GEORGE KURASZ
Technical Center
Associated Spring Corp.
Bristol, Conn.

FATIGUE FAILURE IN SPRINGS

Springs are usually squeezed into the smallest possible space, then stressed to the highest limit. As a result, fatigue failure takes a heavy toll. But fatigue can be avoided by properly balancing such parameters as available space, material, rate of load application, and operating environment.

SPRINGS, by their very nature, are prone to fatigue failure. They are flexed repeatedly, their cross sections are generally thin, and they are stressed to the highest possible limit. So, it's no wonder that the failure rate of springs in fatigue applications is far above normal.

Spring design for fatigue applications involves more than simply selecting the proper cross section and spring style to fit the available space and carry the required loads. It also requires choosing an efficient and economic material that satisfies the life requirements under given load, stress, and environmental conditions.

What's more, material costs can be critically important in fatigue applications. For example, environmental factors may dictate selection of stainless steel over carbon steel, while high quality material may be needed to improve fatigue resistance at critical stress levels.

Generally, the parameters that determine spring design in fatigue applications are:

- Available space and required loads and deflections.
- Method of stressing.
- Rate of load application.
- Operating environment.
- Minimum fatigue life at required reliability.

Space, Load, and Deflection

For a typical spring, load and deflection determine both the spring rate and the amount of energy that must be stored. While the different spring geometries are characterized by different volume efficiencies (see box *Basic Spring Designs*), insufficient room for even the most efficient spring results in excessively high stresses that usually lead to fatigue failure. Too little space (hole too short or not wide enough) limits the volume of material that can be put into a spring. And low material volume means the spring will be overstressed, a condition leading to premature fatigue failure.

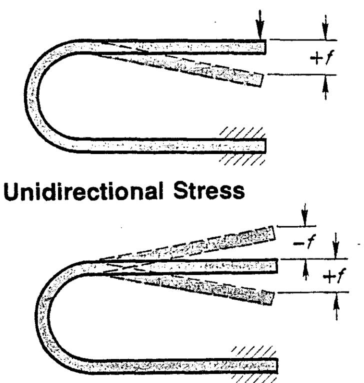
Method of Stressing

How the spring is stressed has a large effect on fatigue life. The four most common stress conditions are constant deflection, constant load, unidirectional stress, and reversed stress.

Under constant deflection, a spring is repeatedly cycled through a specified deflection range. The loads on the spring may cause some set or relaxation which in turn lowers the applied stress.

An automotive valve spring is a good example of a spring operating under constant deflection. The spring is manufactured to a certain free length, but when installed it is compressed to fit into the available space and create a specific preload. In operation, the spring cycles continually over a constant stroke length or deflection. In time, depending on material, stress, and temperature, the spring may relax and reduce the applied load. Usually, though, valve springs are designed to minimize relaxation and, thus, deliver loads within a specified range.

Under constant load (or stress) conditions, the load applied to the spring does not change during operation.



Reversed Stress

Fig. 1 — Comparison of unidirectional and reversed stressing. The stress and deflection ranges of reverse-loaded springs are twice those of springs loaded in only one direction. And even though the maximum applied stress may be the same in both cases, the spring loaded in one direction would be expected to exhibit a better fatigue life.

SPRINGS

Examples include the springs used as vibration mounts under a fixed dead weight. Under these conditions, the springs may also set (or creep), but the applied stress never changes. Consequently, this method of stressing may result in fatigue lives shorter than those found in constant deflection applications.

Unidirectional and reversed stressing are variations of the same load condition. The difference is that in one mode, stress is always applied in the same direction, while in the other, stress is applied first in one direction then in the opposite direction. While most springs are subjected to unidirectional loading, some applications require reversed loading. The two methods may produce vastly different fatigue lives.

For example, consider the two U-shaped springs shown in Fig. 1. One spring is subjected to a unidirectional load that stresses it over the deflection range from 0 to $+f$. The other spring is subjected to the same maximum load, but the load is constantly reversed and deflection ranges from $-f$ to $+f$. The stress and deflection range of the second spring is twice that of the first spring. And, even though the maximum applied stress is the same in both cases, the first spring would be expected to have a longer fatigue life.

