A DIGITAL SHADOW OF FILAMENT WOUND LIGHTWEIGHT COMPONENTS

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ABSTRACT

Many lightweight composite structures which are mostly rotation symmetric are manufactured using a technique called filament winding. While this is a simple technique, programming of CNC machines for manufacturing is not trivial. Winding pattern, speed, fibre width and coverage factor are some of the important parameters which influence the process and hence the manufactured component. In this work, a novel approach for the design of filament wound components is presented. The method of fibre value is proposed, which is a function of winding parameters. Compared to the conventional techniques, this approach also provides reasonably stable results for complex and rotation unsymmetrical geometries, like a propeller blade. This approach is mathematically more rigorous and suitable for prototyping and complex and expensive to manufacture structures.

1 INTRODUCTION

Filament winding is a technique in which fibres are wound on a mandrel for the purpose of reinforcement. Some examples of filament wound components include pressure vessels for storage of fluid at high pressure, torsion tubes, etc. In most of the case, the purpose of reinforcement is to make the component lighter, at a given loading condition. In some cases, like torsion tubes, the mandrel is removed after winding. In most cases the winding is on a rotation symmetric mandrels. In filament winding there are different types the wet/dry-filament winding and hybrid filament (resin pre-impregnated) winding.

Peters [1] and Koussios [2] considers the pressure vessels as shell of revolution and the profile of revolution as a function of different parameters. The quality and mechanical strength of filament-wound parts depends on parameters, such as winding pattern, coverage factor and fibre angle. ComposicaD, Cadfil, CADWIND and µWind (relatively new) are examples of commercial software packages widely used for design and manufacturing of filament wounded parts. For a given mandrel geometry, the user selects the design parameters, selects the winding pattern and uploads the manufacturing data to the machine.

Currently, the design and manufacturing process is only in one direction. This means that there is no coupling or feedback signal from the manufacturing to quantitatively compare the variation in the manufacturing process. Specially in filament winding, this is necessary due to the possible variation and thereof resulting difference in mechanical and structural properties.

In this work, filament wound components are designed using the computer aided tools and feedback signals from the machine is used to develop a digital object of the component. This can be used to perform further analysis to qualify the component.

2 DEVELOPMENT OF AN ALGORITHM

2.1 Basis for the software tool

Even though commercial software available in the market is sufficient for most of the application faced in industry today, they remain insufficient for development of the process or research applications. The geometries available for design are usually limited to special cases, such as axisymmetric surfaces of revolution or T-shaped joints. More complex geometries can be only defined manually. This limitation makes program generation for components like propeller blades, wings or fuselages tidies [3]. The implementation of own post-processing or design algorithms by the end user is impossible, which limits the research applications. Novel winding technologies like the Multi-Supply Filament winding is also not easily programmable by the user.

2.2 Mathematical apparatus

The program is developed in Matlab® for the initial stage and can also be implemented in other platforms based on requirement. The main parameters selected for the optimization is the winding angle and coverage factor. The winding angle is the angle the wound fibre makes with the longitudinal axis of the mandrel and the coverage factor is the percentage coverage of the mandrel surface. For the purpose of simplicity, the "*Optimization Toolbox*" from Matlab and the function *fmincon* for the numerical solution of general optimization problems.

Analytical methods for winding pattern generation are based on parametric differential equations of a single fibre trajectory (see Fig. 1). To generate a winding path, this differential equation is first derived for the given mandrel geometry. Then the user chooses the parameters for the pattern generation. Afterwards, a numerical solution of the equation yields the final fibre trajectory. From the fibre trajectory, the machine trajectory is then calculated.

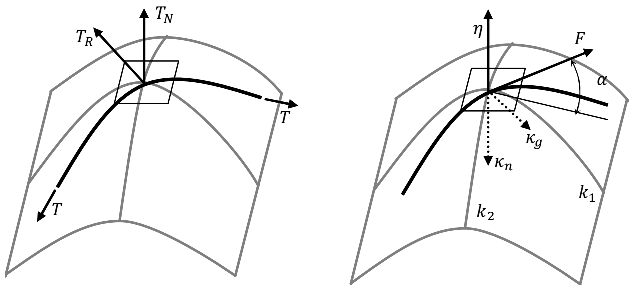

Figure 1: Forces, curvatures and geometric parameters for a fiber element on the mandrel surface [4, 5].

