Fatigue Stress Analysis of Helical Compression Spring, A Study

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Abstract— The objective of this review paper is to provide the information about the fatigue stress for the helical compression spring. Springs are mechanical shock absorber system. The researchers throughout the years have given various research methods such as Theoretical, Numerical, Analytical and Experimental. We usually prefer the Theoretical, Numerical and Analytical FEA methods. This study says Finite Element analysis is the best method for numerical solution calculating the fatigue stress, life cycle and shear stress of helical compression spring. This present work will be beneficiary for the design of helical spring design against fatigue analysis.

Key words: Helical Compression Spring, Maximum Shear Stress, Fatigue Stress, Fatigue Life, Finite Element Analysis

I. Introduction

Helical compression springs are used widely all over the world. It has different type of applications in different areas. According to that the analysis are to be made which are discussed in this present work. The present work further discusses about fatigue loading, Stresses and basic design procedure of the helical compression springs.

Mechanical springs are used in machine designs to exert force, provide flexibility and to store or absorb energy. Springs are manufactured form any different applications such as compression, extension, torsion, power and constant force. Depending on the application, a spring may be in a static, cyclic or dynamic operating mode. A spring is usually considered to be static if a change in deflection or load occurs only a few times, such as less than10000 cycles during the expected life of the spring. A static spring may remain loaded for very long periods of time. The failure modes of interest for static springs include spring relaxation, set and creep.

Helical coil compression springs becomes quite necessary to do the complete stress analysis of the spring. As these springs undergo the fluctuating loading over the service life, it becomes essential to find out the fatigue limit of the same. Mechanical spring is defined as an elastic body that has the primary function to deflect or distort under load, and to return to its original shape when the load is removed. First step in the design of spring in general is to determine the loads and the deflections required for a given spring application depending upon the type of the loading.

Cyclic springs are flexed repeatedly and can be expected to exhibit a higher failure rate due to fatigue. Cyclic springs may be operated in a unidirectional mode or a reversed stress mode. In one case, the stress is always applied in the same direction, while in the other; stress is applied first in one direction then in the opposite direction. For the same maximum stress and deflection between a unidirectional and reversed stress spring, the stress range for the reversed stress spring will be twice that of the unidirectional spring and therefore a shorter fatigue life would be expected.

A. Classification of Spring

In general, spring may be classified as:

1) Wire spring such as helical spring of round or square wire, made to resist and deflect under tensile, compressive and torsional loads.
2) Flat spring which is includes cantilever elliptical types, wound motor or clock type power spring, a flat spring washers, usually called Belleville springs.
3) Special shaped springs.

B. Type of Compression Spring

There are four standard types of helical compression springs. They are plain end, squared end, plain ground end & squared ground end as illustrated by figure 1.

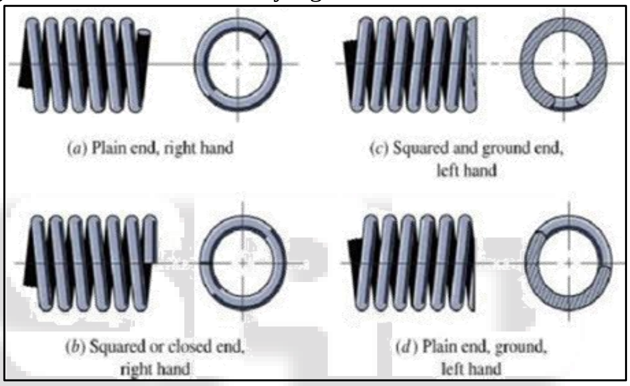

Fig. 1: Shows the Geometry of Four Standard Types on Helical Compression Springs

- A spring with plain ends has non-interrupted helicoids as the ends are the same as if along spring had been cut into sections.
- A spring with plain ends that are squared or closed is obtained by deforming the ends to a zero-degree helix angle.
- Springs should always be both squared and ground for important applications, because a better transfer of the load is obtained.
- A spring with squared and ground ends compressed between rigid plates can be considered to have fixed ends.

C. Concept of Spring Design

The design of a new spring involves the following considerations:

1) Space into which the spring must fit and operate.
2) Values of working forces and deflections.
3) Accuracy and reliability needed.
4) Tolerances and permissible variations in specifications.
5) Environmental conditions such as temperature, presence of a corrosive atmosphere.
6) Cost and qualities needed.

The designers use these factors to select a material and specify suitable values for the wire size, the number of turns, the coil diameter and the free length, type of ends and the spring rate needed to satisfy working force deflection requirements. The primary design constraints are that the wire size should be commercially available and that the stress at the solid length be no longer greater than the torsional yield strength.

