Simple and strong: Twisted silver painted nylon artificial muscle actuated by Joule heating

Seyed M. Mirvakili[a,b*], Ali Rafie Ravandi[a], Ian W. Hunter[b], Carter S. Haines[c], Na Li[c], Javad Foroughi[d], Sina Naficy[d], Geoffrey M. Spinks[d], Ray H. Baughman[c], John D. W. Madden[a]

[a]Department of Electrical and Computer Engineering, Advanced Materials and Process Engineering Laboratory, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada.

[b]Department of Mechanical Engineering, BioInstrumentation Laboratory, Massachusetts Institute of Technology, Cambridge, MA, 02139, USA.

[c]The Alan G. MacDiarmid NanoTech Institute, University of Texas at Dallas, Richardson, TX 75083, USA.

[d]Intelligent Polymer Research Institute, ARC Centre of Excellence for Electromaterials Science, University of Wollongong, Wollongong, New South Wales 2522, Australia.

ABSTRACT

Highly oriented nylon and polyethylene fibres shrink in length when heated and expand in diameter. By twisting and then coiling monofilaments of these materials to form helical springs, the anisotropic thermal expansion has recently been shown to enable tensile actuation of up to 49% upon heating. Joule heating, by passing a current through a conductive coating on the surface of the filament, is a convenient method of controlling actuation. In previously reported work this has been done using highly flexible carbon nanotube sheets or commercially available silver coated fibres. In this work silver paint is used as the Joule heating element at the surface of the muscle. Up to 29% linear actuation is observed with energy and power densities reaching 840 kJ m^{-3} (528 J kg^{-1}) and 1.1 kW kg^{-1} (operating at 0.1 Hz, 4% strain, 1.4 kg load). This simple coating method is readily accessible and can be applied to any polymer filament. Effective use of this technique relies on uniform coating to avoid temperature gradients.

Keywords: artificial muscles; nylon; linear actuators; fishing line; sewing thread

1. INTRODUCTION AND BACKGROUND

Artificial muscle is a generic term used for materials or devices that can reversibly contract, expand, or rotate within one component due to an external stimulus (such as voltage, current, pressure or temperature).[1] A thermally driven actuator has been demonstrated to produce tensile actuation of up to 10% in twisted and coiled multi-walled carbon nanotube yarns infiltrated with wax.[2] Linear and torsional actuation were also observed in wax infiltrated niobium twisted nanowire yarns.[1,3] Recently it was demonstrated that highly oriented polymer fibers with negative thermal

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* seyed@mit.edu, Molecular Mechatronics Lab, University of British Columbia and BioInstrumentation Lab, Massachusetts Institute of Technology.

expansion coefficients – in particular nylon and polyethylene - can be twisted to form coils to produce tensile actuation of more than 40% with a work density of 5.3 kW/kg.[4] These readily available and low cost materials make the actuators easily accessible. In this work we have demonstrated a simple electrically conducting coating that can be applied to nylon coils as a means of electrically heating the actuator while also achieving relatively high energy and power densities.

The actuation mechanisms are presented by Haines *et al* [4], suggesting the twisting of the fibres reorients the aligned polymer chains in a helical fashion. This helically oriented direction then attempts to contract upon heating, while there is also a radial expansion, leading to an overall untwisting of the fibre. When the fibre is coiled, this reversible twisting action produces a change in the coil length. The mathematical relationship between change in twist and coil bias angle (and hence coil length) is described in Appendix A.

2.   METHODS

Coiled and two-ply nylon actuators were made by twisting nylon monofilaments such as nylon fishing lines (River Trail[®] 6526-208, 188 μm, and RedWolf[®] 20 LB , 436 μm) and sewing thread (nylon 6,6 from The Thread Exchange online shop, 296 μm diameter) and painting them with silver paint (SPI[®], flash dry). The silver paint was applied to the twisted nylon during the twisting process just before coiling starts. After the silver paint was fully dried, the twisting procedure was resumed and a coiled structure was achieved. In order to make a two-ply yarn, the same procedure was used except after resuming the twisting procedure, the middle of the yarns was held to make a snarl. Then by lowering the tension, a twisted two-ply yarn was achieved. In both procedures, another thin layer of silver paint was coated on the nylon structure while it was stretch under loads of around 1 to 8 N (depending on the diameter of the filament and structure – coiled or two-ply – different loads were used). Figure 1 shows the test setup for a silver painted nylon actuator.
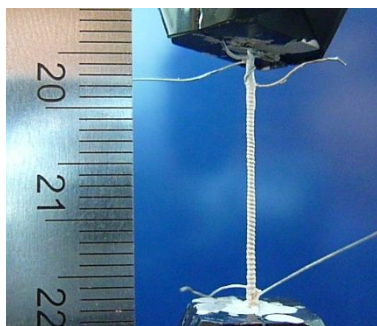

Figure 1 – Optical image of a silver painted nylon actuator.