Stress range is an important factor in comparing spring fatigue resistance. For two springs subjected to undirectional loading and the same maximum stress, the spring operating at the lower stress range generally lasts longer. However, the lower the stress range, the higher the mean stress, which may affect the degree of spring relaxation.

For example, consider the two stress patterns shown in Fig. 2. In one case, a spring is operating under unidirectional stress; that is, from a low tension load to a higher tension load. It is always under some stress, and the mean stress is a positive value. The other spring sees the same maximum stress, but the stress is reversed so mean stress is zero. Therefore, while the first spring may be subjected to a lower stress range, it also operates at a higher mean stress. In time, this higher mean stress may cause some relaxation.

Choice of material condition is also a factor in determining spring performance in fatigue applications. Once again, consider the U-shaped springs in Fig. 1. If the springs are made of hardened and tempered material, the metal is deformed plastically so that after springback the sides of the U are straight and parallel. This deformation

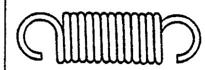
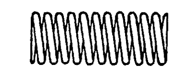
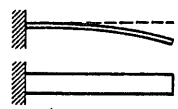
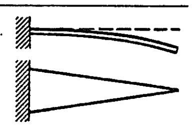
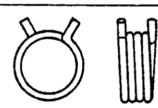
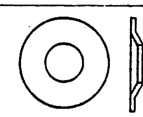
Basic Spring Designs

The fundamental relationship between stress, volume, and energy for round-wire compression or extension springs is: $W/V = S^2/4G$. The equation is uncorrected for various degrees of stress concentration, but it shows that stored energy is directly proportional both to volume and to stress.

The ratio W/V—also noted as U—is called the volume efficiency of the spring. The greater the work per unit volume, the higher the spring efficiency.

The table lists the basic volume efficiency equations for several spring designs. These equations can be used in initial design analysis to choose the most efficient spring for the application. For example, comparing Equations 3 and 5 shows the advantage of a triangular cantilever spring over a rectangular spring (the triangular design is three times more efficient). Also, Equation 1 reveals that round wire is more efficient than square wire in compression or extension springs.

Volume Efficiencies for Various Spring Designs

Type	Equation	Figure
1. Compression or extension spring, round wire	$S^2/4G$	
2. Compression or extension spring, square wire	$S^2/6.5G$	
3. Cantilever beam, rectangular plan	$S^2/18E$	
4. Simply supported beam	$S^2/18E$	
5. Cantilever beam, triangular plan	$S^2/6E$	
6. Torsion spring, rectangular wire	$S^2/6E$	
7. Torsion spring, round wire	$S^2/8E$	
8. Flat, spiral spring	$S^2/6E$	
9. Belleville spring washer	$S^2/10E$ to $S^2/40E$	

induces residual compressive stresses in the outside surface and residual tensile stresses in the inside surface. Under a unidirectional load, the residual stresses reduce applied stress and increase fatigue life. On the other hand, under reversed loading, the residual stresses increase applied stress during half the cycle. Apart from reducing fatigue life, the resultant stress may exceed the yield strength and change the opening dimension of the U.

This doesn't happen to springs made of annealed material, because heat treatment after forming eliminates residual stresses. Therefore, depending on the material and the degree of forming necessary to manufacture the spring, a stress relief treatment after forming could sufficiently lower residual stress so that maximum stress is below the elastic limit.

Another factor to consider is stress concentration. Each different style of spring has inherent stress concentrations. For example, in a round-wire helical compression spring, subjected to fatigue cycling, the stress concentration factor known as Wahl factor must be included in the calculation of maximum stress. The equation for Wahl factor is

$$K_W = \frac{4C - 1}{4C - 4} + \frac{0.615}{C}$$

where C = spring index, D/d; D = mean coil diameter, and d = wire diameter.

Rate of Load Application

In many applications, springs are subjected to reciprocating motions produced by cam or crank mechanisms that can operate at different speeds. At low speeds, the relationship between stress and time may be represented by the simple sinusoidal curve in Fig. 3*a*. However, the stress-time relationship for a spring subjected to rapid reciprocating motion may be much more complex, as in Fig. 3*b*.

