BRAIDING TAKE-UP SPEED OPTIMIZATION - CASE STUDIES

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Abstract
Circular braiding is a composite material manufacturing process for production of bi- and triaxial tubular preforms that are usually impregnated and cured using Resin Transfer Moulding. The process currently lacks automatic generation of optimum machine control data. Helping to solve this problem, a newly developed geometry-based procedure for take-up speed optimization is applied to various complex mandrel shapes to assess its strengths and weaknesses. As a result, the error of the virtual braid angle could be reduced to a few degrees. However, in order to assess the validity of the generated process settings, it is recommended to take into account the manufacturing constraints regarding the prevention of yarn slack and fiber slip.

Introduction
For many years, circular braiding has been a suitable candidate for automated series production of tubular composite preforms with a bi- or triaxial layup. Usually, the next step in the process chain involves impregnation and curing with Resin Transfer Moulding. In the design process, virtual equivalents can involve simulation and optimization of both the product and the manufacturing process. Simulation of the circular braiding process is possible using a kinematic [1,2,3] or a finite element [4,5] process description. Simulations typically require the machine control parameters as input and generate the braided structure as output. However, for the reverse order or ‘inverse solution’ [1,3] with the fiber distribution on an arbitrary mandrel as input and the machine control data as output, an automated method is not publicly available. The latter route is further referred to as the ‘optimization’.

The objective of this work is to numerically apply the optimization method presented in [6] to various mandrel geometries in order to assess the resulting output braid angle and take-up speed profile. In the remainder of this work, first, the braiding process is introduced, followed by a review of previous work. Next, the mathematical model is summarized, followed by its application to mandrel geometries. Finally, the outcome is discussed.

Process description
A schematic representation of the circular braiding process is shown in Fig. 1. The mandrel moves relative to the machine through a circle of warp and weft or ‘bias’ spools. The mandrel moves with an axial ‘take-up’ speed, where the term ‘take-up’ originates from historical context where the machine axis was oriented vertically. The yarns are pulled from spools mounted on carriers that move in the spool plane. One group of spools, denoted as the warp spools, moves clockwise while the other group of spools, the weft spools, move counter-clockwise, both with the same speed. The two yarn groups interlock, forming a closed biaxial fabric on the mandrel. Optionally a third group of stem yarns can be inserted to form a triaxial braid as shown in Fig. 2. Stem yarns are deposited in the mandrel length direction, providing improved structural properties for axial loading and bending. Guide rings can be used to enable reverse braiding and to improve process control. The yarns move from the spools to the mandrel through the funnel-shaped ‘convergence zone’. The point where a yarn comes in first contact with the mandrel is denoted as the ‘fell point’. For multilayered products, the mandrel can be repeatedly overbraided in forward and reverse direction along the full component length or only locally.

Previous work
Earlier optimization approaches are based on a kinematic process description and require the mandrel and machine geometry and the required braid angle \( \alpha \), as shown in Fig. 2, as input. All approaches assume straight yarns in the convergence zone, no slip after deposition and an axisymmetric process. Michaeli et al. [2] presented a procedure for direct control of the machine. In this procedure, non-circular
mandrel cross-sections are approximated by circles. The carrier speed must be provided as input and the take-up speed is output as a function of time. Du and Popper [3] optimized either the carrier speed or the take-up speed, depending on the user’s choice, while keeping the other speed constant. The mandrel geometry is restricted to be rotation symmetric and is approximated by a series of conical segments.

Furthermore, it is assumed that yarns do not interact with each other, no friction between yarns and guide rings occurs and the yarn thickness can be neglected. Based on these assumptions, each yarn can be modeled independently as shown in Fig. 3. Input parameters, as far as required for the purpose of this work, are described next.