Nylon silver coated fibers were used for comparison. The preparation procedure was the same as reported in our recent work.[4] Tensile actuation of the muscle was measured by image processing of high resolution video files. To further analyze the performance of the silver painted nylon monofilaments, thermal images of the artificial muscle were acquired by a high resolution thermographic camera, VarioCAM[®]. In order to compensate for the emissivity of the silver coating and the neat nylon, values of 0.42 [5] and 0.85 [6] were used for calibration, respectively. The nylon was coated

with silver in situ. For the first 20 cycles the load was 5.6 N. After "training" the yarn, a 3.6 N load was used for the thermal measurements. A dynamic mechanical analyzer (Bose, Electroforce 3100) was used to characterize the mechanical properties of the artificial muscle. Life cycles of two coiled structures were measured by hanging weights from the coiled filaments and measuring the strain over time.

3. RESULTS AND DISCUSSION

The silver paint coating offered linear resistance of 100 to 600 Ω per m length of the coiled actuator in the relaxed state (less than 100 Ω per m length of the straight coated nylon) with almost uniform thermal distribution at surface of the artificial muscle (Figure 2).
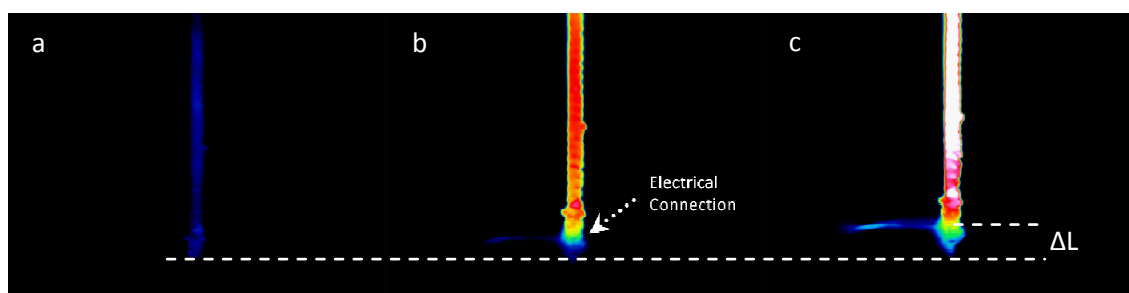

Figure 2 - Thermal image of silver painted nylon actuator a) at onset of Joule heating, b) during actuation, and c) at maximum contraction.

Tensile actuation of up to 29% with respect to the un-stretched coil length was achieved (188 μm nylon, 4.1 MPa load per coil area, 26.8 MPa per filament area). 10% strain with respect to the un-stretched coil length (188 μm nylon, 4.1 MPa load) was observed for coiled and two-ply nylon fibers.

At 29 % only a few cycles have so far been achieved before failure of the coating, increasing to 1,000 cycles at 10 % strain, and 2,000 at 4 % strain. In these cases a load of 14 N or 14.5 MPa – normalized to coil cross-section area – is applied, and the energy and power densities in the half cycle are 580 kJ m^{-3} (365 J kg^{-1}) and 122 W kg^{-1}, 92 MPa – normalized to filament cross-section area - with energy and power density of 3.68 MJ m^{-3} (2.3 kJ kg^{-1}) and 772 W kg^{-1}, respectively. Operation without any loss in the performance for more than 10,500 cycles without observed degradation is achieved at 2% tensile actuation (under a load of 6.3 MPa – normalized to coil cross-section area, 42 MPa by filament area). The energy and power densities reach 840 kJ m^{-3} (528 J kg^{-1}) and an impressive 1.1 kW kg^{-1} (operating a 0.1 Hz, 4% strain, 14 N load). Frequency response was observed for a two-ply nylon yarn by pulsing the actuator with a square wave signal with a duty cycle of 50% (Figure 3).

