

NOTES ON THE DESIGN OF HELICAL COMPRESSION AND TENSION SPRINGS OF ROUND WIRE

1. NOTATION

B	optimisation parameter		
c	spring index = $(D_o - d)/d$		
d	diameter of wire	m	in
D_o	outside diameter of spring	m	in
G	shear modulus of spring material	N/m ²	lbf/in ²
L_c	solid length of spring	m	in
N	total number of coils in spring		
n	number of effective working coils in spring		
P	applied axial load	N	lbf
q	shear stress at intrados* (including curvature correction factor) under axial load	N/m ²	lbf/in ²
δ	deflection of spring	m	in

Both SI and British units are quoted but any coherent system of units may be used.

* The inner surface of the coils.

2. GENERAL NOTES

This Item presents basic concepts and principles relating to the design and operation of helical compression and tension springs of round wire. Detailed treatment of their design is covered in Data Item No. 82008*, and allowable stresses are presented in Data Item No. 83002† to which reference should be made.

The Item is concerned essentially with springs of standard form, that is, having constant wire diameter, coil diameter and coil pitch. Deviations from these conditions are only those permitted by normal manufacturing tolerances (see Section 6.4). However, some notes on other forms are given in Section 8. The types of loading and design features referred to in this Item are restricted to those most likely to be encountered in normal practice.

There are many applications for springs, the more common ones being:

- To store and return energy (as in machine gun recoil mechanisms)
- To apply and maintain a definite force (as in relief valves, governors)

* Data Item No. 82008, "Elastic stresses and deflections of helical compression and tension springs of round wire".

† Data Item No. 83002, "Allowable stresses for helical compression and tension springs of round wire".

- To support moving masses (as in vibratory conveyors, vehicle suspensions)
- To isolate vibration
- To indicate and/or control load (as in weighing machines)
- To provide an elastic support or guide (as in pipe hangers, balancing machines)
- To return a displaced component (as in brake pedals, engine valves).

The energy stored in a spring is proportional to the square of the stress. Hence for efficient use of the volume of spring material the highest reasonable stress levels should be used as the basis of the design.

Applications where spring failure could lead to a runaway condition, for example a governor or a relief valve, require attention to every possible detail. The cost of the spring should be seen in relation to the cost of the associated equipment, dependent on the adequate functioning of the spring. If the consequence of failure of the spring, either by breakage or by reduced performance, would be a hazard to life or cause undue cost in money or time for replacement, it may be considered advantageous to reduce the design stresses. It may even be desirable to have a redundant system. Not all springs perform such critical duties, and since the in-built precision affects the spring costs, attention must be given to the function of each spring.

It is essential that all information resulting from design considerations and calculations is transmitted to the manufacturer in a clear and concise manner, see Section 9.