D. Fatigue Analysis

“Fatigue is the process where repeated variations in loading cause failure even when the nominal stresses are below the material yield strength; and is made up of crack initiation and subsequent crack growth as a result of cyclic plastic deformation.” Independent of the present work, when the fatigue phenomenon is present, the flow shown in figure 2 indicates al the steps necessary to develop the work considering this aspect. The process requires several inputs, such as geometry, load history, environment, design criteria, material properties and process effects. With these inputs, fatigue design is performed through synthesis, analysis and testing. The process from design, analysis and test is highly interactive and iterative. The number of loops is directly related to the quality of the inputs, and the accuracy to predict the life of the component or system. In this work, the focus will be on just one part of the flow, which is related to stress analysis, fatigue life and cumulative damage models, and life prediction.

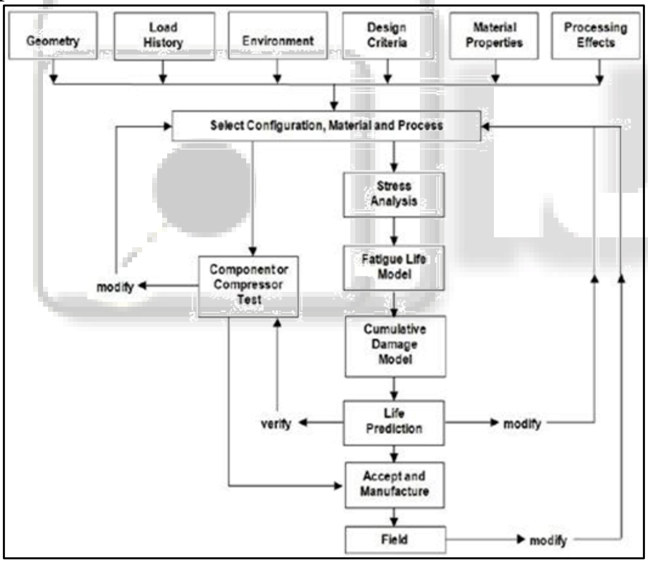

Fig. 2: Fatigue Design Flowchart (Adapted From Stephens Et Al. (2001))

E. Fatigue Stress

All springs have finite fatigue limits, the limit depending fatigue stress and the degree of fluctuating loads. The four most common fatigue stress conditions include constant deflection, constant load, unidirectional stress and reversed stress. A spring inside a valve assembly is an example of a constant deflection where the spring is cycled through a specified deflection range. An example of a constant load spring is the use of vibration springs under a dead weight where the load applied to the spring does not change during operation but the deflection will. A unidirectional stress is one where the stress is always applied in the same direction such as used in the return spring of an actuator. A reversed stress is applied first in one direction then in the opposite direction such as used in a regulator valve. The three stages to a fatigue failure include crack initiation, crack propagation and finally fracture of the spring material.

To determine the stress generated in the spring, consider a helical spring subjected to an axial load “F”, see Fig.3

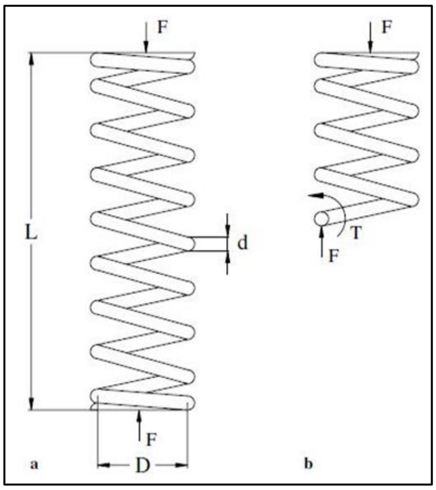

Fig. 3: Helical spring with Axial Load & (B) Free Body Diagram

Now imagine the spring is sectioned at some point, Fig. 3(b). Internal forces are generated to maintain the remaining portion shown in Fig .3(b) in equilibrium. A direct shear force “F” and a torque “T” appear. The maximum shear stress on the wire can be calculated by the following equation [2, 3]:

$$\tau_{max} = \frac{T_r}{J} + \frac{F}{A}$$

Where “J” is the polar moment of inertia, “A” is the cross section area and r is the wire radius. The first term corresponds to torsion contribution and the second term is the direct shear stress. Considering a wire with circular cross section of diameter D (= 2r), the last equation may be reduced to

$$\tau_{max} = \frac{8FD}{\pi D^3} + \frac{4F}{\pi D^2} = K\frac{8FD}{\pi D^3}$$

Where “D” is the mean coil diameter, “K” is the Wahl factor, “C” is the spring index defined by

$$K = 1 + \frac{0.5}{C},\ c = \frac{D}{d}$$

When the external load, “F”, is variable, the induced stress is variable as well. The mean stress τ_m and the amplitude τ are defined by

$$\tau_m = K_s\frac{8F_mD}{\pi D^3} \text{ and } \tau_a = K_b\frac{8F_aD}{\pi D^3}$$

Where K_s and K_b are correction factors due to curvature and F_m and F_a are the mean load and load amplitude, respectively.

