Spring Design, Analysis, and Applications

An Online Continuing Education Course for Engineers

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Spring Design, Analysis, and Applications

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1. Objectives

- Familiarity with different types of Springs for different applications
- Spring Design Steps and Procedures
- Common Spring Nomenclatures for Design Calculations
- Spring Classifications and Spring Design Considerations
- Helical Compression and Tension Springs, Torsion Springs
- Volute, Beam, and Spiral Springs
- Belleville, Power, and Helical Torsion Springs
- Spring Material and Heat Treatment Process
- Selection of Spring Material
- Strength and Fatigue Analysis of Springs
- Design and Reliability Analysis for Helical Springs

2. Introduction

Mechanical springs are basically energy absorbers. Springs are used in between two parts to provide a flexible joint. Springs are similar to capacitors in electrical connections. There are various functions performed by springs, and they are as follows:

- Store kinetic energy in the form of potential energy and convert potential energy to kinetic energy when force or torque is removed from the spring. It works just like a pendulum. During the application of force, springs store energy as potential energy and release the energy when disturbing forces are removed from the spring.
- To absorb or control energy due to continuous shock or impact loading, vibrations, and vibratory motions. During load applications, the spring moves till equilibrium is reached.
- To restrict or control motion, linear or rotary motions, between two mechanical parts connected by the spring.
- Springs could also be considered as dampers to resist shock loading, i.e., dampen the effect of vibratory motion or forces.

Springs have been in use for a very long time, and it is not known when the idea was invented. It has been recorded that the spring concept was used in bow and arrow applications. The spring follows Hooke's Law, i.e., "deflection is proportional to load. " Spring deflection is proportional load, linear or torque, applied on it.

The contents have been put together to focus on two aspects: Various types of spring design principles and applications that can be applied for machine tool industries and automobile applications. The chapter will contain force analysis, durability analysis, and noise reduction for gear applications and will also contain the methods to design gears and gearboxes for durability analysis techniques. The spring nomenclatures and manufacturing will be covered in brief since designers are not required to know those, as spring manufacturers will help the designers select suitable types of spring specific to any application. Spring design and manufacturing have gone through various technology improvements over many years, and the types of springs used in several applications have been reduced to a few common types.

The simple shortcut formulas for designing various types of springs will be demonstrated in this course. The course will demonstrate the methods and processes that the author used to design springs for machine tool applications and automobile applications. For various applications, durability and strength horsepower of helical gear sets, noise reduction, etc, are very pertinent requirements that designers have to satisfy.

The contents should help the designers to a great extent in applying the design principles for the spring design. In general, the design engineers need to know the design approach and design process for springs for machine tools and automobile applications where durability, cost, and vibration reduction are very important design considerations. Applications, examples, and design discussions will be limited to the most commonly used springs that are mostly used in machine tools and automobile applications. Once the requirements are known, the engineer has to decide the type or configuration of the spring suitable for the application. The primary considerations are space, force, deflection, stress, reliability, and cost of the spring. Compression springs have large deflection capability under an applied force and for small deflection under a large force, Belleville springs are used. Volute springs are used to resist shock loadings because it has high damping capacity and resistance to buckling loads. Volute springs are very costly to manufacture. Leaf springs are used for heavy truck applications. Helical torsion and spiral springs are used for resisting torque and twist applications such as door rotation. Spiral hairsprings are used for watches and instruments where forces are very light and space requirements are also very small.

Brush springs are used for holding brushes in electric motors. Power springs are used for clock applications where it stores and releases energy as and when required. Prestressed power springs are used for automobile applications such as seat belts. The extension springs provide resistance against pull forces. There are springs, called Level Torque, which provide constant torque. Retaining rings, spring washers, garter springs, and circlips are also special type special types of springs. Constant force springs are similar to constant torque springs for pull force applications. For machine tool applications, S rings are used to store kinetic energy in terms of potential energy and release this energy when in terms of kinetic energy whenever required. Belleville springs are used almost always for drawbar applications in milling machines. Garter springs are used for oil seals. Spring energy storage capacity is proportional to the square of the spring stress level, divided by the young's modulus for the spring material. The spring selection process consists of a few steps, as shown in Fig. 1 below:

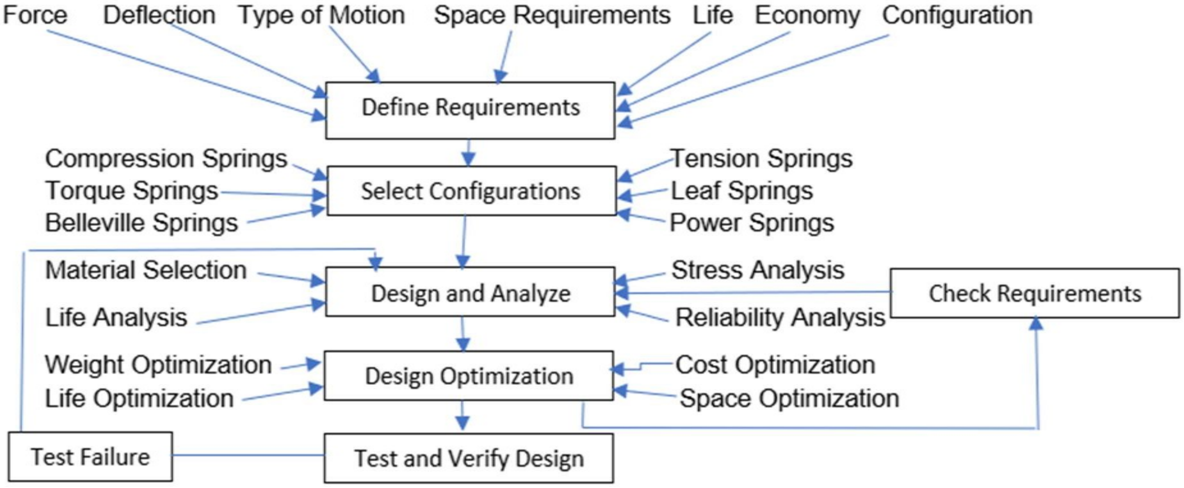


Fig. 1: Spring Design Process Flow Diagram

In any spring application, the first task is to understand the requirements for the spring. Once that is determined, the next task is to select spring configurations suitable for the application. The primary requirements are life, reliability, space requirements, and cost requirements. The process flow diagram is shown in Fig. 1. The Next task is to design, analyze, and optimize the spring design. Once these tasks are completed, verification requirements and test plans also must be completed. For most of the applications, spring stiffness and specific energy absorbed during deflection should be calculated. The frequency and vibration analysis of the system requires the spring rate. In most engineering applications, spring weight is not a significant factor in the design, but spring location, spring rate, spring life, etc., are mostly the determining factors.

In most applications, spring selection depends on the manufacturers who have standard spring configurations for various applications. Spring manufacturers can help designers in the selection process and recommend springs for very cost-effective applications. Recommendations from manufacturers can also save time and cost of engineering during the selection process. Nevertheless, analysis, testing, and verifications are required for critical applications to avoid premature failures and unsafe conditions. For large deflection, helical compression springs are used. Volute springs can provide very high damping between moving parts. Volute springs are very costly to produce. Beam springs are also used for many mechanical applications for machine tools and automobiles.

For twist and torque applications, such as door applications, helical torsion springs are used. Power springs are used for watches to absorb and release energy, creating an oscillatory motion. The energy storage capacity (En) is defined as the total work done on the spring during loading per unit volume of the spring material used. This spring property, energy storage capacity, is proportional to the square of the maximum operating stress level (σ) divided by the shear modulus (G) for the spring material. For example, for round wire helical springs under compressive or tensile force, $En = Constant * (\sigma^2)/G =$

$0.25^* \sigma^2/12e6$. For helical round wire torsion springs, $En = 0.125^* \sigma^2/30e6$. For Belleville springs, $En = 0.10^* \sigma^2/10^*E = 0.10^* \sigma^2/30e6$. In a nutshell, the higher the volume of the spring material, storage capacity is lower, and when the stress level in spring is very high, energy capacity gets higher.

The cost and quality of any spring are always very important selection criteria. Both of these factors are dictated by design methodology, design and selection process. It is always advisable to use stock springs from the manufacturers. Special springs are always very costly, and manufacturers must be contacted before the selection is finalized. Number of springs is also a determining factor for the cost of springs. Material selection and heat treatment processes applied are very important factors for the life of the springs. Spring quality control details can be found in MIL-STD-105.