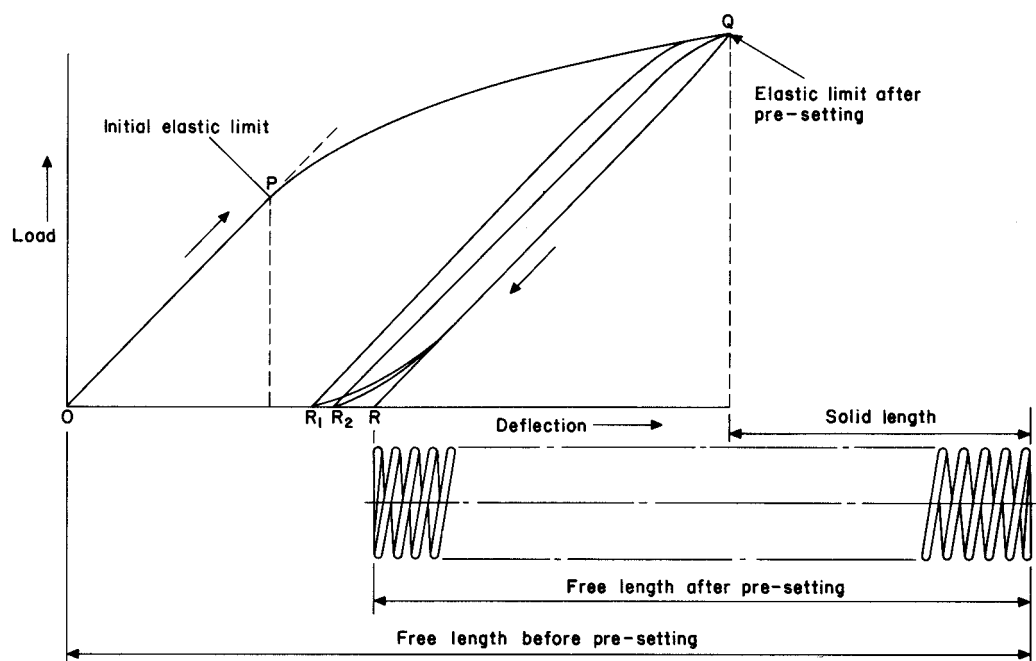
3. PRESTRESSING

The energy storage potential of a spring may be increased by inducing beneficial residual stresses in the spring at the manufacturing stage. One of the usual ways of achieving this is by prestressing. Prestressing of tension springs is difficult and is not usually attempted.

Prestressing (also known as scragging or presetting) is commonly applied to compression springs. To carry out this process, the as-coiled spring must be capable of being stressed into the plastic range by compressive loads. In practice the spring, which is wound over-length, is compressed to solid length (see Section 6.3) a number of times, usually 5 or 6, thus inducing plastic deformation in the outer fibres of the wire. On release of all load, owing to the plastic flow that has occurred, the outer fibres of the wire, which in operation are the most highly stressed, are subjected to a residual shear stress by the inner fibres. This shear stress is in the opposite sense to that applied during operation. The effect of this is to reduce the maximum stress, although the stress range is unchanged. Thus both the static strength and the fatigue endurance of the spring are increased.

Sketch 3.1 shows the load/deflection plot for a spring being prestressed. The first loading cycle is OPQR₁. Successive cycles of load lead to a new load/deflection curve RQ parallel to OP. The process also has the effect of increasing the apparent elastic limit of the material. This means that in static loading the load carrying capacity of the spring is increased.

The improvement in fatigue life and static strength increases up to an optimum value with increasing over-strain. The amount of the increase and the optimum over-strain is likely to vary with the material, and the existing experimental and theoretical work is insufficient to give any useful estimates of the improvement that will be gained. However, the manufacturer can arrange the best possible results from prestressing experimentally during manufacture, and the details need not concern the designer.



Sketch 3.1 Behaviour of a spring during pre-setting

4. CHOICE OF MATERIAL

The choice of material is governed by the following considerations.

4.1 Operation Reliability

Materials of high quality and assured properties are required if the spring is to operate for a large number of cycles, or at an unavoidably high stress (for example, because of space limitations), or because the consequences of failure are particularly serious. Alternatively, materials of lower quality may be acceptable if the spring is loaded infrequently, or is lightly stressed, or if replacement is simple and acceptable. Where the spring weight is to be kept to a minimum (for example, in artificial limbs) it may be advisable to use an expensive material such as a titanium alloy, taking advantage of the physical properties of strength and density.

4.2 Corrosion and Protection

Many spring materials are prone to corrosion, including stress corrosion, and as a consequence their fatigue strength may be seriously reduced. Therefore, care must be taken in the choice of material and of the surface finish if corrosive conditions will be present. Usually it is better practice to use a non-reactive material than to attempt to protect a material that is prone to corrosion, because it is rarely possible to achieve complete and lasting protection by any method.

If it is necessary to provide surface protection, it may be done by various methods. Plating, possible only with compression springs (because of the inaccessibility of the surface of close-coiled tension springs), should be done to an approved specification (for example, BS 1706), although in arduous conditions pin-holes are always likely to occur in the plating, followed by general breakdown of the protection.

Painting or coating the spring with a plastic material such as polytetrafluorethylene (PTFE) is often acceptable, but failure of the protection is always likely at the loading points. Immersion in oil in service

may be a means of providing the required protection. Titanium alloy springs give greatly improved service if they are anodised after manufacture. This treatment offers a secondary advantage in that, by using different anodising times, a range of natural colours may be obtained and these can serve as an identification code. An experienced manufacturer will be able to advise on this method.

If shot peening is carried out (see Section 6.6), the surface of the spring is left in a chemically very active condition. Since it is very susceptible to corrosion, it must be protected immediately after peening. Protection should be applied by the manufacturer as an invariable sequel to peening, but it is advisable to make this clear when ordering.

4.3 Working Temperature

At high temperatures, oxidation and general reduction of the material properties, such as evidenced by stress relaxation, make carbon steel sometimes unacceptable. In such cases it may be necessary to use alloy steels or suitable non-ferrous materials.

At low sub-zero (cryogenic) temperatures, embrittlement may be a problem, and again it may be necessary to avoid the use of carbon steels and some low alloy steels.