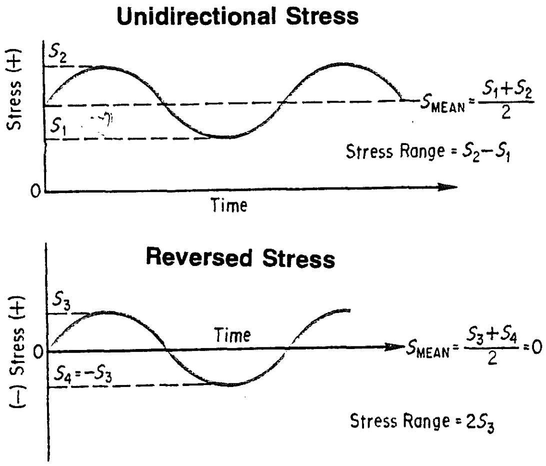


Fig. 2 — Mean stress effects. A spring under a unidirectional stress operates from a low tension load to a higher tension load. Mean stress is always some positive value. On the other hand, a spring under a reversed stress, operates from a tensile load to a compressive load. If the two loads are equal, then mean stress is zero. The spring operating at a mean stress greater than zero may be subject to stress relaxation.

At certain speeds, a resonance may be introduced between the frequency of the periodic motion of the spring end and one of the spring natural frequencies. In this case, the spring vibrates or surges because of the resonance, resulting in stress buildup that may cause premature fatigue failure. Fortunately, though, this type of stress amplification can be minimized in initial design by giving the spring a high natural frequency. In general, the lowest natural frequency of a compression spring fixed at both ends should be at least 13× the maximum cam shaft speed. The equation for this frequency is

$$n = (d/9D^2N)\sqrt{Gg/p}$$

A modification that may reduce surging is to change from uniform pitch (pitch = distance between coils) to variable pitch design. This modification may change the natural frequency characteristics and reduce the amplitude of vibration.

Another solution to surging is to use a stranded wire spring, formed by twisting together two or more wires and molding them into a conventional spring shape. When the spring is compressed, friction between the strands damps out damaging vibrations. If this type of spring is used, the ends must be brazed or welded to prevent uncoiling, and the helix of the spring should be in the opposite direction to the helix of the strands to ensure contact between wires.

A further complication can develop in extension springs operating in a horizontal plane. If the springs sag, transverse whipping may develop in addition to axial surging. Possible solutions to this problem are shown in Fig. 4. First, cone ends and swivel hooks eliminate resonance in some cases. Another refinement places a damper such as a leather strip or rubber dowel inside a spring with coned ends. The damper helps prevent sag, and the coned ends eliminate surging.

A typical design practice for valve springs operating at high speeds is to place a spiral spring made from a flat strip of spring steel inside the valve spring to act as a damper. In leaf springs, multileaf construction helps damp excessive vibration.

Operating Environment

The two environments that affect fatigue life most are temperature extremes and corrosive atmospheres. The effects of these environments should be evaluated early.

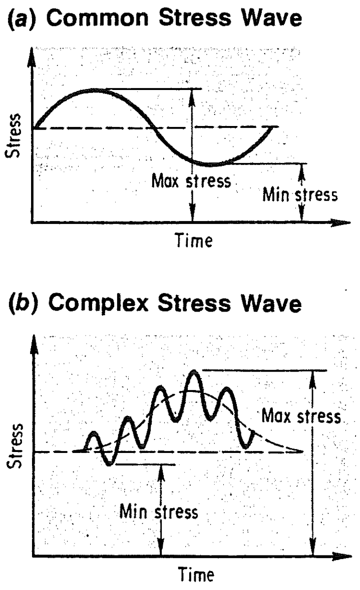


Fig. 3 — Load application rates. Springs frequently are actuated by cams or crank mechanisms that can operate at different speeds. At low speeds, the stress/time relationship may be a simple sinusoidal cirve, *a*. But higher speeds can introduce resonances that make the relationship more complex, *b*

