

WHITE PAPER:

Wire Wound vs. Machined Springs; A Comparison

This white paper addresses the high points of choosing between Machined and Wire Wound Springs, and goes into further detail regarding the unique differences that can significantly affect design considerations.

Wire Wound vs. Machined Springs: A Comparison



3 Identical Rate Compression Springs

Wire Spring	Machined Spring	Machined Spring
Single Start	Single Start	Double Start
Closed & Ground Ends		Machined Ends
Steel Spring Wire		7075-T6 Aluminum Alloy

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Background

The first question generally asked about Machined Springs is how they compare with Wire Wound Springs. Commencing with this question, this review of Machined Springs will proceed.

Wire Springs appeared preceding the Industrial Revolution. They established their value immediately, and have not wavered from that most useful course. Certainly, enhancements in materials and manufacturing have been forthcoming, but the basic concept has not changed much. Spring wire coiled hot or cold with ends configured within the limits of coil wire has proven to be a very cost effective, industrial tool that exhibits elasticity within the bounds of known engineering understanding. Uses range from deep ocean applications to man's reach into the universe. Finding a modern day device large or small, that does not benefit from elasticity, and particularly that provided by Wire Wound Springs, is a rare find.

Machined Springs are similar in function to Wire Wound Springs, but they are manufactured in a different way. Although any machinable material including plastics can be used, metal in the form of bar stock is the most common starting point for Machined Springs. The bar stock is first machined into a thick wall tube form, attachment features are added and then a helical slot is cut revealing multiple coils. When deflected, these coils provide the desired elasticity.

The cost to manufacture Machined Springs exceeds that of winding Wire Springs. Wire Wound Springs can be created with just a few seconds of process time, where a Machined Spring requires minutes at a minimum. The machines used to create both forms are highly specialized and benefit from modern day CNC controls.

Each of the subsequent comparisons will provide descriptions and, if applicable, a decision matrix that can be useful when deciding which of the two spring forms will be most appropriate for a given application.



Small Wire Spring and
Machined Spring
examples

Configuration Differences

Coils

The coils found on Wire Wound Springs are typically round with sometimes rectangular and/or rectangular with rounded OD and ID surfaces. The two latter forms are less common due to cost, but when used, they provide increased stiffness and compactness of design. The rectangular coils are typically used so that the long leg is radial, but making the long leg longitudinal is possible. Rectangular wire comes in set sizes; venturing away from those sizes can be done but at an increased cost and lead time.

Coils used on Machined Springs are square, rectangular (radial or longitudinal) and trapezoidal. Trapezoidal coils are common to springs used in lateral bending and lateral translation. This shape allows for additional lateral motion without coil contact. The size of the coil is easily changed to fit the spring's needs. No standard sizes apply.

Slots

On Wire Wound Springs the space between the coils (slots) is typically uniform for Torsional Springs. For Compression Springs, they are uniform also, but the end slots usually taper to zero. This process is called "closing" the ends, and is created by an additional forming process. Optional grinding then makes the ends nearly flat. Extension Springs can have a uniform slot width from zero to most any size. If desired, the coils can be pre-stressed so that an Extension Spring exhibits a zero slot that furthermore requires a force threshold which needs to be overcome before the coils start to separate.

Currently, Machined Springs come with minimum slot of about 0.020 inch (0.51 mm). Wider slots, but generally not exceeding 0.250 inch (6.35mm), are possible. The slot width can be closed to near zero using a stress relieving process, but no pre-stressing common to Wire Springs is currently available.



Exaggerated Comparison of Slot Widths of Wire and Machined Springs with the same Length, OD and Compression Rate

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If a compression spring application requires the absolutely best repeatability to support calibration and/or high precision uses, it is best that the coils never touch. Even better, the minimum slot width needs to be wide enough to not permit any contamination between the coils from restricting and/or changing the compression motion. Machined Springs are ideal for calibration and precision usages from this standpoint. The closed aspect of Wire Springs ends can result in elastic differences in the presents of common contamination.

Number of Coils

Wire Wound Springs can be made very long. A good example of a long Wire Wound Spring is exhibited by garter springs. The general length limitation is governed by the quantity of continuous wire available on the feed spool.

