A Brief Introduction to Coiled Springs as a Power Source

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ABSTRACT. *Mainsprings are coiled steel ribbons that have been used as a power source for centuries. A major disadvantage of mainsprings is that they do not deliver a uniform torque during unwinding. In service mainsprings are subjected to low cycle fatigue loading, which can be either uniaxial or biaxial. They can either fail in fatigue or fail by becoming tired due to shakedown into a shape where they no longer deliver adequate torque. Some features of the behaviour of mainsprings used as power sources are described and illustrated by examples. Detailed theoretical analysis is difficult so mainsprings are usually designed by using well established rules of thumb. Correct lubrication is important.*

INTRODUCTION

The use of unwinding mainsprings, rather than descending weights, as a power source in clocks, appears to have started in the early fifteenth century [1, 2]. Despite the relatively recent introduction of highly accurate battery powered quartz clocks and watches, mainsprings are still being used as a power source in some clocks and watches [3, 4]. ‘Mainspring’ is primarily a horological term [5]. Here, it is applied to any coiled spring used as a power source. At a more mundane level mainsprings are, and have been for many years, used as a power source (motor) in toys and models [4]. Such toys and are usually referred to as clockwork toys. A motor powered by a mainspring is referred to as a clockwork motor. Mainsprings also have various engineering applications [6], and are sometimes called clock springs or motor springs. Detailed theoretical analysis of mainsprings is notoriously difficult [2, 7, 8]. Displacements are very large and, for a given amount of winding, the shape of the mainspring has to be determined as part of the solution. Also, the effects of friction between adjacent coils are difficult to incorporate into the solution. In practice, mainsprings are usually designed by well established rules of thumb [5, 6, 8]. Suppliers’ catalogues often list the properties of mainsprings to assist selection for a particular application [6].

MAINSPRINGS

Usually, mainsprings are rectangular ribbons of spiral form, made from C-Mn spring steel heat treated to around 400 VPN [9]. In horological terminology, the width of the ribbon is called the height, and the thickness the strength. Sometimes, the ribbon is not precisely rectangular [6]. During manufacture the ribbon is wound round an arbor, and material near the surfaces is stressed beyond the elastic limit. When released the springback results in a spiral which is approximately logarithmic. There are compressive residual stresses on the outer surface of the spiral, and tensile residual stresses on the inner surface. The ends of the mainspring are usually annealed to permit machining for attachments.

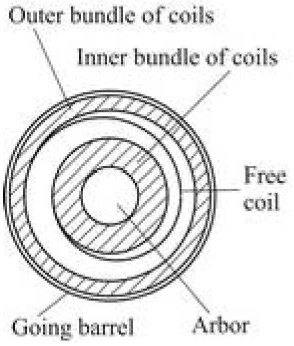


Figure 1. Partly wound enclosed mainspring.

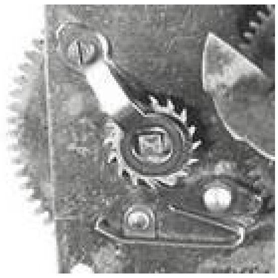


Figure 2. Click work in a mainspring powered clock.

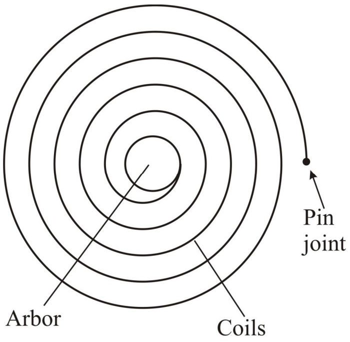


Figure 3. Unwound open mainspring.

Mainsprings are of two main types, enclosed and open. An enclosed mainspring is enclosed in a going barrel, as shown schematically in Fig. 1. Going means that the barrel turns as the mainspring unwinds, and drives the mechanism. The mainspring has a hole at the outer end which engages a hook on the barrel, and a hole in the inner end which engages a hook on the arbor. Except when fully wound or fully unwound, the mainspring is effectively built in at both ends The central arbor has a squared end and the spring is wound onto the arbor by turning the squared end with a key. Click work prevents the arbor turning in the reverse direction. Typical click work in a mainspring powered clock is shown in Fig. 2. This consists of a spring loaded pawl and a ratchet wheel mounted on the squared end of the arbor. In Fig. 1 the mainspring is shown partly wound. There is a closely wound bundle of coils on the arbor, and another closely wound bundle inside the barrel, with free coils in between. Because of minor irregularities adjacent coils in bundles are not fully in contact. Oil applied to bundles is drawn inter interstices by capillary action. As the mainspring unwinds coils transfer from the arbor to the inside of the barrel. One free coil is shown in the figure, in practice the number of free coils increases as the mainspring unwinds. Sometimes stop work is fitted to clocks and watches so that the mainspring is never fully wound or fully unwound. Even if stop work is not fitted, watches usually include a device which releases the mainspring slightly if it is fully wound.