At lower frequencies the filament will overheat, and thus power needs to be regulated. The rate of response is limited in this case by cooling time. Immersion in water leads to much faster response, as seen in Figure 5 (in this case a Nylon 6,6 silver-plated multifilament sewing thread from Shieldex was used).
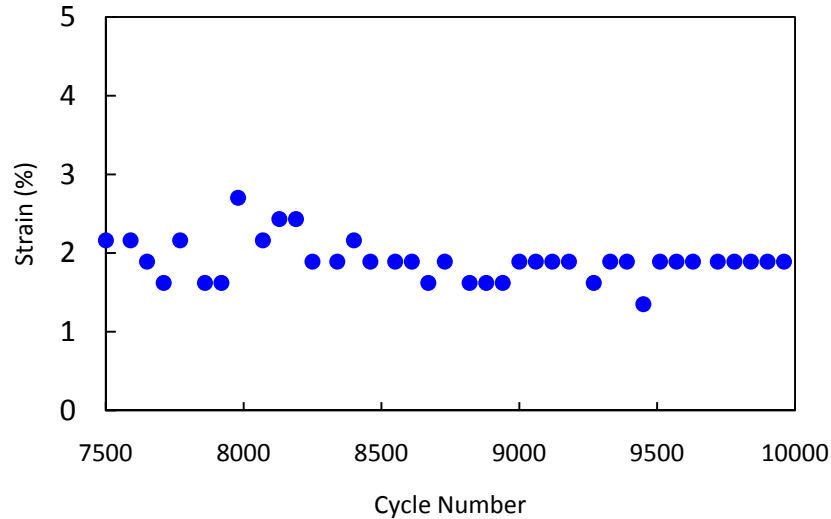
Figure 3 – The last 2500 cycles of the life cycle test. Cycling of a silver painted nylon coiled filament with a 120 g mass suspended from it. The nylon had a coil diameter of 490 μm and filament diameter of 188 μm. Input electrical power of 0.45 W was applied at 0.5 Hz with duty cycle of 50%. After 10,560 cycles of testing at input power of 0.45 W, maximum strain of 11% was achieved by increasing the input power to 0.7 W and decreasing the frequency to 0.16 Hz.

Cycle life in these structures is not as high as with the carbon nanotube coatings [4], perhaps due to the non-uniformity of the coating that is applied by hand, leading to more highly resistive regions that are subject to overheating and also possibly to due to rigid nature of metals which crack under too much deformation. However, life cycle tests show that silver painted nylons can operate for more than 10,560 cycles without any noticeable loss in their performance. The efficiency of silver painted nylon actuators was calculated to be ~ 0.3% based on the input electrical power and mechanical power as output in one half cycle. This is similar to efficiencies reported previously.[4]

Figure 4 shows the frequency response of the same actuator used to obtain the response in Figure 3. Resonance frequency of the coiled yarn was not reached. Operation at lower frequencies than shown required a drop in power to avoid melting. In future such a drop in power might be achieved using closed loop control. The frequency response was limited by cooling time, as the Joule heating and heat transfer through the nylon was achieved much faster (< 0.2 s). The frequency response of a twisted silver-plated multifilament sewing thread under a load of 25 MPa was measured in water at room temperature. Pulses of 46 V were applied at 5 Hz which resulted in symmetric 5% tensile actuation.
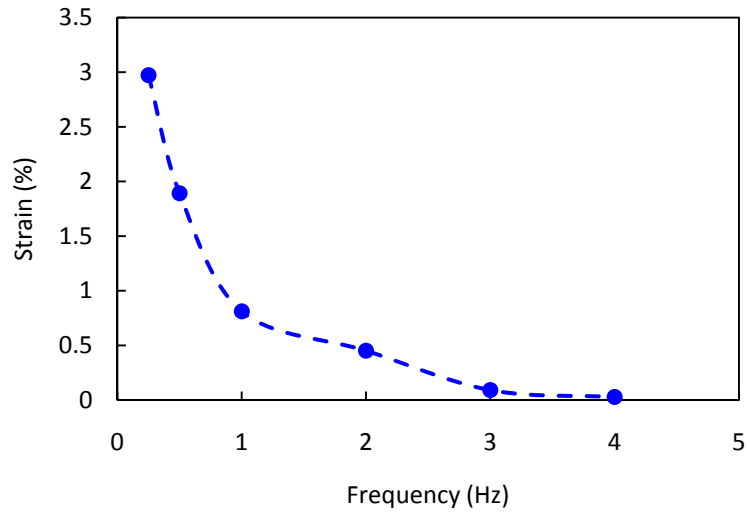
Figure 4 – Frequency response of the actuator in Figure 3. Dashed lines are used to show the trend.
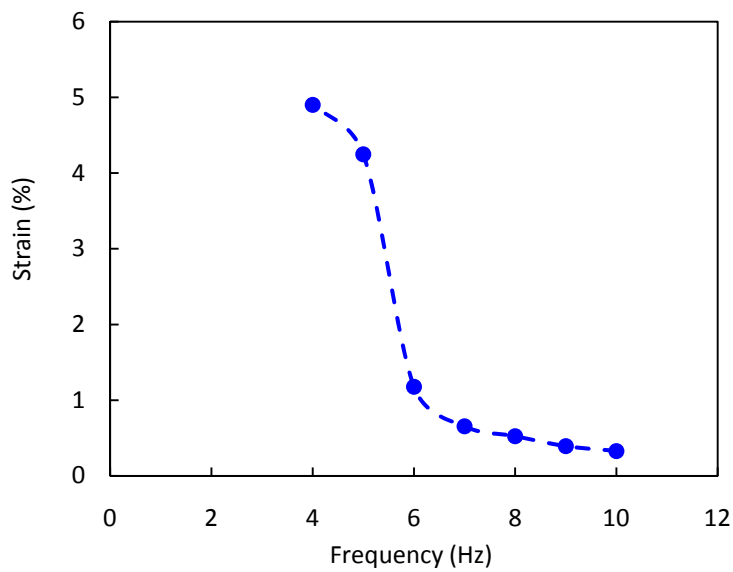