Machined Springs are limited to about 30 coils depending upon size, but Machined Springs with coil numbers above 20 are rare.

Feature	Section	Wire Wound Springs	Machined Springs
Coils	Round	yes	no
	Square	yes	yes
	Rectangular, radial	yes	yes
	Rectangular, radial with high ratio	no	yes
	Rectangular, longitudinal	yes	yes
	Rectangular, longitudinal with high ratio	yes	yes
Slots	Zero width	yes	yes, with special process
	Zero width w/prestress	yes	no
	0.100 inch	yes	yes
	Over 0.250 inch	yes	maybe
Number of coils	1 coil minimum	yes	yes
	20 coils	yes	yes
	50 coils	yes	maybe

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Length

In a Wire Spring, the entire length of the wire contributes to the elasticity of the spring because the forces and moments are distributed end to end with the ends providing the interface with adjoining equipment.

Machined Springs are different. The Flexure, the section providing the desired elasticity is captive between the end sections that provide structure and attachment features. The structure and attachment features have infinite stiffness when compared to the Flexure. Furthermore, the slots on Machined Springs do not taper to zero at the ends; they do remain at the full or initial width, as seen at free length. As a result, to accomplish the same elastic performance, Machined Springs likely need to be longer than wire ones.

Precision

10% precision is readily available from both Wire Wound and Machined Springs.

1.0% precision is available from Machined Springs and possible from Wire Wound Springs when statistical methods are used for selection.

0.1% precision is probably not available from Wire Wound Springs and only available from Machined Springs using post-processing techniques.

The preceding precision discussion is general and uses a somewhat broad brush. The reality is that precise dimensions are easier to accomplish with Machined Springs than with Wire Springs, and precise dimensions are an important part of the foundation for precision performance.

		Wire Wound Springs	Machined Springs
Precision	10%	yes	yes
	1%	maybe	yes
	0.1%	no	maybe

Wire Wound vs. Machined Springs: A Comparison

Cost

Production time is the major influence in cost. Cost wise, Wire Wound Springs benefit greatly from short production times. Machined Springs cannot approach the low cost of wire product. It would be very surprising to find a very simple and inexpensive Machined Spring, produced in high quantities costing less than \$1 USD each.

However, these value enhancements related to Machined Springs usage helps to validate their usage:

- 1 Integrated attachments
- 2 Enhanced performance or functionality
- 3 Via Multiple Starts, more uniform elastic reactions giving better control of internal moments
- 4 Higher precision
- 5 Reduced assembly and acquisition efforts
- 6 No sound creation from coil contacts
- 7 No debris created by coil contacts

Without one or more of these benefits being present, there is usually little justification of pursuing the Machined Spring approach.

Spring Materials

Wire Wound Springs are typically made from medium and high strength steels, nickel alloys, titanium and stainless steels that gain their strength predominately from heat treating and cold reduction. Machined Spring users, on the other hand, use similar, but different materials. Spring wire and malleable bar are common to Wound Springs, but cannot be used for Machined Springs. A completed Wound Spring will retain various amounts of residual stress. While efforts are made via stress relieving to reduce residuals in wound product, the sum is not zero.

A Machined Spring exhibiting residual stress in the free-state will be subject to free-state deformation. Such deformation is always undesirable. To reduce the chance of residual stress in Machined Springs, materials are selected that have been subjected to residual stress eradication such as solution annealing, and the heat treatment (with no cold reduction) is limited to lower temperatures without quenching. Quenching will, by itself, induce residual stress. Martensitic CRES and martensitic steels are preferred.

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Typical Machined Spring materials include:

- 1 CRES (Corrosion resistant steels), moderate to high strength
 - a 17-4 PH per AMS 5643
 - b 15-5PH per AMS 5659
 - c CC455 per AMS 5617
 - d X750 Inconel per AMS 5667 and AMS 5670

- 2 Very high strength steel
 - a C300 per AMS6514

- 3 Other materials of interest
 - a 7075-T6 aluminum (high strength)
 - b 7068-T6511 aluminum (very high strength)
 - c 38644 Beta C Titanium STA (very high strength and corrosion resistant)
 - d Delrin 100 (machinable plastic)
 - e Ultem 2300 (machinable plastic)

- 4 Any machinable material that can be made free of residual stresses is a valid candidate for being use for a Machined Spring.