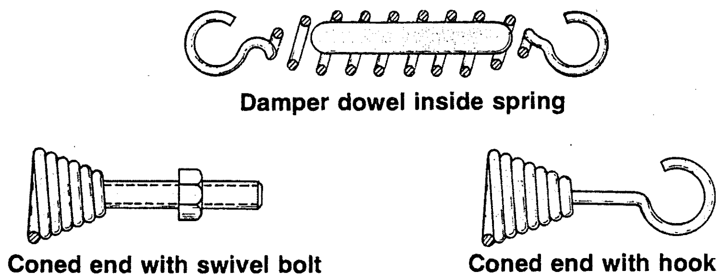


Fig. 4 — Spring dampers. Horizontal extension springs have a tendency to sag, causing surging and whipping. Here are some common ways to eliminate these effects.

Low temperatures, for the most part, have little effect on fatigue life. However, if the spring rate is critical and must be maintained within certain limits, the design must allow for the change in elastic modulus experienced by most materials. Exceptions to this rule are Incoloy 850 and Ni-Span C, which exhibit little change in modulus within the temperature range of −50 to +150 F.

High temperatures, on the other hand, affect spring materials two ways. They reduce the elastic modulus and lower yield strength. The reduction in elastic modulus causes a proportionate reduction in the spring rate. And the lower yield strength reduces the maximum stress that can be applied.

Of equal importance is material relaxation (or creep) which is material, stress, temperature, and time dependent. Relaxation and subsequent load loss under constant deflection often take place even at room temperature (if stress is high enough). Therefore, relaxation may be substantially higher at elevated temperatures, but fortunately, it can be minimized with special manufacturing techniques.

Relaxation at high temperatures may be rapid at first if the applied stress exceeds the lowered yield strength. Depending on material, temperature, and stress, the rate of relaxation may decrease as time progresses. In addition, the residual stresses in the spring may affect total relaxation. For example, a large degree of cold working increases relaxation.

Unidirectional fatigue tests at constant deflection reveal that springs apparently have higher fatigue lives at elevated temperatures. Actually, the springs set or relax during the test, resulting in lower operating stresses. But fatigue data on springs is limited because of the difficulty and expense of testing. Some evidence exists, however, to indicate that springs operating initially within a certain stress range may relax less than springs tested at a static load (temperature and time being constant).

Corrosion fatigue simply means that a spring fractures as a result of the material reaction with the environment. Moist air, water, salt, fuel gases, acids, and soils are typical corrosive agents.

Because springs generally are made of hard materials and operate at high stress levels, they are particularly susceptible to corrosion damage. Selection of a corrosion-resistant material or protective coating depends on many factors, including corroding medium, temperature, fatigue stresses, material strength, and coating cost.

The table lists some generally available spring coatings. While the surface protection of coatings such as paint, lacquer, thermoplastic, and thermosets may be adequate for a given application, great care must be taken to protect them from damage. On the other hand, coatings such as cadmium or zinc, because of their sacrificial nature, continue to protect the base metal even if damaged. For extremely corrosive atmospheres, special alloys such as nickel-base materials might have to be used.

Minimum Fatigue Life

The fatigue life of a spring is related to material strength, stress, and environment. Material strength, in turn, is influenced by surface properties and the density, distribution, type, and size of subsurface impurities. Surface properties depend on material and manufacturing, while impurities are controlled by material processing.

High strength, beneficial residual stresses, and good surface quality are particularly important for high or intermediate-cycle fatigue life (over 100,000 cycles). On the other hand, ductility is the important factor affecting low-cycle fatigue. For example, some materials show stable failure data at high stress and strain levels, indicating the ability of these materials to relieve stress concentrations by local ductile behavior.

To estimate the fatigue life of a group of springs, fatigue tests must be performed on a representative sample. Then, an *S-N* curve is developed from the test data. Such a curve is developed for specific material, design, environment, and load conditions. Fortunately, high quality material generally produces repeatable results; therefore, satisfactory data can be generated by testing only a few diameters of wire. The main problem is the time required to complete a test. For instance, even at the fast cycling rate of 30 Hz, one million stress cycles would require 9¼ hours of testing.