II. LITERATURE SURVEY

A few papers where discussed about developing and validating procedures for predicting the fatigue stress analysis.

James M. Meagher et al. (1996) presented a theoretical model of the general stress state found in helical implantable leads in bending. The author theoretical model for predicting stress from bending agreed with the finite element model within the precision of convergence for the finite element analysis. The linear theory proposed includes the effect of coil pitch and allows for the general analysis of a coil made from two materials. If it is assumed that the core and tube are made from the same material, the proposed model can be directly compared with experimental work. [4]

M. T. Todinov (1999) gave for helical compression spring with a large coil radius to wire radius ratio, the most highly stressed region is at the outer surface of the helix rather than inside. The fatigue crack origin is located on the outer surface of the helix where the maximum amplitude of the principal tensile stress was calculated during cyclic loading; according to the author fatigue design should be based on the range of the maximum principal tensile stress. [5]

Kotaro Watanabe et al. (2001) presented a new type rectangular wire helical spring which is used as suspension springs for rally cars; the stress was checked by FEM analysis and theory on the twisting part. The function of the suspension springs for an automobile are to keep the control stability good and to improve riding comfort. The spring characteristic of the suspension helper spring in a body is clarified. Manufacturing equipment for this spring is proposed. [6]

B. Ravi kumar et al. (2003) analyzed the failure of a helical compression spring employed in coke oven batteries surface corrosion product was analyzed by X-ray diffraction (XRD) and scanning electron microscope - energy dispersive spectroscopy (SEM–EDS). Sulphur and chlorine bearing compounds were detected and indicating fatigue as the mode of fracture and surface pits. The conclusion of this work that the most probable cause of failure of the helical compression springs was corrosion fatigue accentuated by loss of surface residual compressive stress. [7]

Dammak Fakhreddine et al. (2005) presented an efficient two nodes finite element with six degrees of freedom per node, capable to model the total behavior of a helical spring. The shear deformation effects, is based on the assumed forces and resultant forces approximation verifies exactly the resultant equilibrium equations. This element permits to get the distribution of different stresses along the spring and through the wire surface by only one element the finite spring element with two nodes is given, it is a single element that permits to avoid the classical modeling time for resolving problems.[8]

L. Del Llano-Vizcaya et al. (2006) used a critical plane approach, Fatemi–Socie and Wang–Brown, and the Coffin–Manson method based on shear deformation. The stress analysis was carried out in the finite element code ANSYS, and the multi axial fatigue study was performed using the fatigue software n Code. A failure analysis was conducted in order to determine the fatigue crack initiation point and a comparison of that location with the most damaged zone predicted by the numerical analysis is made. The Fatemi–Socie critical plane approach gives a good prediction of fatigue life. While the Wang–Brown criterion over estimates spring fatigue life, the Coffin–Mason model gives conservative results, and fatigue tests were carried out on helical compression springs made of AISI MB steel in order to determine the S–N curve at fixed mean stress and the M method to estimate strain-life properties from the monotonic uniaxial tension test, gives better predictions of the spring fatigue lives than the MM method. [9]

C. Berger, B. Kaiser (2006) presented the first results of very high cycle fatigue tests on helical compression springs which respond to external compressive forces with torsional stresses. The springs tested were manufactured of Si–Cr –alloyed valve spring wire with a wire diameter between 2 and 5 mm, shot-peened, the fatigue limits evaluated in fatigue tests on these springs upto10^7cycles substantial decreases in fatigue strength and the fatigue tests are continued upto108 cycles or even more. The aim should be to elaborate results about and insights concerning the level of the fatigue range in the stress cycle regime upto10^9 cycles, about the mechanisms causing failures and about possible remedies or measures of improvement. [10]

