Comparative deflection analysis of conical compression spring with standard constant rate helical spring

Akanksha Mishra1*, M.L. Aggarwal2

1* M.Tech. student, Department of Mechanical Engineering, JCBUSTYMCA, Faridabad-121006, Haryana, India
Email: mishra16.ak@gmail.com
2Department of Mechanical Engineering, JCBUSTYMCA, Faridabad-121006, Haryana, India
Email: aggarwalmlal@rediffmail.com

Abstract: Springs, indisputably find vast applications in different types of mechanical systems. Springs are utilized everywhere, right from simple playing toys to automobiles and dies. Stiffness is one of the most prominent factors for a spring. While the constant rate helical springs exhibit a linear behaviour, the conical springs display non-linear characteristics. The reason considered behind an increment in stiffness with an increase in deflection in case of conical springs is that the resistance offered by the small-diameter portion is more and hence, it deflects later compared to the larger diameter portion. In this paper, conical springs are studied experimentally under variable test conditions and an effort is made in the direction of further inducing the variable stiffness to a higher extent in the conical spring as compared to presently used constant rate springs for various special-purpose applications.

Keywords: Conical springs, stiffness, characteristic curve, non-linearity, comparative analysis.

Introduction

Springs perform a very pivotal role in our day to day life. From heavy industries to a simple pen, springs are highly prevalent. The characteristic curve is defined as the relationship between load applied externally to the spring under observation and the deformation exhibited by the spring in response. The characteristic curve of helical spring is linear whereas that of the conical spring is non-linear. This difference in the behaviour displayed by the characteristic curve of conical springs makes it suitable for being applied for special purpose.

Standard constant rate helical springs are commonly used springs for most of the applications but in some cases, there is a requirement of springs with non-linear character, that is, conical springs. The non-linearity gives an added advantage to the conical springs including increased resistance against buckling under load application. There is a need to study the properties of conical springs in depth for various special emerging applications, where, comfort and load sustainability are of utmost importance.

The available literature on the variable stiffness springs is very limited and are mostly concentrated in the automobile applications.
L.J.A. Den Boer (2009) presented a thesis in which he modelled a system with 2 degrees of freedom to study the behaviour of conical springs. His study was focussed on a system of telescopic conical springs having constant pitch and carrying a top mass. The model was applied for a dynamic numerical analysis of the system and the results and graphs obtained theoretically and experimentally were presented in the thesis.

Paredes and Rodriguez (2009) proposed the approach for the optimization of the design of the conical springs to provide the ease of synthesis to the design engineers.

Azadi et. al (2011) proposed a new design for variable stiffness spring that was simpler and easier in terms of design and application compared to available designs. The proposed design was a simple prestressed mechanism of cables that was being used to control stiffness. The configuration of variable stiffness spring was decided after an in-depth study of the design in terms of its stability and kinematics.

Anubi et. al (2013) presented a paper on design and experimental analysis on a suspension system with variable stiffness. The research through numerical analysis, experiment on energy dissipation concept and simulation concluded that variable stiffness improves the performance of the suspension system.

Sui et. al (2014) proposed an idea about designing of variable stiffness micro springs with MEMS technology and through the simulation result concluded that variable stiffness springs, when used in fuse devices can effectively result in improved reliability and safety.

Liu et. al (2015) proposed the design of two types of variable stiffness micro springs, using the concept of contact pair of different sizes, one being stiffness increase spring and other stiffness convexity spring. ANSYS was used for characteristic analysis of the proposed design. Simulation result was used to make changes in the structure.

Jugulkar et. al (2016) developed a variable stiffness shock absorber consisting of springs combination and fluid damper. The numerical analysis and simulation using MATLAB and SIMULINK is used to make the design more effective.

Ibrahim et. al (2017) developed a variable stiffness damping device consisting of a combination of springs and magneto-rheological damper, which could display a variation in stiffness in the presence of variable magnetic field. The variations in response and the equivalent stiffness was analysed. Accuracy of the system as obtained through analysis was 6.2%.

Li et. al (2017) presented a paper regarding a variable stiffness spring produced by metal forming and heat treatment process using a wire made from an alloy of Fe, Ga and Al in a specific proportion. Processing was followed by strengthening of soft magnetic properties and tuning of the spring displayed a considerable variation in the spring stiffness.