A guide to the suitability of a number of acceptable materials for high quality, precision springs, such as would be required in relief valves, is given in Tables 4.1 and 4.2. For more specific data on spring material properties, reference should be made to the quoted Standard in the tables, to Reference 2 of this Item, or to the manufacturer.

TABLE 4.1 Some Spring Steels

Material				Maximum wire diameter mm	Normal working temperature range of spring °C	
Type		Specification	Minimum		Maximum	
Carbon steels		BS 5216 : HS2	13.25	−20	+130	
		BS 5216: HS3	13.25	−20	+130	
		BS 970: Pt5: 070A72	12.0	−20	+150	
		BS 970: Pt5: 070A78	12.0	−20	+150	
		BS 2803: 094A65 HS	12.5	−20	+150	
Low alloy steels	Silicon-manganese 0.6–0.9% chromium	BS 970: Pt5: 250A58	40.0	−20	+150	
		BS 970: Pt5: 250A61	40.0	−20	+150	
		BS 970: Pt5: 527A60	80.0	−20	+150	
	0.5% Nickel-chromium- molybdenum	BS 970: Pt5: 805A60	80.0	−40	+150	
	1% Chromium-vanadium	BS 970: Pt5: 735A50	40.0	−20	+175	
Alloy steels	Austenitic chromium-nickel	BS 2056: En58A	10.0	−200	+250	
		BS 970: Pt4: 302S25	25.0	−200	+250	
	Austenitic chromium- nickel-molybdenum	BS 2056: En58J	10.0	−200	+250	
		BS 970: Pt4: 416S16	25.0	−200	+250	
	17-7 Chromium-nickel precipitation hardening	DTD 5086 [*] FV 520B [†]	10.0 70.0	−90 −90	+320 +400	

* UK Ministry of Defence specification.

† UK Trade description.

TABLE 4.2 Some Spring Alloys

Material		Maximum wire diameter mm	Normal working temperature range of spring °C	
Type	Specification		Minimum	Maximum
Phosphor-bronze with 8% Tin	BS 2873 ASTM B159-46	6.5	0	+100
Beryllium-copper 2% Beryllium	BS 2873 ASTM B197-51T	6.5	−50	+100
Ni-span C902*	–	3.0	−50	+100
Nickel-copper (Monel 400 [†])	BS 3075-NA13	10.0	−40	+200
Nickel-copper-aluminium (Monel K-500 [†])	BS 3075-NA18	8.0	−200	+230
Nickel-chromium-iron (Inconel 600 [†])	BS 3075-NA14	10.0	−200	+370
Nickel-chromium-cobalt (Nimonic 90 [†])	BS 3075 2HR	8.0	−200	+550
Nickel-chromium P.H. (Inconel X-750 [†])	–	12.5	−200	+540
Titanium alloy (Ti-6Al-4V)	IMI 318 [†]		−200	+125

* USA Trade description

† UK Trade description

4.4 Special Requirements

The choice of material may be restricted by special physical properties which may be required. For example, instrument springs may require exceptional stability of material properties or low hysteresis; good electric conductivity and non-magnetic properties may be needed for electrical machinery and also some instrument springs. For these latter applications beryllium-copper is frequently used. A special alloy Ni-span C902 may be used when a constant modulus over a range of temperature is required.

5. LOADING

The manner of loading to which a spring is subjected will affect both the permissible stress level and the magnitude of the induced stress.

At no time after the completion of the manufacturing process (that is, during assembly and operation) should the spring be stressed outside the elastic range of the material. (This is particularly important with tension springs, for which inadvertent overstressing is likely.) Therefore the nominal working stresses should be low enough to preclude overstressing, despite the additional loading factors described below, which tend to increase the stress values. However, the main objective is energy storage, and for a given volume of material the energy stored is proportional to the square of the stress. It is therefore advantageous to select a material that will permit the highest possible stress. The designer must attempt to optimise between these two opposing requirements by adjusting the geometry or by using nested springs (see Section 8.1).

5.1 Cyclic Loading and Fatigue Properties

If the spring is cyclically loaded, consideration should be given to the fatigue endurance of the specified material in relation to the life that is required of the spring. In addition, there are two effects that increase the working stress. These are the non-uniform distribution of strain along the length of the spring, and resonance, see Section 9 of Data Item No. 82008. The actual size of these effects depends on the relationship

of the loading frequency to the natural frequency of the spring. However, the spring natural frequency will be accurately known only when its dimensions are precisely fixed.