Figure 5 – Frequency response of a silver-plated multifilament sewing thread under a load of 25 MPa. Dashed lines are to illustrate the trend.

The spring constant of a coiled structure with coil diameter of 688 μm, length 55 mm was measured to be 1.6 kN.m^{-1} (Figure 6). This property suggests an effective modulus (based on coil area) of 240 MPa.   Thus it takes a coil area normalized stress of 24 MPa to produce a 10 % extension of the coil, and a 70 MPa stress to produce a 29 % extension. Previous work [4] has shown that the magnitude of active deflection is nearly independent of load. If a load is applied and then lifted, then in order to lift it at least back to the unloaded length (and hence do zero or more work in one

cycle), the maximum loads are less than or equal to 24 MPa for 10 % strain and 70 MPa at 29 % actuation. This maximum load, akin to a blocking force in muscle, will be reduced by any creep in the material when it is exposed to high temperature under load, and will also be affected by the modulus in the high temperature state. Further work is needed to establish the true blocking forces for these new actuators.
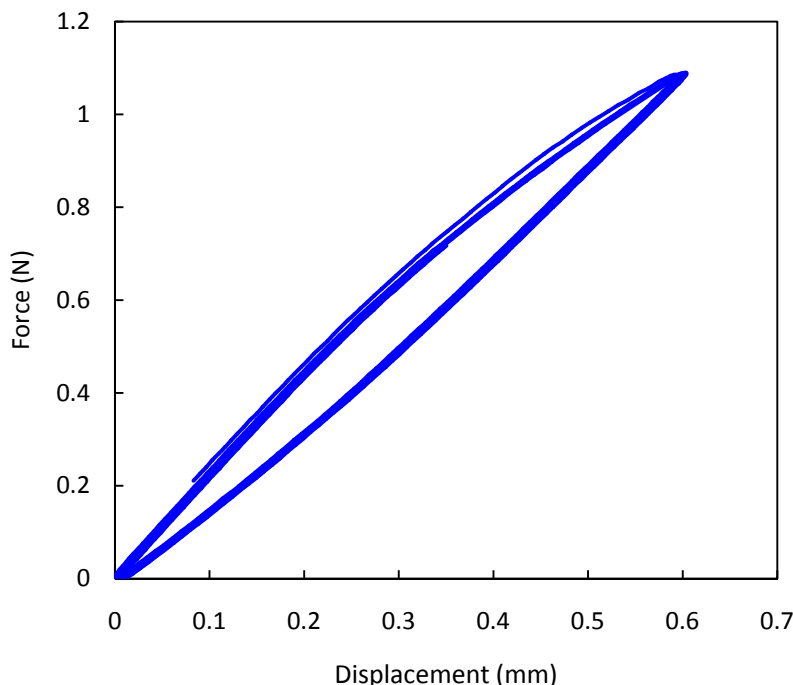

Figure 6 – Force vs. displacement measurement on a 688 μm diameter nylon 55 mm long nylon coil.

