Gauge-invariant Geometry of Space Curves: Application to Boundary Curves of Möbius-type Strips

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We derive gauge-invariant expressions for the twist $T_w$ and the linking number $Lk$ of a closed space curve, that are independent of the frame used to describe the curve, and hence characterize the intrinsic geometry of the curve. We are thus led to a frame-independent version of the Calugareanu-White-Fuller theorem $Lk = T_w + W_r$ for a curve, where $W_r$ is the writhe of the curve. The gauge-invariant twist and writhe are related to two types of geometric phases associated with the curve. As an application, we study the geometry of the boundary curves of closed twisted strips. Interestingly, the Möbius strip geometry is singled out by a characteristic maximum that appears in the geometric phases, at a certain critical width of the strip.

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Construct a Möbius strip (MS) by taking a long rectangular strip of paper, making a half-twist at one of its ends, and bringing the ends together. This strip has only one edge or boundary curve, which is a closed twisted space curve. Now, keeping the width constant, slide one of the ends on top of the other, so as to effectively decrease the length of the strip, and watch how the geometry of the boundary curve changes. Once the ratio of the width of the strip to its length increases to a certain value, a sharp twist appears on the boundary, which soon develops into a cone-like singularity. Since the boundary curve of the strip encodes information about this ratio, a key question is how the geometry of the curve changes with this parameter. Answering this is important in view of the fact that diverse systems, such as biopolymers\textsuperscript{1}, vortex filaments in a fluid\textsuperscript{2}, magnetic field lines\textsuperscript{3}, twisted optical fibers\textsuperscript{4}, and phase space trajectories in dynamical systems\textsuperscript{5}, can be modeled using closed twisted space curves. To this end, we first present a novel framework to describe the geometrical characteristics of a general twisted space curve, and then apply it to the boundary curve of the MS, as well as to other strips related to the MS, i.e., strips with several half-twists.

A basic concept in the study of the geometry of a space curve is that of a thin ribbon\textsuperscript{6}, one of whose edges is the given curve. To construct the other edge of the ribbon, one must first choose an orthogonal frame to describe the curve. A result which is widely applied is the celebrated Calugareanu-White-Fuller (CWF) theorem for a closed ribbon\textsuperscript{6–9}. It states that the integer linking number $Lk$ of the two edges of the ribbon can be written as the sum of the twist $T_w$ of the ribbon and the writhe $W_r$ of the space curve. $T_w$ characterizes the twist of the ribbon about its axis, while $W_r$ is a measure of the non-planarity and non-sphericity\textsuperscript{10} of the space curve.

Now, given a space curve, an infinite number of ribbons can be associated with it, owing to the inherent freedom in the choice of the orthogonal frame used. Each frame will yield a certain value for $T_w$, and hence for $Lk$. It is therefore desirable to find a way to define an intrinsic twist $T_w^g$ of a curve about its axis, which would have a unique value, independent of the frame used. In this Letter, we achieve this by invoking the principle of gauge invariance. This leads us to the definition of an intrinsic linking number $Lk_g$ of a space curve. In short, we obtain a ribbon-independent, gauge-invariant version of the CWF theorem for a closed space curve, given by

$$Lk_g = T_w^g + W_r.$$ (1)

We also show that $T_w^g$ can be viewed as a geometric phase or an anholonomy associated with the space curve. This classical geometric phase bears a close analogy to the quantum geometric phase obtained in the Aharonov-Anandan formulation\textsuperscript{11}. Further, we show that $W_r$ can also be interpreted as another distinct type of geometric phase, that can be associated with a certain moving space curve\textsuperscript{12}. It follows that the linking number $Lk_g$ of a closed space curve can be viewed as the difference between two distinct geometric phases associated with the curve.

Our analysis has a distinct advantage over the usual ribbon formulation\textsuperscript{6} in the geometric characterization of curves with inflexion points, i.e., points where the curvature vanishes. Although curves with inflexion points are common in many applications, one assumes their absence in the standard formulation. In contrast, while $T_w$ and $Lk$ change discontinuously by unity whenever the curve develops an inflexion point, $T_w^g$ and $Lk_g$ remain unaffected. Hence the relationship (1) holds even when the curve has inflexion points, which is a very desirable feature in applications. To illustrate this, we present a systematic study of the change in geometry of the boundary curve of the Möbius strip, as well as those of other multi-twisted strips, as the strip-width varies. These curves typically acquire inflexion points at a certain critical strip-width.
We begin by developing a frame-independent formalism for describing the geometrical characteristics of a general closed space curve \( C_1 = r(s) \) of length \( L \), parameterized by the arc length \( s \). The unit tangent vector to the curve is \( T(s) = r_s \), where the subscript \( s \) stands for the derivative with respect to \( s \). Let \( U \) be a unit vector perpendicular to the curve, so that \( T, U, V = T \times U \) define an orthogonal frame at every point on the curve. Since \( U \) must lie on the plane perpendicular to the tangent, there is an inherent freedom in choosing its direction on this plane, signifying a certain gauge freedom in its choice.