The simulation uses a time-stepping method with a constant time step size \( \Delta t \) and the carrier rotational speed \( \omega(t) \) and take-up speed \( v(t) \) given as input. The mandrel is represented by a triangulated surface \( S \) and arbitrary centerline \( L \). \( S \) must be a single closed shell without holes or large protrusions and is defined in the global Cartesian mandrel coordinate system with unit axes \( \{x,y,z\} \). The surface region to be overbraided is bounded by a planar start- and end contour on \( S \). The machine orientation is represented using a local Cartesian machine coordinate system with origin \( m \), here assumed to be coincident with- and tangent to the centerline, and unit axes \( \{u,v,w\} \) which moves as a function of time. The machine is parameterized with the machine spool plane circle radius \( r_{sp} \) and the optional inner and outer guide ring radii \( r_{gr.in} \) and \( r_{gr.out} \) and heights \( h_{gr.in} \) and \( h_{gr.out} \). The number of yarns per yarn group is given by \( n_y \).

Assuming \( \omega(t) \) constant, the spool trajectory for the \( i \)-th spool of a bias yarn group is approximated with a helix-like curve \( Q_i \) around the centerline. \( \varphi \) is the spool plane angle and the spools are distributed evenly over the spool plane circle using

\[
\varphi_{0,i} = \frac{2\pi i}{n_y} \quad (1)
\]

Define the ‘supply point’ position vector \( s \) as the point from which a yarn is supplied, obtained by

\[
s = \begin{cases} 
q, & \text{if no guide ring contact,} \\
r, & \text{if guide ring contact.} 
\end{cases} \quad (2)
\]

Define the ‘creating circle’ as the circle that contains \( s \). The ‘free segment’ is defined as the yarn from \( p \) to \( s \). Depending on the input parameters, \( s \) may alternate between the spool plane circle and guide ring circles. The resulting supply point trajectory of \( s \) is denoted by \( T \).

For a centered cylindrical mandrel, the braid angle is expressed using the ‘classical solution’ [7] or

\[
\alpha = \arctan \left( \frac{\omega_{in}}{v} \right) \quad (3)
\]
where $r_m$ is the mandrel radius. This relation is sometimes [1] generalized for mandrels with an arbitrary cross-section using

$$r_m = \frac{p_m}{2\pi}$$

where $p_m$ is the mandrel cross-sectional perimeter. For arbitrary shapes, a deposition model similar to [8] is used where contact between the free segment and element edges in the neighborhood of the fell point is checked at each time step. The interlacement of the resulting deposited bias yarns provides geometrical bounds that form ‘tunnels’ through the biaxial braid for optional stem yarns, assuming a ‘regular’ 2/2-twill braid. The centerline of each tunnel forms a stem yarn trajectory as described in [9]. As a result, the simulation outputs yarn trajectories $Y$, and, implicitly, convergence zone length $H$ as a function of, among others, the spool trajectories $Q$.

![Figure 3. Process model for a single yarn, showing only the outer guide ring for clarity.](image)

**Optimization model**

The goal is to optimize the take-up speed $v(t)$ for a minimum error in braid angle at a constant carrier speed $\omega$ and required braid angle $\alpha_{req}$. The proposed procedure is independent of optional axial yarns. For the optimization, the spool trajectory helix $Q$ is calculated as a function of the yarn trajectory $Y$, the inverse of the simulation model. For each bias yarn group, the required fiber direction, implicitly providing $\alpha_{req}$, is required as input in the form of a discrete vector field on the mandrel surface as schematically shown in Fig. 4. This field can be generated manually or using structural optimization tools. A constant carrier speed $\omega$ is also provided as input. The machine position and orientation relative to the mandrel is assumed continuous and differentiable, and the instantaneous geometry of the supply point trajectory is assumed to be a helix on a cylindrical surface with the radius of the creating circle and the axis coincident with the instantaneous machine axis. For the two close points on a streamline through the required fiber direction vector field, geometrical analysis and frictionless force equilibrium at an optional guide ring as illustrated in Fig. 4 yields the instantaneous optimum take-up speed

$$v = \omega \frac{\Delta z}{\Delta \varphi}$$

for a single bias yarn. For all bias yarns, a weighted average of the individual optimal take-up speeds is used to generate the optimum process take-up speed. At point $a$, either the instantaneous streamline tangent can be used, or the actual deposited fiber tangent to form ‘feed-back’ for a more aggressive optimization yielding a faster response. The weight factor can be changed by optionally choosing a dominant ‘master’ mandrel side. The optimization procedure can also be used to determine the optimal start position of the mandrel relative to the machine. For details, see [6]. Note that yarn interaction, including friction, is not taken into account, likely leading to a significant systematic error that is not treated in this work.