Pop et. al (2017) researched the properties and behaviour of a helical spring having a changing cross-section of spring wire with the application of theoretical and numerical approaches that resulted in providing a non-linear feature to the spring.

Bogrash and Philip (2018) patented an invention related to the development of springs in form of hollow tubing with flexible cross-section areas that extends or contracts with pressure variation and hence, can change the stiffness of the spring, through slight adjustments.
This research paper deals with an in-depth study of the nonlinear behaviour of conical springs and also aims to check the variations caused by varying the extent of non-linearity through changes in the testing conditions.

**Experimental setup**

![Spring Load Stiffness Tester](image)

**Fig 1: Spring Load Stiffness Tester**

The experimental setup shown in the figure is used for testing the stiffness of spring samples. The spring sample to be tested is fixed between the two anvils, the lower one being fixed and the upper one movable. The upper anvil is moved to adjust the sample using the handwheel. The lower anvil is connected to the load cell.

When the spring is compressed, the load is applied to the load cell which induces a strain that is converted into an electric signal displayed through a digital display unit in form of load in the units of kgf. The displacement can be checked from the scale on the frame. The ratio of load to the deflection gives stiffness.

In the present work, conical springs were checked for its stiffness. Also, springs are heat-treated to analyse the variations caused to the stiffness. The 2 samples were heat treated in the muffle furnace and their
hardness were increased from HRC 32 to HRC 48. The results were tabulated and graphs were plotted for comparison and analysis.

![Image of springs](image1.png)

Fig 2: (a): Conical springs (b) Standard rate helical springs

Spring Material and parameters:

**Helical Spring:** Material - ASTM A229, C 0.6-0.7% C, Mn 0.7-0.8%, cold drawn steel wire, wire diameter – 3 mm, mean coil diameter – 30 mm, length – 10 cm, Number of turns – 8.

**Conical Springs:** Material – ASTM A229, C 0.6-0.7% C, Mn 0.7-0.8%, cold drawn steel wire, wire diameter – 3 mm, smaller end diameter – 2.2 cm, large end diameter – 4 cm.

- **Sample 1:**
  Length – 15 cm, number of turns - 11
- **Sample 2:**
  Length – 12.5 cm, number of turns –10
- **Sample 3:**
  Length – 10 cm, number of turns – 8

Results and Discussion

In this section, the conical springs were tested in spring load tester and the results were compared with the results of the standard constant rate helical springs. Deflection and stiffness were analysed for various spring samples, at varying loading conditions as follows:
The graph proves the non-linearity of the conical spring that makes it more deflected to adjust according to the varying load conditions as compared to the standard constant rate helical springs. This is because larger diameter coil of conical springs is deflected first.
In sample 2, with load application, stiffness first increases and then decreases, whereas, in helical spring, stiffness rate remains constant. The graph proves the non-linearity of the conical spring that makes it more deflected to adjust according to the varying load conditions compared to the standard constant rate helical springs.

![Image of Load Vs Deflection graph]

**Fig 5: Comparison between conical and constant rate helical spring and non-heat-treated spring sample 3**

In Sample 3, the graph proves the non-linearity of the conical spring that makes it more deflected in parabolic pattern to adjust according to the varying load conditions compared to the standard constant rate helical springs.

To increase stiffness of conical springs, spring samples were heat-treated from HRC 32 to HRC 48. The results were analysed for Sample 2 (Figure 6). When it was heat-treated from HRC 32 to HRC 48, sample 2 exhibited an increasing trend in load carrying capacity and stiffness.
**Conclusions**

Conical springs offer non-linear variation in stiffness in individual and in combinational applications. This behaviour is extremely beneficial for usage in places where comfort and elimination of sudden jerks and/or buckling are the most important factors. It is established that conical springs are better in following aspects:

- Deflection in conical spring is more as compared to standard constant rate helical spring at varying load.
- Load requirement in conical spring is lesser for producing same deflection as in case of standard constant rate helical spring. Therefore, the conical spring is more comfortable.
- Stiffness of conical spring is variable due to non-linearity while it is constant in case of standard constant rate helical spring.
- Heat treatment followed by air cooling or furnace cooling improves the variable stiffness of the conical springs. This provided more comfort as well as higher stiffness, thereby, increasing its utility in products.
References