In tension springs it is important to take account of the initial tension that may be present in an unloaded spring. Such pre-loading stresses have a significant effect on the fatigue life of the spring.

5.2 Transverse Loading

There are many applications, particularly with compression springs, where lateral loading occurs. Almost invariably, the transverse load does not act alone, and the spring carries an axial load also. Vibratory conveyors mounted on helical springs provide a typical example of this form of loading.

The increase in stresses due to the transverse load must be determined in order to preclude premature failure. The combined stresses due to axial and transverse loading should not exceed the solid stress due to axial load alone. In some installations it may be necessary to provide a stop to prevent excessive deflections in both planes. The design procedure is dealt with in Data Item No. 82008. The designer must pay attention to the housing and end location to ensure that the spring will remain in position under the transverse load.

5.3 Impact

Many springs are used to carry shock loads, as in engine valves or pneumatic drills. An impulsive load creates a surge wave of torsional stress which travels along the wire of the spring. While it is possible to determine the magnitude of the stress wave, it has to be assumed that the coils do not clash. In practice it may not be possible to assign precise values to the impact parameters, and the only expedient in the presence of impact loads is to reduce the value of the design stress.

5.4 Eccentric Loading

Eccentric loading does not present a problem with tension springs. It is, however, difficult to load compression springs through their end coils without introducing loads eccentric to the longitudinal axis. The end effects may introduce a lack of symmetry which, even with an axial external load, may cause eccentric loading in the coils. The designer may be able to reduce this eccentricity considerably by calling for very fine tolerances on end squareness and parallelism.

An eccentric load will have a significant effect on the behaviour of the spring. The load/deflection characteristic will depart from the axially loaded one, there will be a greater tendency to buckle, and the maximum stresses will be higher. A further phenomenon experienced with helical compression springs is that the eccentricity of the load with respect to the axis of a deflected spring induces uneven loading round each coil of the spring. The effect of this is to cause the spring coils to warp, or take up a form other than their truly helical shape. Helix warping increases the maximum stress in the spring, but is decreasingly significant as the number of coils is increased. The stress enhancement due to warping is given in Data Item No. 82008.

5.5 Buckling

Buckling of helical compression springs often occurs when the free length is four or more times the mean diameter. It is recommended, however, that all spring designs be checked against buckling (Figure 5 of Data Item No. 82008). The onset of buckling is affected greatly by the type of seating which may be represented by the theoretical end condition factor, C . These values are given in Sketch 7.2 of Data Item No. 82008 for various types of seating. Because the spring ends tend to lift off a non-pivoted seating as the critical buckling deflection is approached, and also because there is some slight initial curvature of the spring axis and out-of-squareness of the ends, buckling occurs in practice earlier than predicted by theory.

Experience shows that these effects may be accounted for by reducing the theoretical end condition factor by approximately 20 per cent. In the case of pivoted seatings, the position of the pivot in relation to the plane of the spring end is important (see Data Item No. 82008).

If the spring as designed is found to be unstable, and its dimensions cannot be altered sufficiently to avoid this condition, it may be acceptable to allow buckling but to restrict the lateral deflection by means of a close fitting internal rod or external housing. The resulting friction may, however, produce significant changes in spring rate or load at a given deflection, and may lead to fretting fatigue failure. Alternatively, with pivoted seatings, it may be possible to move the pivot longitudinally, to a more favourable position. When a long spring, say 10 to 20 times its diameter, is required, it may be preferable to use several springs over a rod, with spigotted washers between the springs, as this will reduce the tendency to buckle.

6. DESIGN FEATURES

6.1 End Forms

Although the centre coils, remote from the ends, are the truly functional part of a spring, the shape and the form of the ends are extremely important. In both compression and tension springs the load carrying capacity may be governed by the end shape. The type of end coil formulation will affect both the free length of the unloaded spring and the solid length of the fully compressed spring. Section 3 of Data Item No. 82008 gives guidance on the estimation of free length, and Section 6 deals with the solid length calculations for each type of end coil formation. It is always good practice to locate the ends of each spring in a recess or over a spigot. If there are significant lateral loads, such end location is essential.

6.1.1 Compression springs

There are various forms used for the end coils of compression springs. The more common ones are those illustrated in Sketch 6.1. They are:

- (a) Coils left unclosed and not ground
- (b) Coils left unclosed, but ends ground square to the axis
- (c) One or more coils at each end closed but not ground
- (d) One or more coils at each end closed and ground square to the axis