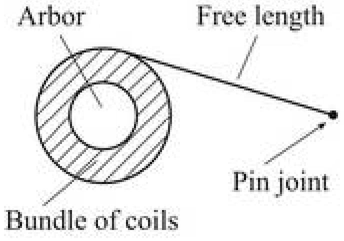


Figure 4. Fully wound open mainspring.

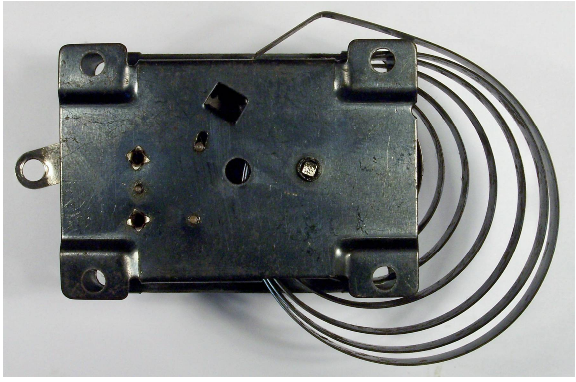
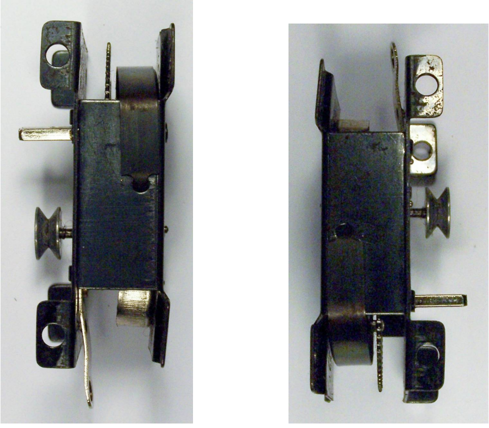


Figure 5. A Meccano Magic motor with fully unwound mainspring. Hole for hook at side of casing. Mainspring width 7 mm.



(a) (b)

Figure 6. Meccano Magic motors with fully wound mainsprings. Mainspring width 7 mm. (a) Hole for hook at side of casing. (b) Hole for hook at corner of casing.

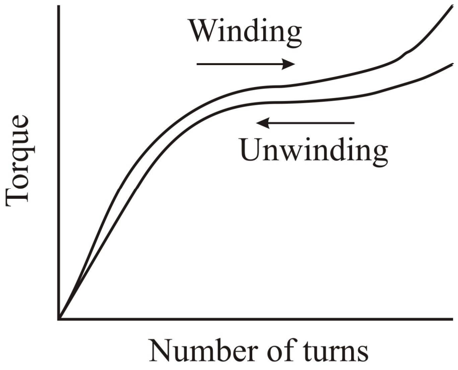


Figure 7. Hysteresis during winding and unwinding of a mainspring.

An open mainspring is shown schematically in Fig. 3. The mainspring has a hole at the inner end which engages a hook on the central arbor. This central arbor is used for both winding the mainspring, as for an enclosed mainspring, and for driving the mechanism. The outer end is pin jointed. This may be by a hook which engages in a hole, or by a loop around a pillar. In the latter case it is called a looped mainspring. Figure 3 shows the mainspring unwound. Fully wound (Fig. 4) there is a closely wound bundle of coils around the arbor, and a nearly straight free length extending to the pin joint. An unlubricated open mainspring tends to unwind from the outside of the bundle of coils, whereas a properly lubricated open mainspring unwinds uniformly, with immediate separation of adjacent coils. In practice, because of inference with other parts, the shape of an unwound open mainspring, is usually noticeably asymmetrical. For example, Figure 5 shows a fully unwound Meccano Magic motor. In addition, there is kink near the outer end of the mainspring. The outer end of the mainspring has a hook which engages a hole part way along one side of the motor casing (Fig. 6a). The kink is caused by the annealed portion of the mainspring bearing against the motor casing when fully wound. A different version of Magic motors has the hole at the corner of the casing (Fig. 6b) and no kink forms.

The major disadvantage in the use of mainsprings as a power source is that they do not deliver a uniform torque during unwinding [5-9]. Mainsprings have to be properly lubricated to wind and unwind smoothly. Nevertheless there is usually some hysteresis due to friction, as shown schematically in Fig. 7. Typically, the torque during unwinding is 10 to 20 per cent less than that during winding.

Very little information is available on the fatigue lives of mainsprings, that is the number of cycles (windings and unwindings) to failure. Analysis of some clock records shows that the maximum numbers of cycles known to have been sustained without failure are 3300 for an open mainspring and 2200 for an enclosed mainspring.