Chang-Hsuan Chiu et al. (2007) presented four different types of helical composite springs were made of structures including unidirectional laminates (AU), rubber core unidirectional laminates(UR), unidirectional laminates with a braided outer layer(BU), and rubber core unidirectional laminates with a braided outer layer (BUR), respectively. It aims to investigate the effects of rubber core and braided outer layer on the mechanical properties of the aforementioned four helical springs. According to the experimental results, the helical composite spring with a rubber core can increase its failure load in compression by about12%; while the spring with a braided outer layer can not only increase its failure load in compression by about18%, but also improve the spring constant by approximately16%. Helical composite springs have significant advantages over the traditional helical metals springs as discussed in this paper. Therefore, author wants to say that the shock absorbers with high performance might be expected to come soon. [11]

L. Del Llano-Vizcaya et al. (2007) discussed that unfavorable residual stresses is partially eliminated by the heat treatment, which reduces considerably the spring strength and service life. An experimental investigation has been conducted to assess the stress relief influence on helical spring fatigue properties. First, S–N curves were determined for springs treated under different conditions (times and temperatures) on a testing machine specially designed to do this task. Next the stress relief effect on spring relaxation induced by cyclic loading was evaluated. Finally, residual stresses were measured on the inner and outer coil surfaces to analyze the effect of heat treatment. The results of this work will help in the spring design and manufacture methodologies. [12]

N. Benghanem et al. (2007), according to the authors, they will limit only to the cases of the simple and twin helical spring filaments. The theoretical study of the behavior of these filaments needs the knowledge of internal efforts distribution, deformations modes, and their evolutions. In this paper, they have developed an analytical method and used a numerical finite element model. The analytical method is only valid in the case of a vertical position. For the twin helical spring filaments, analytical calculations showed certain dependence with respect to the angles of inclination of the whorls. Indeed, for small angles, the filament is inflected primarily. While for raised angles, torsion tends to prevail on the inflection. The horizontal position proves to be most disadvantageous for this filament, because torsion and bending moments evolves proportionally. Lastly, they noted that the effects of the variation in the temperature, for linear elastic behavior, remain negligible with respect to those due to the self-weight. [13]

C. Berger et al. (2011) presented a long-term fatigue tests up to a number of 10^9 cycles on shot peened helical compression springs with two basic dimensions, made of three different spring materials. The test springs were manufacture do foil hardened and tempered of SiCr-and SiCrV-alloyed valve spring steel wires and of a stain less steel wire with diameters of 1.6mm and 3.0 mm with shot peened. It becomes obvious that the various spring types in test exhibit different fatigue properties and different failure mechanisms in the VHCF regime while the SN-curves for springs made of SiCr or SiCrV-alloyed spring steel wires are similar, the SN-curves for springs made of 1.4568stainless steel spring wires show a much steeper slope.[14]

Mehdi Bakhshesh et al. (2012) used helical spring is the most common used in car suspension system, steel helical spring related to light vehicle suspension system under the effect of a uniform loading has been studied and finite element analysis has been compared with analytical solution and steel spring has been replaced by three different composite helical springs including E-glass/Epoxy, Carbon/Epoxy and Kevlar/Epoxy The most safety factor is related to case that fiber position has been considered to be perpendicular to loading and it is for Carbon/Epoxy composite helical spring.[15]

Brita pytel et al. (2012) presented helical compression springs which are used generally in fuel injection system of diesel engines, where it undergoes cyclic loading for more than 10^8 numbers so cycles and along the length of the spring at inner side. Finite element analyses were carried out, using ABAQUS 6.10. The simulation results show an oscillatory behavior of stresses along the length at inner side. Shear stresses along the length of the spring were found to be asymmetrical and with local maxims at starting of each middle coil. The FEA needs to be modified further for cyclic analysis and failure analysis to be used with ABAQUS. [16]

P. S. valsange (2012) performed is a fundamental stress distribution, characteristic of helical coil springs. Thus the springs are to be designed for higher stresses with small dimensions. This requires critical design of coil springs. This leads to critical material and manufacturing processes In the F.E.A. model of corrosion the linear triangular element is used and for part model of imperfection the linear quadrilateral element is used. [17]

C. Berger et al. (2013) presented a long-term fatigue tests on shot peened helical compression springs were conducted by means of a special spring fatigue testing machine at 40 Hz. Test springs were made of three different spring materials-oil hardened and tempered SiCr-and SiCrV-alloyed valve spring steel and stainless steel up to 500 spring with a wire diameter of d = 3.0 mm or 900 spring with d = 1.6 mm were tested at different stress levels. The paper includes a comparison of the result of the different spring sizes, materials, number of cycles and shot peening conditions and outlines further investigations in the VHCF-region. The size effect would imply higher fatigue strength for smaller wire diameters. For both investigated wire diameters the influence of the material state and probably the residual stress state seems to be very important. Further very high cycle fatigue tests will be conducted on springs to investigate the influence of end coil geometry, heat treatment and the shot peening procedure on fatigue strength. [18]