As mentioned in the beginning, the ribbon is bounded by \( C_1 = r(s) \) and a neighboring curve \( C_2 = r(s) + \epsilon U(s) \), where \( \epsilon \) is small. The twist \( T_w \) of the ribbon is defined\(^6\) as\(^6\) 

\[
T_w(r, U) = \frac{i}{2\pi} \int_0^L (T \times U) \cdot U ds = \frac{i}{2\pi} \int_0^L Q^* \cdot Q_s ds.
\]

Since we seek frame-independent geometrical characteristics of the curve, we make a gauge transformation \( Q \rightarrow q = (u + iv)/\sqrt{2} = Q e^{i\eta(s)} \), which is essentially the rotation of the frame about the tangent, by an angle \( \eta(s) \). It is easy to verify that \( q^* \cdot q_s = Q^* \cdot Q_s + i \eta_s \). On integration, this leads to

\[
i \int_0^L q^* \cdot q_s ds = i \int_0^L Q^* \cdot Q_s ds + [\eta(0) - \eta(L)].
\]

We refer to this as tangent anholonomy, since the plane is related to an

\[
T_w(r, U) = \frac{i}{2\pi} \int_0^L Q^* \cdot Q_s ds = \frac{1}{2\pi} \arg \left[ Q^*(0) \cdot Q(L) \right].
\]

In what follows, we will be called the gauge-invariant linking number of the curve. Combining Eqs. (4) and (6), we obtain Eq. (1), the gauge-invariant form of the CWF theorem.

The advantage of the gauge-invariant formulation is that the expressions for \( Tw_g \) and \( Lk_g \) can now be written down in any frame. It is convenient to use the Frenet-Serret (FS) frame\(^13\), where \( U \) and \( V \) are the principal normal \( T_s/T_s \) and the binormal \( B = T \times N \), respectively. The frame rotation is given by the FS equations, \( T_s = \kappa N + B \), \( N_s = -\kappa T + \tau B \), \( B_s = -\tau N \), where \( \kappa = |T_s|/r \) is the curvature and \( \tau = T \cdot (T_s \times T_{ss})/(T_s \cdot T_s) \) is the torsion. Setting \( U = N \) in Eqs. (2) and (5), and substituting into Eq. (4), we get

\[
T_w = \frac{1}{2\pi} \int_0^L \tau ds - \phi_T(r, N).
\]

In what follows, we show that \( T_w \) can be viewed as a geometric phase or an anholonomy associated with the space curve. Using the FS equations, we see that the first term in Eq. (9), i. e., the integrated torsion, is the rotation of the \( (N, B) \) plane about the tangent, as it moves once around the curve. This is called Fermi-Walker transport\(^14\). This term can be regarded as the dynamical phase accumulated by the \( (N, B) \) plane. The second term in Eq. (9) is obviously the corresponding total phase. Therefore, the gauge-invariant geometric phase \( \phi_g \) associated with the \( (N, B) \) plane rotation on the curve is just the difference of the two phases above, i. e.,

\[
\phi_g = \phi_T(r, N) - (2\pi)^{-1} \int_0^L \tau ds.
\]

Using Eq. (9), we get

\[
\phi_g = -T_{w_g},
\]

showing that the gauge-invariant twist \( T_{w_g} \) is just the negative of the geometric phase \( \phi_g \) (in units of \( 2\pi \)). This result is valid for both open and closed curves. We refer to this as tangent anholonomy, since the plane involved is perpendicular to the tangent.