Metal Improvement for Spring Materials

Wire Springs are often shot peened for enhanced fatigue resistance. This process is possible because the gap between the coils is typically wide enough to permit passage of shot that can condition the inside of the opposite coil, as well as the outside of the coils.

Machined Springs typically have coil slots that are too small for the passage of shot. Hence, shot peening is not common. To insure fatigue resistance, features such as stress relief holes and slots can be added to the slot ends. Selecting high strength, fatigue resistant, materials is also a significant benefit.

Plating of Springs

It is not uncommon to plate Wire Springs with materials such as zinc and nickel for corrosion protection.

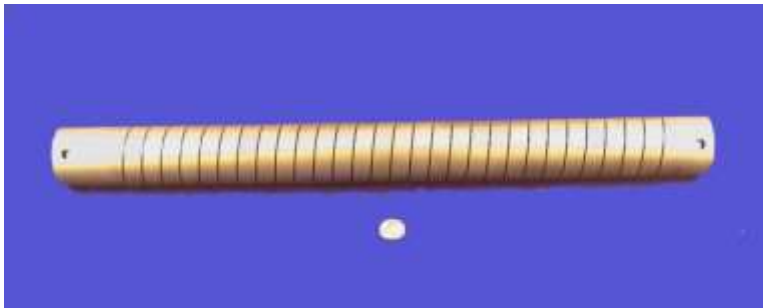
Plating Machined Springs is uncommon because of the existence of sharp edge corners that typically receive insufficient coverage. The use of CRES and titanium materials provides excellent corrosion protection for most Machined Spring applications.

Machined Springs made from aluminum are typically anodized or coated to prevent corrosion.

Machined Spring Sizes

The size of Wire Wound Springs range from very small delicate springs made from cold forming, fine wire to very large, hot rolled ones that originate as bar stock. This range is quite impressive.

Machine Spring sizes are limited by machining practicality. The smallest springs are about 0.100 in (2.54 mm) in diameter, and the largest are 6.0 inch (152 mm). Maximum length is about 24 inch (610 mm), but this applies to 1.0 inch (25.4mm) to 3.0 inch (76 mm) diameter springs. Smaller and/or larger diameter springs will need to be shorter.



A long, torsion Machined Spring using a dime for size comparison



A small, compression Machined Spring

Machined Spring's Advantage of Custom Attachments

Wire Wound Spring attachments include the following:

Compression Springs

- 1 Clipped end or natural.
- 2 Closed.
- 3 Closed and ground.
While a little more expensive, this is the most common because it provides the most perpendicular surface to the spring centerline.

Extension Springs

- 1 Hooks.
- 2 Loops.

Torsion Springs and Wrap Spring Clutch

- 1 External tang.
- 2 Internal tang.
- 3 Longitudinal tang.



Hook and loop attachments typical of Wire Springs

While Wire Springs are limited to the use of wire form attachments, time has shown that creativity in the use of the wire has provided numerous, cost effective attachment solutions.

In addition to the following, Machined Springs can possess any feature that can be machined.

Compression Springs

Since the spring is fully machined, the ends, if selected to flat, can be very perpendicular to the longitudinal axis of the spring.

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Extension Springs

Machined studs, threaded holes, flanges and many other features are available to Machined Springs.

Torsion Springs

If a tang similar to Wire Spring usage is desired, it can be accomplished in such a way to make the tang very rugged. This choice will eliminate the chance of a failure at the tang root. Tang usage is designed to provide a moment on a Torsion Spring. To accomplish this, a force at a distance is employed. The spring provides the moment reaction, but there needs to be an additional reaction to the force. Typically, Torsion Springs using a tang are called upon to rub on a guide on either the OD or ID to resolve this force. In a Machined Torsion Spring, the application of a moment is possible using a pure couple. Features that facilitate the use of a pure couple include double tangs (external, internal and longitudinal), slots, splines (internal and external) and bolt circle configurations. One can also resolve the moment by an integral torque restraint on the coil side.