Using silver paint has some advantages, for example fabrication of this actuator is simple, fast, and relatively inexpensive. By changing the resistivity or thickness of the coating material a lower or higher voltage can be used to obtain the same power input. This can be achieved for example by thinning the silver paint (using acetone or ethanol or paint thinner in general). In the case of breakdown (damage to the coating), it can be fixed easily by recoating the yarn in situ. And last but not least, virtually anyone can make this actuator (without any need to grow carbon nanotubes). A disadvantage is that the cycle life is significantly lower than that reported in other nylon actuators [4].

4. CONCLUSION

In conclusion, in this work, a simple method for fabricating nylon fishing line artificial muscle is presented. The application of a conductive paint - silver paint in this case - to the structure enables up to 29% tensile actuation upon Joule heating. Actuator fabrication requires only a twisted nylon thread, a drill or rotary motor (for twisting and coiling), conductive paint, and a low voltage source (which could be batteries). With this technique, linear actuation up to 29% is observed with energy and power densities reaching 840 kJ m^{-3} (528 J kg^{-1}) and 1.1 kW kg^{-1} (operating a 0.1 Hz, 4% strain, 1.4 kg load). The technology is readily accessible, unlike many previous artificial muscle technologies where high voltages [9], or specialty materials [2], [3], [10] are needed.

Appendix A: Theory of the muscle mechanics:

Nylon fishing lines are composed of polymer chains that are largely oriented along the length of the nylon. By inserting twist in the monofilament, the length of the filament decreases; however, the diameter increases. This can be explained by the helical model in reference [3]. When heat is applied, the nylon fiber contracts in length while it expands in diameter due to its semi-crystalline structure [7] shown in figure 7. This anisotropy in thermal contraction amplifies the actuation and leads to a tensile actuation of up to 20% for the case of silver painted fishing lines.
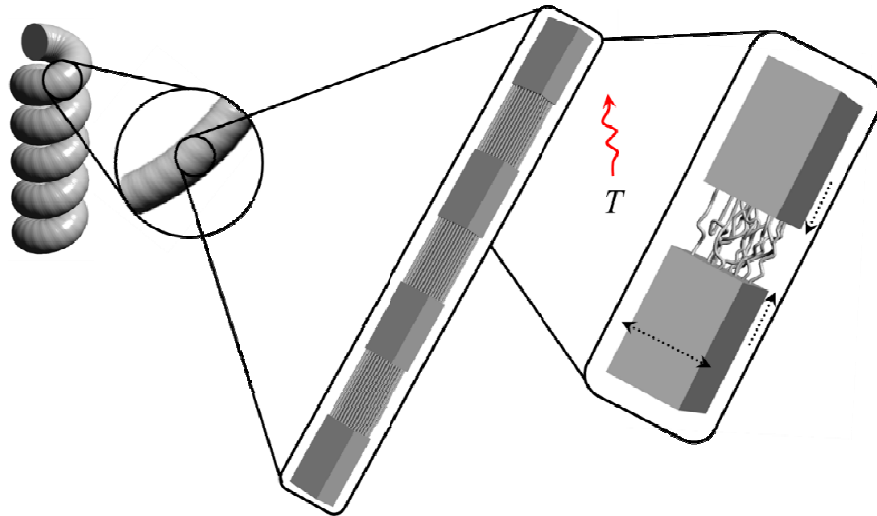

Figure 7 – Semi-crystalline structure of the polyethylene and nylon. Increasing the temperature leads to thermal expansion of the crystalline region and thermal contraction in fiber axis.