Next, we show that the writhe \( W_r \) is related to another type of geometric phase. In Eq. (7) for \( W_r \), the linking number \( Lk(r, U) \) of the curves \( C_1 \) and \( C_2 \) depends on the choice of \( U \), and \( W_r \) is the writhe of the curve. Following Dennis and Hannay\(^10\), we find it convenient to cast the usual expression\(^6\) for \( W_r \) in terms of the chord \( C \), as follows:

\[
W_r = \frac{1}{4\pi} \int ds_1 \int ds_2 \left( \frac{\partial C}{\partial s_1} \times \frac{\partial C}{\partial s_2} \right) \cdot C.
\]
unit chord $C$ is a function of two independent variables, $s_1$ and $s_2$. Thus $C$ can be regarded as a unit tangent vector to a certain space curve parameterized by $s_1$ for a given $s_2$, and which moves as $s_2$ varies. Therefore we can use the frame evolution formalism for a moving space curve[12]. Using the idea of Fermi-Walker transport once again, it can be shown that $W\tau$ is geometric phase associated with the rotation of the plane perpendicular to the chord $C$. Hence $W\tau$ can be viewed as a chord anholonomy. These results show that $Lk_g$, which is an integer, is the difference between the chord anholonomy and the tangent anholonomy, which are not necessarily integers.

We now apply the gauge-invariant CWF theorem to study the geometry of the boundary curves of twisted closed strips. These strips are surfaces described by

\[
\begin{align*}
x &= \left(R + w \cos \frac{nt}{2}\right) \cos t, \\
y &= \left(R + w \cos \frac{nt}{2}\right) \sin t, \\
z &= w \sin \frac{nt}{2},
\end{align*}
\]

(10)

with parameters $-\alpha \leq w \leq \alpha$ and $0 \leq t \leq 2\pi$. The length of the strip is $2\pi R$, and we set $R = 1$ for convenience. $\alpha$ is the half-width of the strip, and the integer $n$ is the number of half-twists on the strip (so that $n = 1$ refers to the well-known Möbius strip). The boundary of the strip corresponds to $w = \pm \alpha$ in Eq. (10). For odd $n$, the strip is a non-orientable surface with one boundary curve, so that the range of $t$ is $[0, 4\pi]$. For even $n$, the strip is orientable, with two boundary curves with similar geometries, and the range of $t$ is $[0, 2\pi]$ for each curve. Topologically, for all widths, the boundary curves of the odd-$n$ strips with $n > 1$ are knotted curves (e. g, it is a trefoil knot for $n = 3$, a five-pointed star knot for $n = 5$, etc.), while those of the even-$n$ strips are not knotted. The boundary curve of the MS clearly does not fall in either of these classes, since it is the only case in which the boundary curve of a non-orientable strip is not a knot. For all $n$, the geometry of the boundary curve of the strip has a non-trivial dependence on its width, as we shall show explicitly.

Symbolic manipulation[15] facilitates the analytic calculation of curvature and torsion of the boundary curves of the strips given by Eq. (10). For each $n$, when the half-width attains a critical value $\alpha_c = (1 + \frac{\alpha}{2} n^2)^{-1}$, the curvature vanishes at $n$ points on the boundary curve[16]. For the MS, the critical boundary curve, corresponding to a half-width $\alpha_c = \frac{1}{2}$, has a single inflexion point (labeled by $t = t_c$). Plotting the boundary curves of the MS with various half-widths in Fig. 1, we see that the critical value at the above $\alpha_c$ is distinguished by a local ‘straightening’ of the curve around the point $t_c = 2\pi$.

A Taylor expansion of $\kappa(t)$ and $\tau(t)$ near $\alpha_c$ and $t_c$ gives

\[
\kappa \simeq (\alpha - \alpha_c)^2 + 9b^2 v_c^2 (t - t_c)^2 |d\tau/dt|_{t_c} \text{ and } \tau \simeq -3b(\alpha - \alpha_c)/(\alpha - \alpha_c)^2 + 9b^2 v_c^2 (t - t_c)^2,
\]

where $b = \frac{S}{2}$ and $v_c = |d\tau/dt|_{t_c} = 1/\sqrt{5}$. These expressions show that at $t = t_c$, $\tau$ is singular at $\alpha_c$, and changes sign as the parameter $\alpha$ passes through $\alpha_c$. We point out that the functional form of $\kappa$ and $\tau$ near the inflexion point is identical to that obtained in an earlier study[3], which investigated the behavior of a curve in the vicinity of an inflexion point, the only difference being the value of $b$, which was unity for the illustrative example of the curve chosen there.

To find the effect of the above singularity in $\tau$, we calculate the angle of twist of the ($\mathbf{N}, \mathbf{B}$) plane over an interval $2t_0$ centered about $t_c$: this is $\int_{t_0}^{t_0 + t_c} \tau v dt = \tan^{-1} \left( t_0/[b v_c (\alpha - \alpha_c)] \right)$. As we pass through $\alpha_c$, this angle changes from $-\pi$ to $\pi$ (irrespective of the value of $t_0$), giving rise to a jump of $2\pi$, as discussed in Ref. [3].