In this chapter, we will learn about the following aspects of spring design applications:

- Spring Functions, Nomenclatures, and Configurations
- Spring Material and Heat Treatment Process
- Properties and Strength of Spring Materials
- Spring Design and Selection Principles
- Stress, Fatigue, and Reliability of Springs

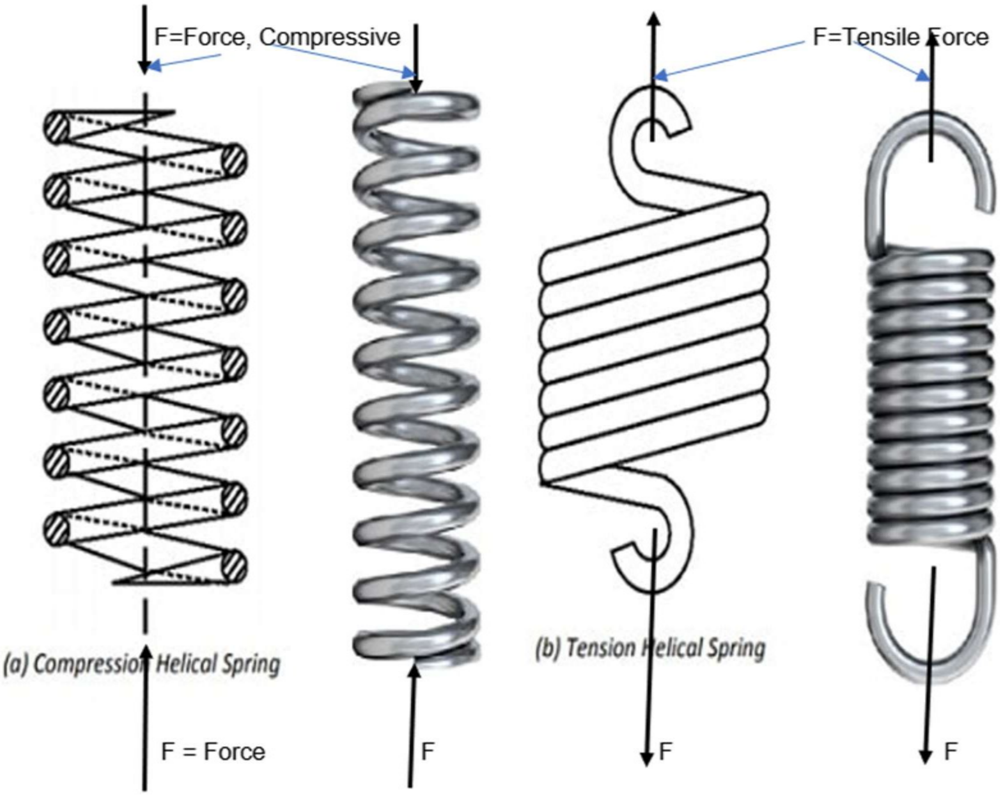
Spring Terminologies

- Active Coils: It is less than the total number of coils. These coils are assumed to deflect under load.
- Buckling: Under severe loading and without guidance, compression springs could move laterally or sideways.
- Closed and Ground Ends: The first and last coils are ground flat for better spring support. The ground coils are flat and square to the spring axis.
- Deflection: The movement of spring under external load: Force or Torque
- Elastic Limit: Maximum stress of material to avoid permanent set
- Endurance Limit: Maximum strength of any material under which a spring will not fail or is expected to have infinite life.
- Free Length: Length of any spring without any external load.
- Helical Springs: Compression, Extension, or torsion springs.
- Mean Diameter: The outside diameter of a helical spring minus the wire diameter.
- Natural Frequency: Natural Vibration of spring due to material and weight of the spring.
- Patenting: Heat treatment of springs to have a pearlitic microstructure of the material.
- Pitch: Distance between centers of adjacent coils of an open wound spring.
- Plain Ends: Ends of spring when it is not squared and ground.
- Permanent Set: Permanent change of free length of the spring due to overloading or over-stressing beyond the elastic limit of the material
- Residual Stress: Material Stress remaining in the material due to the heat treatment process or winding and forming process