**Test cases**

Unless specified otherwise, the following applies to all optimizations. The braiding machine setup is such that each carrier contains a spool, yielding a regular 2/2-twill braid with stem yarns, resulting in a triaxial braid. The used parameters are shown in Table 1 and all dimensions are in millimeter. The required bias braid angle of 60° can be used to obtain a quasi-isotropic layup. No master side or yarn group was specified, allowing each mandrel side to participate in the optimization with an equal weight of 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>max. machine take-up speed $v_{\text{max}}$</td>
<td>40 mm/s</td>
</tr>
<tr>
<td>required braid angle $\alpha_{\text{req}}$</td>
<td>60°</td>
</tr>
<tr>
<td>master side</td>
<td>none</td>
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<tr>
<td>master yarn group</td>
<td>none</td>
</tr>
<tr>
<td>optimization feed-back</td>
<td>no</td>
</tr>
</tbody>
</table>

*Table 1. Default braiding parameters*
The mandrel called ‘exhaust’ from Fig. 5, as used in earlier research [1, 10], was used for optimization using the settings in Table 2, generating the take-up speed profile shown in Fig. 7. The values are close to those when calculated using the classical solution (3) and (4). Although the take-up speed is calculated as the average of all bias yarns, it contains noise which is affected, amongst others, by the mesh ‘roughness’ and the optimization arc length on the fiber streamline, shown in Fig. 4 as the distance on the mandrel surface from a to b. Note the counter-intuitive overshoot at 800mm, exceeding 40 mm/s. Fig. 6 shows the resulting fiber distribution, including stem yarns that are deposited as a function of the deposited bias yarns. The braid angle is plotted in Fig. 8, showing a maximum error of approximately 6 degrees for this optimized model.

Fig. 4. Geometry for the optimum take-up speed calculation. Points a and b result in points a’ and b’, respectively, in turn providing the instantaneous spool helix.

Exhaust

The mandrel called ‘exhaust’ from Fig. 5, as used in earlier research [1, 10], was used for optimization using the settings in Table 2, generating the take-up speed profile shown in Fig. 7. The values are close to those when calculated using the classical solution (3) and (4). Although the take-up speed is calculated as the average of all bias yarns, it contains noise which is affected, amongst others, by the mesh ‘roughness’ and the optimization arc length on the fiber streamline, shown in Fig. 4 as the distance on the mandrel surface from a to b. Note the counter-intuitive overshoot at 800mm, exceeding 40 mm/s. Fig. 6 shows the resulting fiber distribution, including stem yarns that are deposited as a function of the deposited bias yarns. The braid angle is plotted in Fig. 8, showing a maximum error of approximately 6 degrees for this optimized model.

Fig. 4. ‘Exhaust’. The four sides are numbered for easy reference. Dimensions: mm
Table 2. Exhaust braiding parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
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<td>spool plane radius ( r_{sp} )</td>
<td>840 mm</td>
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<tr>
<td>inner guide ring radius ( r_{gr, in} )</td>
<td>200 mm</td>
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<tr>
<td>inner guide ring height ( h_{gr, in} )</td>
<td>350 mm</td>
</tr>
<tr>
<td>outer guide ring radius ( r_{gr, out} )</td>
<td>200 mm</td>
</tr>
<tr>
<td>outer guide ring height ( h_{gr, out} )</td>
<td>385 mm</td>
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<td>number of yarns per group ( n_y )</td>
<td>48</td>
</tr>
<tr>
<td>carrier speed ( \omega )</td>
<td>36 deg/s</td>
</tr>
</tbody>
</table>

Fig. 7. Take-up speed versus the position of the machine origin expressed in the mandrel coordinate system. Up to \( \sim 450 \) mm, the take-up speed is 100 mm/s to let the machine travel to the optimal start location with idle carrier rotation speed.