Wire Wound Torsional Springs with tangs



Some of the many Machined Spring Attachments

Machined Spring's Advantage of Multiple Starts

While Wire Wound Springs are limited to Single Start configurations, Machined Springs have the potential of both Single Starts and Multiple Starts.

In nature, a DNA molecule is effectively a Double Start. This form provides balance and functionality which is essential to life. In the world of springs, the Double Start Machined Spring makes the transition from basic functionality to concepts that are intrinsic to the function of mechanical devices.

In regards to Compression and Extension Springs, Multiple Start Springs allow for a pure force reaction. A moment is created by compression and/or extension forces occurring at the spring coil which occurs a distance from the spring centerline. This force at a radial distance is defined to be a moment. In Multiple Start Springs these moments resolve to zero within the body of the spring. Hence, Compression and Extension Springs configured with Multiple Starts provide elastic motion without the need of corrective moments. In Single Start Springs, Wound or Machined, these moments must be resolved at the interface between the spring and the components providing the force and deflection.

Multiple Start Spring configurations significantly unify the lateral bending and lateral translation forces and moments around the spring's circumference given a lateral deflection. Multiple Start configurations as high as five have been employed to unify the lateral reaction of Machined Springs.

For the designer, a reminder stating that "Multiple Starts also adds to the length of Machined Springs" must be acknowledged, in addition to knowing that should a failure occur, the remaining coil(s) insure some functionality albeit degraded due to the missing coil.



Multiple Start Flexures in
Machined Springs

Machined Springs used in Compression and Extension

Stresses in both Machined and Wire Wound Springs used in compression and extension are dominantly torsional shear. The membrane analogy fits the circular cross section of wire much better than the square or rectangular section of Machined Springs. In Machined Springs subject to compression and extension, the maximum stresses are located on the spring ID and on the coil sides. It is very rare to find the maximum stresses on the spring OD. Stresses at the sharp corners are functionally very low.

Machined Springs used in compression may benefit from Stress Relief Holes (SRH) or elongated holes at the slot ends, but that is the design engineer's call. Machined Extension Springs nearly always require a SRH (or an equivalent feature) at the slot ends to mitigate the effects of harmful, tensile stresses. Without a SRH the spring's performance must be greatly reduced to avoid a failure caused by the tensile stress riser at the coil ends.



Machined Compression Springs

Linearity of Compression and Extension Springs is influenced by five factors:

- 1 Geometric changes in the spring during elastic deformation from free length.
- 2 Residual stresses in the material.
- 3 Increasing coil contact during deflection (Compression Springs only).
- 4 Boundary condition fixation.
- 5 Spring rotation during deflection.

When helical springs are compressed and extended, end to end, twisting occurs. Three remedies exist with Machined Spring to do away with the torsional deformation.

- 1 Fix the end of the spring using the myriad of attachment techniques available. Constraining the spring end will increase the elastic rate.
- 2 Use two concentric springs one with a RH Flexure and the other LH. When properly designed, the twisting of the inner spring counteracts that of the outer one.

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- Place two Flexures on a single spring blank. Make one Flexure RH and the other LH. This configuration allows the interface between the RH and LH Flexures to twist, but the ends do not.



Machined Spring Flexure Configurations for Compression and Extension Springs that resist rotating given deformation

Since Machined Springs have a constant slot dimension, there exists a slot width at both of the spring's ends that does not close. When that dimension is added to solid structural end of a Machined Spring, one finds that a Machined Spring used in compression is longer than an equivalent Wire Spring. This means that given the envelope of a fully optimized Wire Spring used in compression, a Machined Spring cannot be configured to provide equal performance. Hence, when it comes to Compression Springs, equivalent Machined Springs are always longer than Wire ones.