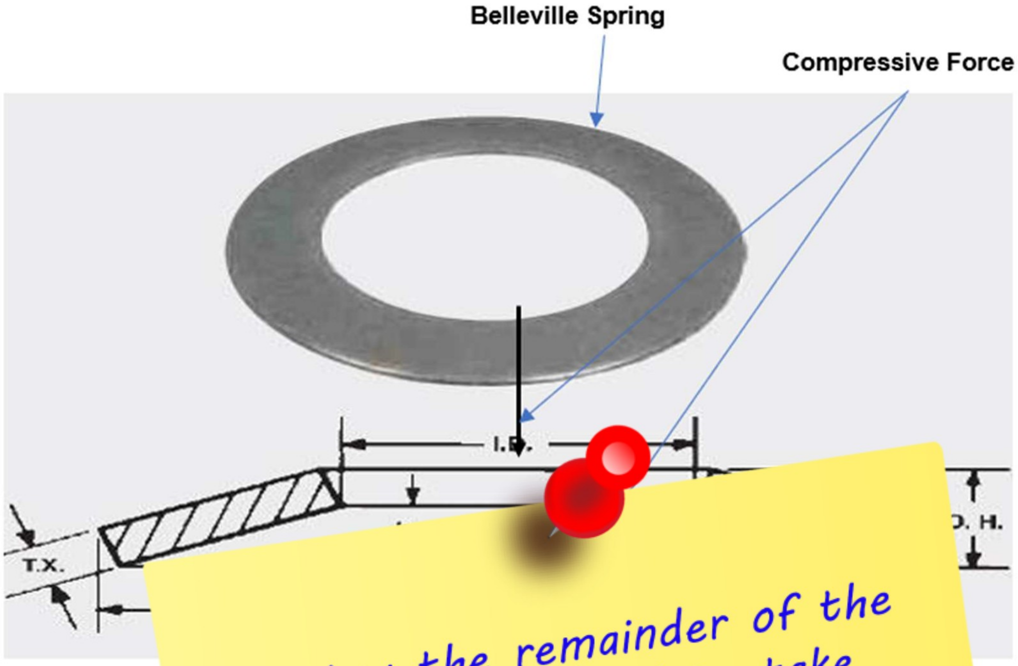
- Spring Rate: Load per unit deflection of the spring.
- Shot Peening: Blasting the spring with steel pallets to induce compressive stress in the material to enhance the fatigue life of the spring.
- Slenderness Ratio: length of spring divided by the outside diameter of spring (L/D)
- Solid height: Length of the compression spring when adjacent coils touch each other under compressive loading.
- Spring Index: Mean diameter divided by the wire diameter.
- Stress relief: A process where the material is subjected to low temperature for a long time to remove residual stress.

3. Spring Configurations

Springs are classified according to the shape of the springs as shown in Fig. 2 B:



(Note: Spring Pictures are borrowed from websites of spring manufacturers and modified for Clarity and description)



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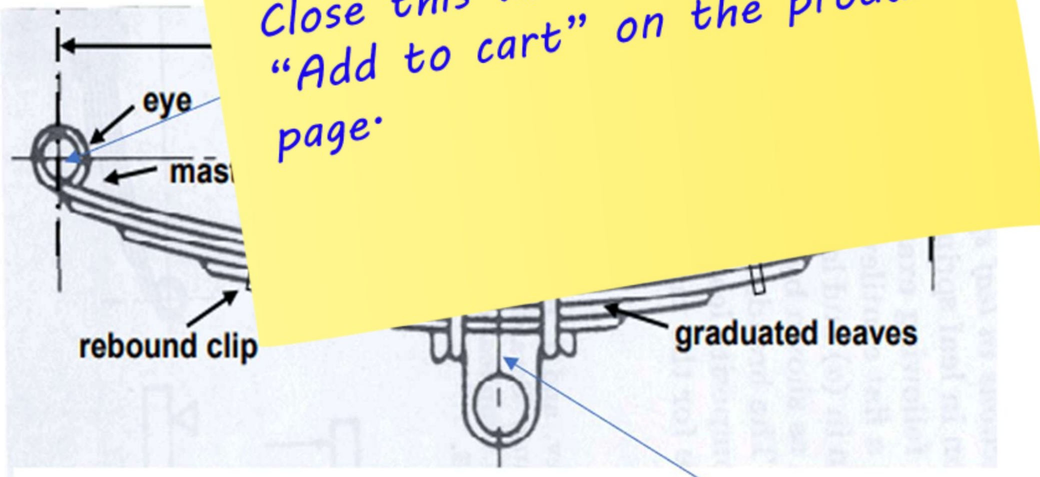

Laminated semi-elliptic spring

Fig 7.3.5

(Note: Spring Pictures are borrowed from websites of spring manufacturers and modified for Clarity and description)