MAINSPRING FAILURES

When a mainsprings fails in fatigue the usual place for failure is two coils out from the centre of the wound mainspring [10]; there is a region of increased bending, and hence increased stress, where the coil passes above the hook on the arbor. A general view of a typical mainspring fatigue failure is shown in Fig. 8a. The crack profile is shown in Fig. 8b. This is a typical bending fatigue failure with the crack approximately straight across the mainspring. The fracture surface is shown in Fig. 8c. The bright, polished spot near the centre of the figure would be opposite the hook on the arbor when the mainspring was fully wound. This has caused a slight bulge, which has become polished due to relative movement between adjacent coils. The fatigue failure appears to have originated at a similar, less well defined spot, two coils out from the hook. In an enclosed mainspring [2] a fatigue crack started similarly, but then turned and spiralled along several coils towards the outer end. Fatigue failures sometimes take place elsewhere, as shown in Fig. 9. In this example the mainspring has broken into 6 pieces (Fig. 9a). The four pieces that are broken at both ends are all about the same length (Fig. 9b). What was probably a fatigue failure has been observed in an open mainspring where one of the coils had been pressed against a pillar of a Meccano No. 2 clockwork motor.

As a mainspring is repeatedly wound and unwinds during service there may be permanent deformation due to shakedown [1]. Such a mainspring is said to be set or tired. An extreme example of a tired open mainspring in an 8 day clock is shown in Fig. 10 (cf Fig. 4). In the figure the mainspring is fully unwound in the sense that the available torque had become insufficient to operate the clock’s escapement. With the mainspring in this condition the clock will only run for two days.

Witness marks on failed mainsprings (Figs. 8c and 9b) show that during winding and unwinding there is relative movement between adjacent coils in contact. This implies that correct lubrication is important, and also implies that friction between adjacent coils must be taken into account in a complete theoretical analysis.


(a) (b) (c)

Figure 8. Fatigue failure of a 12 mm wide enclosed mainspring, two coils from the centre of the wound mainspring. Mainspring supplied by courtesy of John Nuttall. (a) General view. (b) Crack profile. (c) Fracture surface.

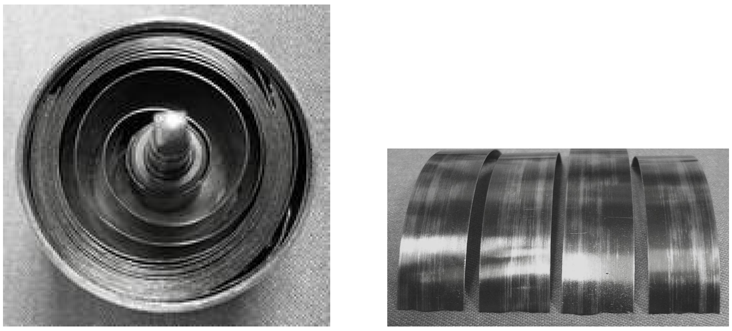

(a) (b)

Figure 9. An enclosed mainspring broken into 6 pieces. (a) Still in the barrel, with cover removed. (b) Pieces broken at both ends. Photos courtesy Bill Butcher.

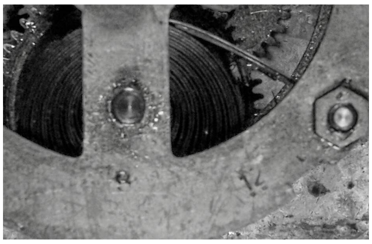


Figure 10. A tired open mainspring in an 8 day clock, fully unwound.

THEORETICAL ANALYSIS OF MAINSPRINGS

In general, an enclosed mainspring is loaded in bending, with loading and unloading moving along the mainspring as it is wound and unwinds. The bending moment in the free coils is constant, and it is this bending moment that provides the torque needed to drive the going barrel. Bending moments in the outer bundle of coils are smaller than in the free coils, whereas bending moments in the inner bundle are larger. An approximate analysis by Rawlings [8], based on engineer's theory of bending, shows that to maximise stored energy, the tensile surface stress on the outer surface of coils must be as high as is compatible with adequate fatigue life. Rawlings' analysis can also be applied to an open mainspring. In an open mainspring the bending moment is, in general, constant along the mainspring and changes as it is wound and unwinds. In an open mainspring the bending moment drives the arbor.