The contraction in fiber length (due to the negative thermal coefficient of expansion) then should be compensated by untwist in the filament, providing that the nylon is kept at constant length. As the structure of this actuator suggests, spring mechanics [8] can be used to model the mechanical performance of the muscle and helps to find the amount of change in twist. Equation 1 relates the torsion as function of radius and twist angle, as derived in the appendix. The equation is derived here by starting from Frenet-Serret equations. Figure 8 illustrates the required parameters for deriving the equation.
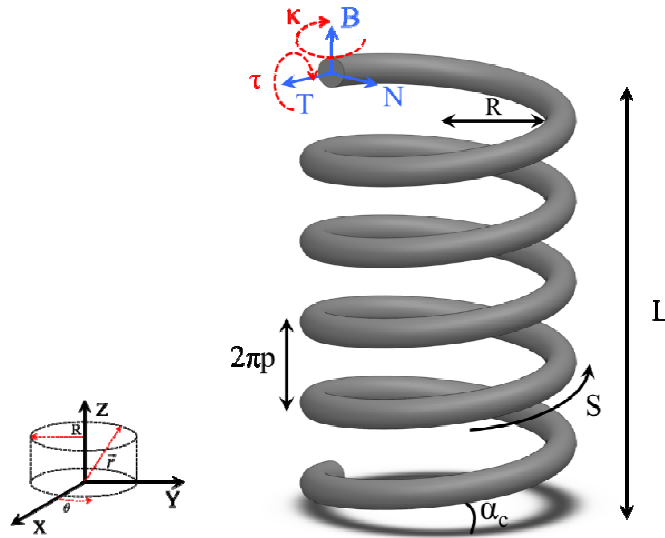
Figure 8 – $\vec{r}(s,t)$ is the position vector as a function of time and S is the length coordinate along the spring axis.

By taking derivative of tangential $\hat{T}(s,t) = \dfrac{\partial \vec{r}(s,t)}{\partial s}$, normal $\hat{N}(s,t) = \dfrac{\partial \hat{T}(s,t)}{\partial s} \bigg/ \left\| \dfrac{\partial \hat{T}(s,t)}{\partial s} \right\|$, and binormal

$\hat{B}(s,t) = \hat{T}(s,t) \times \hat{N}(s,t)$ unit vectors with respect to ds, Frenet-Serret relations can be obtained as: $\dfrac{\partial \hat{T}}{\partial s} = \kappa \hat{N}$,

$\dfrac{\partial \hat{N}}{\partial s} = \tau \hat{B} - \kappa \hat{T}$, and $\dfrac{\partial \hat{B}}{\partial s} = -\tau \hat{N}$, where κ and τ are the curvature and torsion (as shown in Figure 8) and are

defined as: $\kappa = \hat{N} \cdot \dfrac{\partial \hat{T}}{\partial s}$ and $\tau = \hat{B} \cdot \dfrac{\partial \hat{N}}{\partial s}$.

The position vector, $\vec{r}(s,t)$, in the Cartesian coordinate, can be written as:

$\vec{r} = x\hat{i} + y\hat{j} + z\hat{k} = R\cos(\theta)\hat{i} + R\sin(\theta)\hat{j} + h\theta\hat{k}$, where $h = \dfrac{H}{2n\pi}$ is the helix pitch per radian. Now ds can be

found from $ds = \sqrt{R^2 \sin(\theta)^2 + R^2 \cos(\theta)^2 + h^2}\, d\theta = \sqrt{R^2 + h^2}\, d\theta$.

The tangential, normal, and binormal unit vectors can be written in terms of $\hat{i}, \hat{j}, \hat{k}$ as:

$\hat{T} = -\cos(\alpha)\sin(\theta)\hat{i} + \cos(\alpha)\cos(\theta)\hat{j} + \sin(\alpha)\hat{k}$,

$\hat{N} = -\cos(\theta)\hat{i} - \sin(\theta)\hat{j}$,

$\hat{B} = \sin(\alpha)\sin(\theta)\hat{i} - \sin(\alpha)\cos(\theta)\hat{j} + \cos(\alpha)\hat{k}$.

By using the curvature and torsion definitions and applying chain rule, curvature and torsion can be found to be:

$\kappa = \dfrac{\cos(\alpha)}{\sqrt{R^2 + h^2}}$ and $\tau = \dfrac{\sin(\alpha)}{\sqrt{R^2 + h^2}}$. Since $\cos(\alpha) = \dfrac{R}{\sqrt{R^2 + h^2}}$ and $\sin(\alpha) = \dfrac{h}{\sqrt{R^2 + h^2}}$; therefore,

$\kappa = \dfrac{\cos^2(\alpha)}{R}$ and $\tau = \dfrac{2\sin(\alpha)\cos(\alpha)}{D}$. Torsion can be written in units of turns and therefore the number of turns is:

$$\Delta T = \frac{\Delta \tau}{2\pi} = \frac{\sin(\alpha')\cos(\alpha')}{\pi D'} - \frac{\sin(\alpha)\cos(\alpha)}{\pi D}, \qquad (1)$$

where α' and α are the final and initial bias angle.

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