Percentage of Compression based upon Free Length	Wire Wound Springs	Machined Springs
10%	yes	yes
20%	yes	yes
30%	yes	yes
40%	yes	yes
50%	yes	maybe
60%	yes	maybe
70%	maybe	no
80%	maybe	no
90%	no	no

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Compression and Extension Machined Springs that have the Multiple Start feature have proven to be very successful in systems that operate at resonance. The combination of consistent elasticity, continuous slot dimension (no touching at coil ends at any time guarantees no noise or debris generation), internally resolved moments and uniform cross axis stiffness has contributed to this success.

Compression Springs can exhibit Tipping, Bowing and Buckling. While Buckling is often blamed for Tipping and Bowing, it is a separate phenomenon which needs engineering review when springs are in the design stage. Tipping and Bowing may precede Buckling, and as such, encourage Buckling.

Tipping

As springs are compressed, a potentially unresolved moment is created at the coil ends. If insufficient restraint exists (typical with Single Start springs both Wire Wound and Machined) the spring tends to lift off the compressing platen at one point on each end. The spring ends are said to be tipping when they lift off. Tipping does not occur in Multiple Start Machined Springs because the reaction moments created at the coil ends are resolved to zero.

Bowing

This is a different issue. All coils bow some when compressed. This phenomenon applies to both Wire Wound and Machined Springs. Multiple Starts don't help either. In fact, when viewing a compressed, Double Start spring one may be able to observe each of the coils bowing opposite to each other. When coils bow, the coil ends stay in the same parallel planes, end to end, as when the spring was at Free Length. It is only the coils that displace laterally to a small amount.

Buckling (Static Instability)

The word buckling comes from static instability in columns. Static instability is a function of load, geometry and elasticity (a material property). The issue of buckling becomes more prevalent as the number of coils increases.

Because of their inherent stability, Extension Springs poses no buckling concerns.

Machined Springs used in Torsion

Machined Torsion Springs benefit from attachments as previously discussed, and beyond that, differ from Wire Torsion Springs in that the coil ID can be reduced to add stiffness to the torsional rate. Adding stiffness to Wire Torsional Springs requires a change in the basic configuration (OD, ID, wire size, number of coils, etc.) or a change in the wire shape. Wire is available in rectangular and trapezoidal sections. Trapezoidal sections are generally selected for smaller ID springs so that post wound sections will approach being rectangular.

Since the stress in Torsion Springs is that of simple bending stress applied to a curved beam, there are no benefits from using Multi Start configurations. Said differently, if one wanted to double the stiffness of a Torsional Machined Spring, one could simply double the coil thickness or employ a Double Start configuration using the original coil thickness for both starts. In this case, the result would be very similar, except that the Double Start Spring would be more expensive, longer and possibly become a candidate for static instability (buckling).

The maximum, tensile, beam stresses discussed are located on the OD when the spring is subject to windup deflections; conversely, the stresses on the ID are at maximum compression. When the spring is subject to unwind, the stresses are the opposite. Of importance is that that the area where the stresses are at maximum there can be no nicks or cuts that would act as a stress riser (a crack initiator). For the same reason, Machined Torsional Springs should most often contain Stress Relief Holes (or slots) to help mitigate stress risers as the coil section makes the transition into the solid, structural section of the spring end.



Torsional Machined Springs

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If a Machined Spring were subject to equal deflections in wind-up and unwind, stress would be considerably higher in the unwind condition. This situation caused by geometry and is, unfortunately, unavoidable.

Typically, torsional Machined Springs are a little longer than equivalent Wire ones because of the additional attachments.

Since Torsion Springs are potential candidates for static instability (buckling), analysis for both wind-up and unwind springs forms is prudent. This issue becomes more prevalent as the number of coils increases and as the coil width decreases.

Attachment Types	Wire Springs	Machined Springs
Tang (Radial) External and Internal	yes*	yes*
Dual Tang (Radial) External and Internal	no	yes**
Tang (Axial) External and Internal	yes*	yes*
Dual Tang (Axial) External and Internal	no	yes**
Dual Pin Holes (Axial)	no	yes**
Geometric OD and ID Shapes (flats, square, hex, etc)	no	yes**

* Force at distance requiring force resolution

** Pure moment drive

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On the following page, one will find figures related to both Wire and Machined Spring attachments.