Interestingly, the above jump in the integrated torsion resulting from an inflexion point is accompanied by an identical jump in $\varphi_T(r, \mathbf{N})$. A Taylor expansion of $\mathbf{N}$ near inflexion point yields $\mathbf{N} \simeq \kappa^{-1} [a_1(t - t_c), a_2(\alpha - \alpha_c), a_3(\alpha - \alpha_c)]$, where $a_i(i = 1, 2, 3)$ are constants. This shows that at $t = t_c$ for $\alpha \to \alpha_c - 0$, $\mathbf{N}$ rotates by $\pi$ about the tangent, while for $\alpha \to \alpha_c + 0$, it rotates by $-\pi$. The same is also true for $\mathbf{B}$. Therefore, the angle of rotation of the ($\mathbf{N}, \mathbf{B}$) plane increases by $2\pi$ as we pass the inflexion point. As a result, $Tw_g$ computed from Eq. (9) does not show a jump if the curve develops an inflexion point. The same behavior holds good for $Lk_g$.

Next, we report the results for the dependence of $W\tau$ and $Tw_g$ of the boundary curves of the closed twisted strips (Eq. (10)) on the strip width. $W\tau$ of the boundary curve was directly computed from Eq. (7) using numerical integration. In Fig. 2, we plot the dependence of the writhe $W\tau$ of the boundary curves of various twisted strips on the dimensionless parameter $a = (\alpha - \alpha_c)/\alpha_c$. We find that for the boundary curves of infinitesimally

\[\text{FIG. 1: Boundary curves of Möbius strips with half-widths } \alpha = 0.6, 0.8 \text{ and } 1.0. \text{ The middle curve is the critical curve with } \alpha = 0.8, \text{ and the local straightening of this curve near the inflexion point is clearly visible.}\]
thin narrow-width strips with $\alpha \simeq 0$, $WR = n$ for all odd $n$, while $WR = 0$ for all even $n$. We have therefore plotted, for convenience, a shifted write ($WR - n$) for $n = 1, 3, 5, 7$. For $n = 2, 4, 6$, $WR$ has been plotted without such a shift.

As seen in Fig. 2, $WR$ does not undergo jumps, and remains smooth as the boundary curve develops inflexion points at a corresponding critical width. The variation of $WR$ with strip-width is significantly larger for the odd $n$, non-orientable class of strips, as compared to the even-$n$, orientable class. Another notable feature is that the MS boundary curve gets singled out due to its characteristic maximum near the critical width. This is a reflection of the fact that the MS boundary curve with $n = 1$ is indeed special, as it belongs to a class distinct from the rest, as we have discussed above.

Analytical expressions for $\tau$, $N$ and $B$ were used to calculate $Tw_g$ from Eq. (9). The variation of $Tw_g$ with $a$ for various $n$ values turns out to be essentially complementary to the variation of $WR$ given in Fig. 2, and hence is not given here. It is sufficient to note that $Tw_g$ for the MS boundary curve has a characteristic minimum, and so the geometric phase $\phi_g = -Tw_g$ has a maximum. By adding $WR$ and $Tw_g$, we find that $Lk_g = (n + 2)$ for odd values of $n$, while $Lk_g = 1$ for even values of $n$.

The general CFW theorem Eq. (1) relates topological and geometric properties of a space curve, and would therefore find many applications in physics and biology. For instance, the two boundary curves of an orientable twisted strip can represent the two strands of a closed DNA[1], the distance between them being the strip width. Our results may also find application in the fabrication of biomaterials using molecular architecture[17], where information about the conformational changes in the strands caused by the variation of width-to-length ratios, number of twists, etc., would be useful.

Since the geometric phase describes the change in the polarization of light[4] as it propagates along a nonplanar circuit, our results on the dependence of the geometric phase $\phi_g$ on the width-to-length ratio of the strip can be exploited to tune polarizations. This can be achieved by fabricating an optical fiber glued to the boundary of an opaque twisted strip, and studying light propagation through the fiber.

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\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig2.png}
\caption{Dependence of $WR$ of boundary curves of various $n$-twisted strips (shifted down by $n$ for all odd $n$) on $a = (\alpha - \alpha_c)/\alpha_c$. The top curve corresponds to the M"obius strip with $n = 1$, followed by three curves that correspond to $n = 2, 4, 6$ (top to bottom). The three other curves below these correspond to $n = 3, 5, 7$.}
\end{figure}