Fig. 8. The modeled braid angle after optimization, measured at each mandrel side as indicated in Fig. 5. The vertical grid lines indicate sharp mandrel geometry transitions. X and O denote warp and weft yarns, respectively.

Fig. 6. Fiber distribution after optimization as visualized in Gmsh [11], showing the yarn centerlines for warp (red, from top left to bottom right), weft (green) and stem yarns (blue).
Nozzle

In an analysis similar to the previous, the following results are obtained for the ‘nozzle’ from Fig. 9. As shown in Table 3, no guide rings are used. The carrier speed value of 8.33 corresponds to 100 ‘picks per minute’. The generated take-up speed as shown in Fig. 11 shows that reverse braiding occurs when the fell point crosses the ‘downbraiding’ region in the z-interval from approximately 300 to 400 mm. This could lead to slack yarns, which is not yet taken into account as a manufacturing constraint. Fig. 10 shows the resulting fiber distribution. Fig. 12 shows that the resulting braid angle is close to the required braid angle, having a maximum error of less than 2 degrees. Assuming a rotation symmetrical fiber distribution, which is confirmed by Fig. 11, only a single measurement path is required to represent the global braid angle distribution.

![Fig. 9. Rotation symmetrical ‘nozzle’](image)

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
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<tr>
<td>spool plane radius $r_{sp}$</td>
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<tr>
<td>number of yarns per group $n_y$</td>
<td>72</td>
</tr>
<tr>
<td>carrier speed $\omega$</td>
<td>8.33 deg/s</td>
</tr>
</tbody>
</table>

*Table 3. Cone braiding parameters*

![Fig. 11. Take-up speed profile. Up to ~650 mm, the take-up speed is 40 mm/s to let the machine travel to the optimal start location with idle carrier rotation speed.](image)

![Fig. 12. The modeled braid angle for both yarn groups. The measurement path is the curve from start- to the end section, obtained as the intersection of the mandrel surface and the yz-plane at the positive y-side.](image)

![Fig. 10. Fiber distribution.](image)
Cone

The ‘cone’ from Fig. 13 is optimized for the braid angle using the parameters from the nozzle. The generated take-up speed profile as shown in Fig. 15 shows a counter-intuitive peak at the start and end of the conical segment. The braid angle, again showing rotation symmetry in Fig. 14, matches the required braid angle very well as shown in Fig. 16, having a maximum error smaller than 1 degree.

Fig. 13. Rotation symmetrical ‘cone’. Dimensions between parentheses are driven.

Fig. 15. Take-up speed profile.

Fig. 16. The modeled braid angle $\alpha$ for both yarn groups after optimization. The measurement path is defined analogous to that for the nozzle.

Fig. 14. Fiber distribution.
Cylinder

The ‘cylinder’ from Fig. 18 was optimized for the braid angle using the parameters in Table 4. It contains a stepwise change in the required braid angle from 45 to 60 degrees. The generated take-up speed and resulting braid angle are shown in Fig. 19 and Fig. 20, respectively. The used optimization does not use feed-back, leading to a delayed response of the braid angle with an exponential trend close to the exact solution from [10], using \( r_{\text{grout}} \) as the creating circle. In contrast, when using feed-back, a short period of backward braiding is generated, leading to the much faster response shown in Fig. 22. However, the feasibility of this solution has yet to be shown with respect to yarn slack. In Fig. 17, the tendency to slip is shown in practice, based on the local ratio of the geodesic and normal yarn curvature components [12]. This suggests that in the case of the optimization with feed-back, the yarns have a more localized yet larger maximum tendency to slip after deposition. If the tendency to slip exceeds the coefficient of friction \( \mu \), slip can occur. When assuming \( \mu \approx 0.2 \) to 0.3, the slip indicator suggest more slip for the optimization with feed-back, which matches intuition. However, the occurrence and the extent is also affected by the braid structure. The presence of stem yarns, for example, can prevent most slip.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
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<tr>
<td>spool plane radius ( r_{\text{sp}} )</td>
<td>840 mm</td>
</tr>
<tr>
<td>inner guide ring radius ( r_{\text{grin}} )</td>
<td>100 mm</td>
</tr>
<tr>
<td>inner guide ring height ( h_{\text{grin}} )</td>
<td>300 mm</td>
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<tr>
<td>outer guide ring radius ( r_{\text{grout}} )</td>
<td>100 mm</td>
</tr>
<tr>
<td>outer guide ring height ( h_{\text{grout}} )</td>
<td>400 mm</td>
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<td>number of yarns per group ( n_y )</td>
<td>48</td>
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<td>carrier speed ( \omega )</td>
<td>36 deg/s</td>
</tr>
<tr>
<td>optimization feed-back</td>
<td>no and yes</td>
</tr>
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</table>