WTS = Wire Torsion Spring figure A-D

MTS = Machined Torsion Spring figure A-D

The eight figures shown are done so in an attempt to illustrate the importance and differences of torsional load application techniques.

Wire Wound Torsional Springs historically use either external (projecting beyond the OD) or internal (projecting into the ID) tangs. Figures WTSA-D illustrate these tangs. What becomes quickly clear is that a force applied to the tangs will create a moment useful for deflecting the torsional spring, but a secondary restraining force is required to prevent rigid body motion. This restraining force, shown in figures WTSA and WTSB, must be equal in magnitude to the torque inducing force and must also be opposite in direction. This restraining force will potentially cause friction on the spring that will likely consume some of the torsional performance of the spring.

In Figures WTSC and WTSD, moment transferring, spring tang interfaces are shown that when employed on either the OD tang or ID tang have the potential of removing the restraining force. The only problem is that the fit between the tang and the moment providing configuration must be either select or rigid to insure that a pure moment is transferred. A secondary issue occurs at the bend of the wire spring between the tang and the torsional spring body. High stresses at this location often become sufficiently high to encourage structural failure. It is this form of failure that has become viewed as the Wire Wound Torsional spring's Achilles ankle.

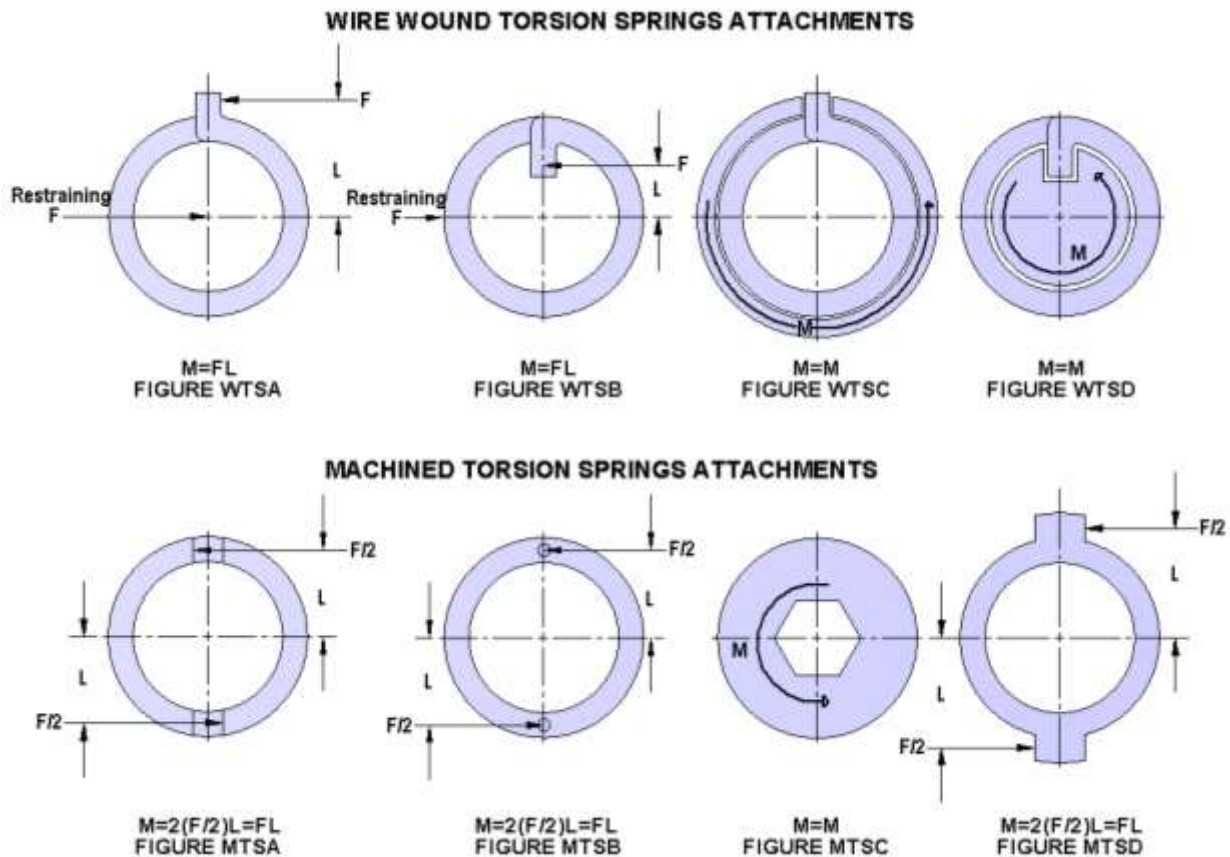
The major benefit of Machined Torsional Springs is the associated with the large number of available attachments. Indeed, a Machined Torsional Spring with a tang is available, and can be selected to replace Wire Torsional Springs simply because the tang base is more robust. This may be the only opportunity available to substitute a machined spring for a wire one without there being dimensional or performance compromises.