III. Discussion & Conclusion

The above literature review presents that the helical compression springs becomes quite necessary to do the complete stress analysis of the spring. These springs undergo the fluctuating loading over the service life. In addition, FEM software has been use for performing meshing simulation. Almost in all of the above cases, fatigue stress, shear stress calculation play more significant role in the design of helical compression springs. This study shows that shear stress and deflection equation is used for calculating the number of active turns and mean diameter in helical compression springs. Compression of the theoretical obtained result by the shear stress equation to the Finite Element Analysis result of helical compression springs is the mode of our present work, by this analysis it will possible in future to provide help to designers for design of spring against fatigue condition.

References

[1] B. bhandari. Design of machine elements. Published by Tata McGraw Hill education private limited, 7 west Patel Nagar, New Delhi 110008
[2] Shigley J. Mechanical engineering design. New York: McGraw-Hill; 1981.
[3] Carlson H. Spring designer’s handbook. New York: Marcel Dekker Inc.; 1978.
[4] James M. Meagher and Peter Altman. Stresses from flexure in composite helical implantable leads S 1350-4533(96)00022-7.
[5] M. T. Todinov. Maximum principal tensile stress and fatigue crack origin for compression springs. International Journal of Mechanical Sciences 41 (1999) 357—370
[6] Kotaro Watanabe, Masashi Tamura, Ken Yamaya, Takahiko Kunoh. Development of a new-type suspension spring for rally cars. Journal of materials processing technology 111 (2001) 132-134
[7] B. Ravi Kumar, Swapan K. Das, D. K. Bhattacharya. Fatigue failure of helical compression spring in coke oven batteries. Engineering Failure Analysis 10 (2003) 291–296
[8] Dammak Fakhreddine, Taktak Mohamed, Abid Said, Dhieb Abderazek, Haddar Mohamed. Finite element method for the stress analysis of isotropic cylindrical helical spring. Journal of mechanics A/solids 24 (2005) 1068-1078
[9] L. Del Llano-Vizcaya, C. Rubio-Gonzalez, G. Mesmacque, T. Cervantes-Hernandez. Multi axial fatigue and failure analysis of helical compression springs. Engineering failure analysis 13 (2006) 1303-1313
[10] C. Berger, B. Kaiser. Results of very high cycle fatigue tests on helical compression springs. International journal of fatigue 28 (2006) 1658-1663
[11] Chang-Hsuan Chiu, Chung-Li Hwan, Han-Shuin Tsai, Wei-Ping Lee. An experimental investigation in to the

mechanical behaviors of helical composite springs. Composite Structures 77 (2007) 331–340
[12] L. Del Llano-Vizcaya, C. Rubio-Gonzalez, G. Mesmacque. Stress relief effect on fatigue and relaxation of compression springs. Material and design 28 (2007) 1130-1134
[13] N. Benghanem, S. Kaoua, A. Becheur, M. Azzaz. Modification of thermo elastic linear behavior of tungsten filaments in simple and twin helical spring configurations. International Journal of Solids and Structures 44 (2007) 8159–8176
[14] B. Kaiser, B. Pytel, C. Berger. VHCF-behavior of helical compression springs made of different materials. International journal of fatigue 33 (2011) 23-32.
[15] Mehdi Bakhshesh and Majid Bakhshesh. Optimization of Steel Helical Spring by Composite Spring. International journal of multi-disciplinary science and engineering, vol.3, No.6, June 2012.
[16] Brita Pytel, K K Ray, Isabel Brunner, Abhishek Tiwari, S. A. Kaoua. Investigation of probable failure position in helical compression springs used in fuel injection system of diesel engines. IOSR Journal of Mechanical and Civil Engineering (IOSRJMCE) ISSN:2278-1684 Volume 2, Issue 3(Sep-Oct.2012), PP24-29
[17] P. S. Valsange. Design of Helical Coil Compression Spring. International Journal of Engineering Research and Applications ISSN: 2248-9622 Vol. 2, Issue 6, November-December 2012, pp. 513-522
[18] B. Pytel, I. Brunner, B. Kaiser, C. Berger, M. Mahendran. Fatigue behavior of helical compression springs at a very high number of cycles–Investigation of various influences. International Journal of Fatigue (2013), S0142-1123 (13) 00017- 0, JIJF 3037.