The forces on a cross section of a mainspring can be decomposed into a bending moment and a direct force. The end fittings for a mainspring are designed to resist tensile forces, so any direct forces in a mainspring can be assumed to be tensile. Tensile forces arise when a mainspring is fully wound. The outer fitting of a mainspring usually approximates to a pin joint. That shown in Figs. 5 and 6a is an exception that has resulted in different behaviour. However, in general the section of mainspring from the closed bundle of coils to the outer fixing is approximately straight (Fig. 4) and forces in the mainspring are dominated by an axial tension along the mainspring. This tension has a circumferential component that results in a torque which drives the barrel of an enclosed mainspring and, indirectly, the central arbor of an open mainspring. This effect is illustrated in Fig. 10 where the open mainspring has shaken down into a coil with a nearly straight portion leading to a loop around a pillar at the outer end of the mainspring. The second nearly straight portion visible in the figure is the tail of the loop at the outer end of the spring.

If friction between adjacent coils in the bundle of a fully wound mainspring is zero, then relative movement between adjacent coils is possible, and the tensile force is the same along the length of the mainspring, However, if the friction between adjacent coils is sufficiently large, then relative movement between adjacent is not possible, and tensile forces are not transmitted along the length of the mainspring. The central bundle of coils is then effectively solid, and there is a cusp where the straight length meets the bundle. The stress singularity at the tip of a cusp is the same as that for a crack so stress intensity factors can be defined [12]. Energy rate analysis of a crack in a similar configuration [13] shows that Modes I and II stress intensity factors, K_I and K_II, are present for both a bending moment and a direct force. In both cases K_I is roughly equal to K_II. However, for a mainspring K_I must be zero, unless adjacent coils are bonded together, Since K_II is present there will be a small amount of relative movement between adjacent coils in the vicinity of a cusp, analogous to a crack tip plastic zone [1]. In practice, the effects of friction will be somewhere between the two extremes described. The arguments also apply to the cusps at the ends of the free coils of a partly wound enclosed mainspring (Fig. 1).

The clock shown in Fig. 10 had been stored for many years with the open mainspring fully wound. Adjacent coils in the bundle were bonded together by solidified lubricant, and fresh oil was not drawn into the bundle. The clock ran after rectification of an escapement fault, and the mainspring unwound inwards, with the cusp moving towards the inner end of the mainspring. Hence, the Mode I stress intensity factor at the cusp must have been high enough to debond adjacent coils. On subsequent windings, the mainspring unwound uniformly, as is usual for an open mainspring.

FATIGUE LOADS ON A MAINSPRING

A mainspring used as a power source is subjected to low cycle fatigue loading and, can fail either by breakage due to fatigue, or by shaking down into a shape in which it can no longer supply adequate power. Fatigue loads on a mainspring, and their effects, can be summarised qualitatively as follows.

Repeated winding and unwinding of a mainspring results in an approximately constant amplitude low cycle fatigue loading. The upper load depends on how hard the key is turned as the mainspring becomes fully wound. However, in a clock fitted with stop work this upper load is constant. The lower load depends on how far the spring unwinds before being rewound. In a clock rewound on a regular schedule, as is usual, the lower load is approximately constant, but in a clockwork motor the lower load tends to vary.

The main fatigue loading on a given cross section of a mainspring is bending between an upper and lower bending moment. This is a uniaxial loading. When a mainspring is fully wound, or nearly so, axial tensile forces appear in the vicinity of the outer end, and loading on cross sections in this vicinity becomes biaxial. Depending on lubrication conditions biaxiality can extend as far as the inner end, and rotation of stress tensors will occur on some cross sections during winding and unwinding.

A mainspring fails either in fatigue or by becoming tired so that it no longer delivers sufficient power to operate the mechanism correctly. Fatigue failure of a mainspring is usually by the initiation, propagation and final failure of a dominant fatigue crack. Final failure takes place when the cross section is so reduced that the upper load can no longer be sustained. Fatigue cracks initiate on the outer surface of a coil, where stresses due to fatigue loading are tensile, and then propagate through the thickness until failure occurs. Fatigue failure usually takes place near the inner end of a mainspring (Figs. 8 and 9) where distortion due to the presence of the hook on the central arbor introduces distortion and concomitant additional stresses.

The fatigue failure shown in Fig. 9 is unusual in that five fatigue cracks have initiated, apparently at the same circumferential location near the outer end of the fully wound mainspring. It is not clear why the cracks initiated at this particular location. When final failure took place at one of the fatigue cracks the resulting jolt as the mainspring expanded apparently caused final failure at the other four fatigue cracks.

CONCLUSIONS

(1) Mainsprings are subjected to a low cycle fatigue loading, which can be either uniaxial or biaxial.

(2) Mainsprings can either fail in fatigue or fail by becoming tired due to shakedown into a shape where they no longer deliver adequate torque.

(3) Detailed theoretical analysis is difficult so mainsprings are usually designed by using well established rules of thumb.

(4) When friction between coils is high there is a Mode II stress intensity factor at the cusp where a free coil meets a bundle of coils.

(5) Correct lubrication of a mainspring is important.

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