Historically, Machined Torsional Spring attachments are of the form to allow for the application of a pure moment via the use of a couple. Moments created by couples require no additional restraints to control free body motion. Figures MTSA, MTSB and MTSD illustrate moments created by couples. A couple is a force of equal and opposite direction separated by a distance equally and opposite oriented. The moment created by a couple is computationally equal to two times the force times one half the distance between the subject forces.

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Figure MTSC shows a hex drive, but it could be a square drive, or any related shape in which a couple is created. A traditional shaft with a colleting attachment also qualifies. Even a shaft with a tight keyway qualifies as a pure moment drive free of needed restraints.

The words “Pure Moment” have been used to describe the moment reaction capability of machined springs. What this label is saying is that with machined springs, there is a substantial opportunity to create a moment attachment free of an additional force. A traditional statics evaluation would label this definition as a “couple application” which translates into being a moment only attachment. The following illustration shows the previously described configurations of wire and machined firstly without and then with the “Pure Moment” concept employed.



Machined Springs used in Lateral Bending

If a spring is anchored at one end and the other is subject to a moment, the Load Case is labeled as Lateral Bending. While it is possible to subject a Wire Spring to Lateral Bending, Machined Springs are more commonly used in this Load Case because of the availability of attachments.

Buckling is rarely a concern for Lateral Bending Springs.

Machined Springs used in Lateral Translation

Like the preceding Load Case, Lateral Translation occurs when one end of a spring is anchored and the other end is laterally displaced by a force plus a moment to insure the end faces of the spring remain parallel. Such deflections are again better suited to Machined Springs because of attachment availability.

Rate consistency for deflections between orthogonal axis found in the plane on the parallel ends increases with the Number of Starts (1, 2, 3 with 3 being best) and with the number of coils being 2 or more.

Similar to Lateral Bending, buckling is rarely a concern for Lateral Translation Springs.

Machined Springs used as a Wrap Spring Clutch

At one time the use of Wrap Spring Clutch was a major component in motion control systems, but with the growth of sophisticated, electronic motor controls, the demand for Wrap Spring Clutches has declined.

There are, however, remaining markets in avionic flight controls and in specialized areas where the traditional Wrap Spring Clutch are preferred because of their non-electrical needs and rugged nature.



Machined Springs used as a No Back and Wrap Spring Clutches

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Wrap Spring Clutches function basically in two ways:

- 1 Engage and disengage torque transfer in a torque line by the selection of direction of rotation and engagement or disengagement of a tang.
- 2 The avionic industry has a component called a No Back. It limits the amount of torque that can be transferred in a torque line, and is used to protect flight controls from damaging, over-torque situations.

The benefits of robust tangs, machinable coil features and unusual geometries are the perceived benefits associated with Machined, Wrap Spring Clutches used in avionic controls.

How Linear?

In regards to rate consistency, often called "linearity", Helical Machined Springs used in extension, compression and torsion are considered to be very linear. This characteristic is much beneficial for most static or near-static elastic applications, and it is a significant and necessary component of dynamic systems demanding resonant performance.

Machined Springs are generally considered to be linear for the load cases stated here, but a brief review of each load case stating when linearity is compromised may be beneficial for those exploring performance limits.

