac{D^o_o}{D_o}\frac{C^I}{C} = D\left[\frac{C+1}{C^I+1}\right]\frac{D^o_o}{D_o}\frac{D^o}{d^o}\frac{d}{D}$$

From which

$$d^o = d\left[\frac{C+1}{C^I+1}\right]\frac{D^o_o}{D_o}$$

But from assumptions $D_o = D_o^o$

Hence

$$d^o = d\left[\frac{C+1}{C^I+1}\right] \qquad (17)$$

From equation 17

$d^o = f(d,c)$

Wire size (d^o) for hybrid configuration has been plotted as a function of wire size (d) for existing configuration for different values of 'C' (C^I has been computed from C) from equation 17 in figure 4.

Applying equation 3 for internal layer of hybrid configuration gives

$$D^i_o = D^i\left[\frac{C^I+1}{C^I}\right]$$

$$D^i_o = C^I d^i\left[\frac{C^I+1}{C^I}\right]$$

From which wire size of inner spring is

$$d^i = \left[\frac{D^i_o}{C^I+1}\right] = \frac{D^o_o - 2d^o}{C^I+1} \qquad (18)$$

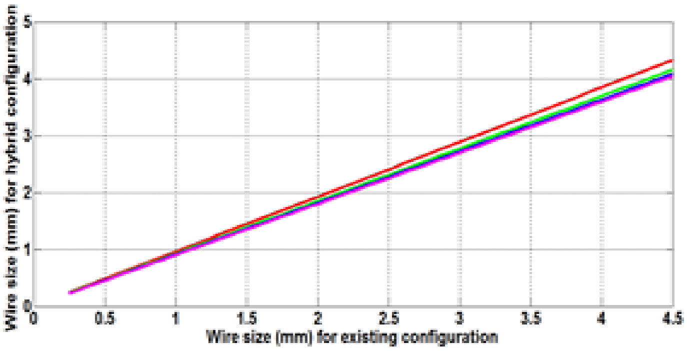

Fig. 4: Variation of wire sizes for C =3,6,9,12

Number of active coils for outer and internal layers of hybrid configuration are

$$n^{o} = \frac{L_s}{d^{o}} \qquad (19)$$

$$n^{i} = \frac{L_s}{d^{i}} \qquad (20)$$

However outside diameter of outer spring is same as that of existing spring.
Outside diameter of internal spring is

$$D_o^{\ i} = D_o^{\ o} - 2d^{\ o} \qquad (21)$$

D. Solid Modeling

3D CAD models of existing spring and hybrid configuration evolved from above mentioned dimensions are shown in figure 5.

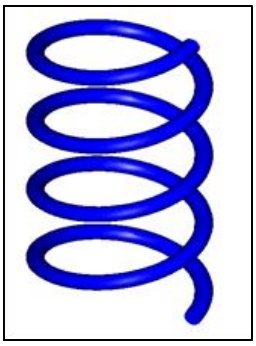
Fig. 5(a): Existing spring

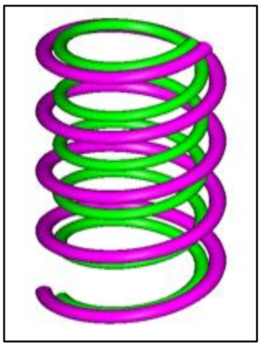
Fig. 5(b): Hybrid spring

III. Results

Selective design parameters pertaining to hybrid configuration are compared with that of existing one in Table

Sl. No.	Design Parameter	Existing configuration	Hybrid configuration
1.	Spring index	9.09	10.12
2.	Max.shear stress	433	348 MPa
3.	% reduction in stress	--	19.7 %
4.	Free length(mm)	227.5 mm	227.5 mm
5.	Shear stress factor	1.055	1.049
6.	Size of wire(mm)	11	9.9808(Outer) 8.186(Inner)
7.	Number of turns	4	4.4085(Outer) 5.3751 (Inner)
8.	Outer diameter(mm)	111	111 (Outer) 91.04(Inner)
9.	Mean coil diameter(mm)	100	101.02 (Outer) 82.85 (Inner)
10.	Functional load(N)	2150	1285.4 (Outer) 864.6 (Inner)
11.	Deflection(mm)	150	150 mm

Table 1: Selective design parameters

IV. CONCLUSION

An analytical method and monograms are evolved as an outcome of the project using which a hybrid configuration having least stress is evolved to replace existing spring in Maruti Suzuki 800CC car. Use of proposed hybrid configuration not only yields to least stress configuration but also results in increased fatigue life. Proposed hybrid configuration exhibited reduction in maximum shear stress by 19.7 % compared to that of existing configuration. Analytical method thus evolved is transformed to a general purpose codes in MATLAB software using which designer can quickly arrive at hybrid configuration meeting his requirement. It is recommended to implement the hybrid configuration.

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