Because early fatigue failures are particularly interesting, *S-N* curves generally are developed for 90% to 95% probability of survival. Fig. 5 shows a 90% survival rate curve developed for round-wire, shot-peened helical compression springs made of 0.80-in. diam ASTM-A-228 material.

The springs were tested at various maximum stresses and at a constant stress ratio of 0.125. The fatigue lives for 90% survival then were derived from plots on Weibull probability paper. These plots were subsequently modified with the aid of a Goodman diagram to yield the fatigue lives for 90% probability of survival at zero stress ratio. Fig. 5 is the *S-N* curve for these fatigue lives.

Fig. 5 combined with a Goodman diagram can be used to estimate the fatigue life of similar springs cycled at various stress ratios and in the same environmental, load, and frequency conditions. Similar plots can be derived for other spring designs to estimate life.

□

Nomenclature

C = Spring index
D = Mean spring diameter
d = Wire diameter
E = Modulus of elasticity
f = Spring deflection
G = Torsional modulus of elasticity
g = Gravitational constant
K_W = Wahl factor
N = Number of active coils
n = Spring natural frequency
p = Material density
S = Stress
U = Volume efficiency
V = Spring volume
W = Stored energy

Salt Spray and Temperature Resistance of Common Spring Coatings

Coating	Salt Spray Resistance (hr)	Temperature Resistance (F)	Description
Cadmium	96 to 528	400	Electroplated or mechanically plated
Zinc	100 to 480	400	
Japan	15 to 18	450	Dark-colored, usually dipped, cured by baking
Lacquer	32 to 96	400	Usually applied by spraying; air dried
Enamel	55 to 425	250	Hard finish; applied by spray, brush or dip; cured by air or baking
Paint	27 to 300	350	
Oil	1 to 325	200	Lubricating, rust-inhibited, hard-drying, and nondrying oils
Phosphate	78 to 638	500	Chemical treatment; provides bond for oils and paints.

Data based on laboratory-controlled applications and tests. Protective material, part cleanliness, application method, subsequent operations, and part usage affect performance. Choice of finish must also consider shipping, assembly, end use, and total costs.

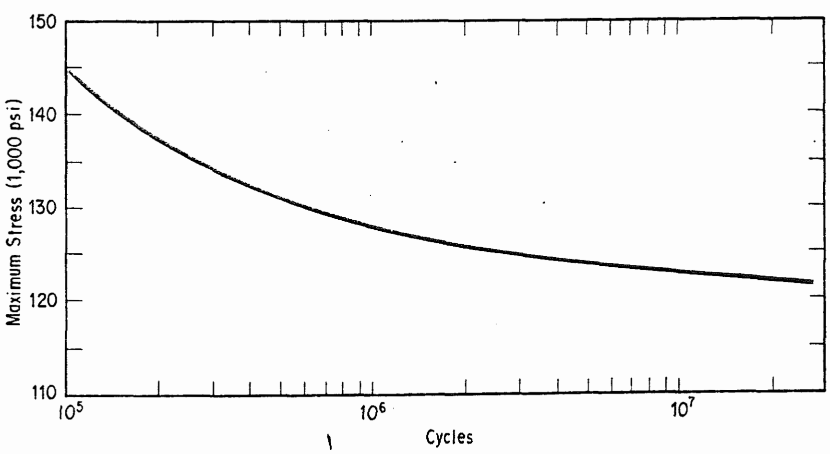


Fig. 5 — S-N curve for 90% survival at zero stress ratio. This curve was derived from fatigue tests on helical compression springs made of ASTM-A-228 material and tested in a noncorrosive atmosphere. Load was applied in a sinusoidal mode at 30 Hz. The calculated natural frequency of the springs was 452 Hz, and stress ratio was 0.125. The fatigue data then was normalized to produce a curve for zero stress ratio. This curve, combined with a Goodman diagram, can be used to estimate the fatigue lives of similar springs tested under the same conditions but at different stress ratios.