*Table 4. Cylinder braiding parameters*

![Fig. 18. Rotation-symmetrical ‘cylinder’](image1)

![Fig. 19. Take-up speed profile.](image2)

![Fig. 20. The modeled braid angle for both yarn groups after optimization. The measurement path is defined analogous to that for the nozzle.](image3)

![Fig. 17. Fiber distribution and the slip tendency of the warp yarn group for the optimization without (top) and with (bottom) feed-back.](image4)
**BRAIDING TAKE-UP SPEED OPTIMIZATION**

First, the optimization was performed without a master side, making deposition contributions on all sides equal. As a result, the take-up speed profile shown in Fig. 24 was generated. The noise has not been explained yet, but could be related to the combination of element size and optimization arc length. The outliers near $z = 1000$ mm seem to have no physical meaning, and could be related to the machine origin crossing the centerline transition from the arc to the linear segment at the end section. Replacing the linear segments by an extension of the arc may let the peaks disappear. The braid angle shown in Fig. 26 with a dashed line is closest to the target at the inside and outside for both bias yarn groups, because these sides remain least affected by the machine coordinate system rotation relative to the mandrel. This geometry seems not suited to provide a uniform braid angle around the circumference. Focusing at the upside, both yarn groups have a significant error in the braid angle. Alternatively, when assigning the upside as the master side, ignoring deposition at all other sides, then results are the same (not shown). However, when additionally assigning the warp yarn group as the master yarn group and ignoring the weft at the master side, then the take-up speed profile changes and the braid angle for the warp yarns improves significantly as shown for the upside warp yarns in Fig. 26. The downside weft yarns improve as well due to symmetry, but the rest still deviates significantly from the target $60^\circ$ braid angle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>spool plane radius $r_{sp}$</td>
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<td>inner guide ring radius $r_{gr,in}$</td>
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<tr>
<td>outer guide ring radius $r_{gr,out}$</td>
<td>100 mm</td>
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<tr>
<td>outer guide ring height $h_{gr,out}$</td>
<td>100 mm</td>
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<tr>
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<tr>
<td>master side</td>
<td>none and upside</td>
</tr>
<tr>
<td>optimization feedback</td>
<td>yes</td>
</tr>
</tbody>
</table>

Table 5. Torus braiding parameters

**Torus**

The quarter ‘torus’ from Fig. 23 is used with the parameters in Table 5.

**Fig. 21.** Take-up speed profile after optimization with feed-back.

**Fig. 22.** The modeled braid angle for both yarn groups after optimization with feed-back.

**Fig. 23.** Quarter ‘torus’.
Fig. 24. Take-up speed profile.

Fig. 25. Fiber distribution, showing a small amount of fiber waviness.

Fig. 26. The modeled braid angle for both yarn groups after optimization. The dashed lines correspond to the case without master mandrel side and without master yarn group, the solid lines to the case with the warp (X) yarns at the upside specified as ‘master’.
Conclusions
A new optimization method was applied to various complex mandrel shapes to generate a take-up speed profile for a given required braid angle. The optimization can yield solutions where the take-up speed is temporarily reversed to enable rapid changes in braid angle or mandrel geometry. It was also shown that use of feed-back in the optimization can speed up the response of the braid angle. Finally, the effect of assigning a master side and master yarn group was illustrated. However, in order to assess the validity of the generated process settings, it is recommended to take into account the manufacturing constraints regarding the prevention of yarn slack and fiber slip. Moreover, the effect of yarn interaction may be significant and is a topic for further analysis. Experiments will be performed in the near future to check the validity of the model results.

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References