Compression

Since these springs are processed in such a way to eliminate the existence of residual stresses, the toe of the force-deflection curve exhibits the least possible 0-0 offset of any elastic form. As the spring is compressed without any touching of the adjacent coils, the helix angle of the coils decreases. This decrease in helix angle geometry encourages the rate to decrease slightly (0.5 to 5.0 %). Then, when coils begin to touch, the rate increases to infinity. It is, however, never recommended to allow Machined Compression Springs to be compressed to the point where coils contact each other because of the chance of setting of the spring.

Extension

This load case is similar to compression in regards to the toe of the force-deflection curve. The absence of residual stress is a great asset here also. Since the helix angle in this load case always increases until yielding occurs, the rate also increases (possibly up to a 10% increase).

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Torsion (unwind)

While also benefiting from minimal, residual stress, the 0-0 start of load exists with virtually no offset. This load case has two compensating aspects. Unwind tends to reduce the total number of coils which thus increases the rate. However, the coils also tend to increase the OD which reduces the rate. Usually, the net amount of rate change is very small and will be biased dependent upon geometry.

Torsion (windup)

The 0-0 load offset is again virtually nil because of the very low residual stress status. Windup increases the number of coils, thus decreasing the rate magnitude. Compensating for this aspect is the reduction of OD which increases the rate magnitude. Like before, the net amount of rate change is very small and will be biased dependent upon geometry.

Lateral Bending

This rate is quite linear for small displacements, but will increase when displacements approach 90 degrees and when coil contact occurs.

Lateral Translation

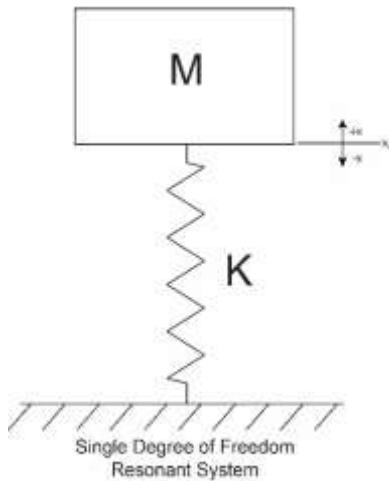
Like bending, this rate is linear for small for displacements, but will increase with increased displacements and when coil contact occurs.

Modal Response of Machined Springs

Both Wire Springs and Machined Spring possess mass and elasticity. When these two properties are present, modal vibration response is likely. With wire Springs, changing the wire size and number of coils may facilitate one's ability to shift vibration modes to more desirable frequencies, but this is done at the sacrifice of desired elastic properties. Machined Springs have this ability also. Since the mass and elasticity change significantly when the section modulus is altered in Machined Springs, a significant opportunity exists to maintain a spring's elastic characteristics while shifting the modal response to neutral frequencies. Vibration rich, aerospace applications often benefit from this Machined Spring capability.

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Multiple Start Machined Springs have a history of providing effective Single Degree of Freedom elastic elements for such systems.

Double Start Springs set the baseline for such usage, but the Triple Start Springs are the gold standard because of their uniform stiffness in all lateral directions.

Machined Spring Computations

Much analytical work has been accomplished by well known, spring experts such as A. M. Wahl, S. P. Timoshenko, J. N. Goodier and others. Design guides have been provided by SAE in the Spring Design Manual AE21, The Spring Manufacturers Institute and others. For the most part, all this work has been accomplished to provide closed form solutions for wire products. Since the geometries can be similar between Wire and Machined Springs, it is not uncommon for one to attempt to use the equations sets for both.

There is a concern particularly with Machined Springs users that closed form solutions may not fully apply. Many options exist in regards to boundary conditions and actual geometries that may exceed that researched for Wire Springs. Since geometries also change with displacement, it is unwise to not include these effects in computations. Simply said, closed form solutions for Machined Springs are sometimes correct, sometimes a little in error and sometimes very much in error, and it is difficult to determine which is what. As a general rule, closed form equations wane on accuracy when the number of coils is less than 3 and/or when the ratio of coil sides exceeds 2, height to width. For these reasons, quality FEA is nearly always needed for elastic and stress computations related to Machined Springs.