1. A. Agrawal, “Response of semi-active variable stiffness and damping systems to pulse-type excitations: Analytical and experimental study”, 2004.
2. D. Pop, S. Haragâş and D. Popa, “Helical Spring with Variable Wire Diameter”. Romanian Journal of Technical Sciences - Applied Mechanics, 62(3), pp.1-14, 2017.
3. G.H. Liu, L. Sui, G.C. Shi and X.H. Guo, “Micro-Spring’s Variable Stiffness Design and Characteristics Analysis”, In Key Engineering Materials, 645, pp. 830-835. Trans Tech Publications, 2015.
4. J. Wang and G. Meng, “Magnetorheological fluid devices: principles, characteristics and applications in mechanical engineering”, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 215(3), pp.165-174, 2001.
5. L. Sui, Z. Wang, G.C. Shi, and G.Z. Li, “MEMS variable stiffness spring and its application in fuze”, Sensors & Transducers, 168(4), pp.101-107, 2014.
6. L.J.A. Den Boer, “Nonlinear dynamic behaviour of a conical spring with top mass” (Doctoral dissertation, Master Dissertation, Eindhoven University of Technology, Eindhoven, Netherlands), 2009.
7. L.M. Jugulkar, S. Singh and S.M. Sawant, “Analysis of suspension with variable stiffness and variable damping force for automotive applications”, Advances in Mechanical Engineering, 8(5), pp.1-19, 2016.
8. M. Azadi, S. Behzadipour and G. Faulkner, “Performance analysis of a semi-active mount made by a new variable stiffness spring”, Journal of Sound and Vibration, 330(12), pp.2733-2746, 2011.
9. M. Azadi, S. Behzadipour and S. Guest, “A new variable stiffness spring using a prestressed mechanism”, In ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection, pp. 301-307, March 2011.
10. M. Li, J. Li, X. Bao, Y. Liu, J. Wang, Y. Zhao and X. Gao, “Variable stiffness Fe82Ga13. 5Al4. 5 spring based on magnetoelastic effect”, Applied Physics Letters, 110(14), p.142405-1-4, 2017.
11. M. Paredes and E. Rodriguez, “Optimal design of conical springs”, Engineering with computers, 25(2), pp.147, 2009.
12. M.F. Ibrahim, K.H. Siang, L.K. Quen and S.C. Loon, “Experimental Analysis on Variable Stiffness And Variable Damping Device”, 2nd Multidisciplinary Conference on Mechanical Engineering, pp. 269-277, 2017.
13. O.M. Anubi, D.R. Patel and C.D. Crane III, “A new variable stiffness suspension system: passive case”, Mechanical Sciences, 4(1), pp.139-151, 2013.
14. P. Bogrash, “Springs with Dynamically Variable Stiffness and Actuation Capability”, U.S. Patent Application 15/773,716, 2018.
15. P. Tan, F. Zhou and W. Yan. “A semi-active variable stiffness and damping system for vibration control of civil engineering structures”, In 2004 ANCEER Annual Meeting, 2010.
16. V.M. Faires, “Design of machine elements”, No. TJ230, F3, 1965.
17. X.Z. Zhang, X.Y Wang, W.H. Li and K. Kostidis, “Variable stiffness and damping MR isolator”, In Journal of Physics: Conference Series, 149(1), pp.012088. IOP Publishing, 2009.
18. Y. Liu, H. Matsuhisa and H. Utsuno, “Semi-active vibration isolation system with variable stiffness and damping control”, Journal of sound and vibration, 313(1-2), pp.16-28, 2008.
19. Y. Xu, M. Ahmadian and R. Sun, “Improving vehicle lateral stability based on variable stiffness and damping suspension system via MR damper”, IEEE Transactions on Vehicular Technology, 63(3), pp.1071-1078, 2013.
20. Y. Zhou, X. Wang, X. Zhang and W. Li, “Variable stiffness and damping magnetorheological isolator”, Frontiers of Mechanical Engineering in China, 4(3), pp.310-315, 2009.