The condition of fibre stability can be reduced to Eq. (1) (see [6]):

$$\lambda = \left\| \frac{\kappa_g}{\kappa_n} \right\| = \left\| \frac{F_R}{F_N} \right\| \leq \mu \tag{1}$$

λ is the slippage coefficient, κ_g is the geodesic curvature, κ_g is the normal curvature, μ is the friction coefficient.

Literature provides many ways to determine the friction parameters. While most of these methods provide an approximate value to start with, not all of them consider the actual winding geometries and conditions, which may have an influence. Hence, in most cases engineers depend on experience values for the friction coefficient. Once this is known, Eq. (1) can be used to generate slippage winding path on a given mandrel.

The mathematical foundation is called as fibre value method. First, a suitable mathematical representation for the middle line of a fibre on mandrel surface is to be selected. In order to be used for iterative fibre trajectory generation (optimisation), the method is required to allow a simple and time-efficient calculation of winding quality parameters and its derivatives.

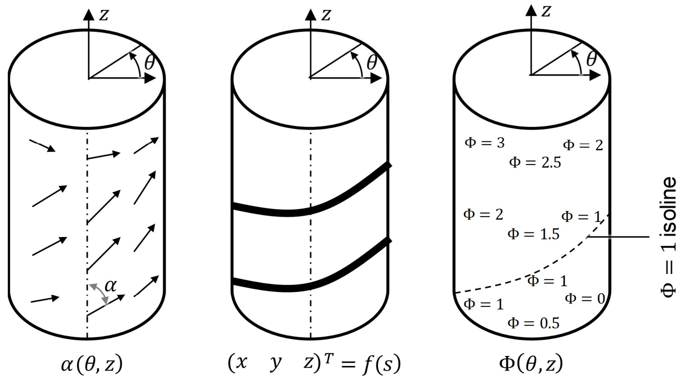

Figure 2: Possible fibre trajectory representations: assigning a winding angle to every point of the mandrel (left), fibre trajectory given by a parametric function (middle), implicit curves given by a field Φ(u,v) (right).

In this work, the fibre trajectory is represented using implicit curves (see Fig. 2) on the surface, also known as isolines. The concept is familiar in daily live from landscape contour maps, which consists of multiple contours (isolines), on which the elevation from the sea level is constant. This means, that a constant elevation produces one distinct curve.

2.3 The whole problem

The same concept is applied to represent the fibre trajectory on a continuous surface. When winding on a mandrel, the fibre trajectory must be on a continuous surface. Say, $\Phi(x, y)$ is some arbitrary function which is differentiable. This function assigns a fibre-value Φ to each point (x, y) of the surface in the same way a scalar value (such as temperature $T(x, y)$) can be assigned to every point of the earth surface. Now a combination of the fibre-value function $\Phi(x, y)$ and the set of N isovalues $\varphi = \{\varphi_1, \varphi_2, \dots, \varphi_N\}$ defines N fiber trajectories. Solving the level set equation (Eq.(2)), the fibre trajectory of the fibre n can be obtained. Notice that this is defined a 2D equation, for a 3D fibre trajectory. However, if the element on which the trajectory is calculated is small enough, this can be assumed to be a 2D surface.

$$\Phi(x, y) = \varphi_n \tag{2}$$

After the basic quality parameters are defined as function of Φ, a way to calculate the function $\Phi(\mathrm{u}, \mathrm{v})$ on a given geometry is proposed. First, a target cover factor C_t and fibre angle α_t must be assigned to every point of the geometry. To get the target winding angle and target coverage, the error between the target value and the actual value needs to be reduced, and the change rate of the fibre value should be as low as possible. The optimisation problem is given by Eq. (3).

$$\min_{\Phi(u,v)} \iint a\left(\overbrace{\begin{pmatrix}\Phi_u\\ \Phi_v\end{pmatrix}\cdot\begin{pmatrix}\cos(\alpha_t)\\ \sin(\alpha_t)\end{pmatrix}}^{\text{Winding angle}}\right)^2 + b\left(\overbrace{\left\|\begin{matrix}\Phi_u\\ \Phi_v\end{matrix}\right\| - C_t}^{\text{Coverage rate}}\right)^2 + c\overbrace{\left({\Phi_{uu}}^2 + {\Phi_{vv}}^2\right)}^{\text{Trajectory change rate}} du dv \tag{3}$$

The value of the functional within the integral is equal to zero, when all fibre trajectories are geodesic, produce the target cover factor C_t and are oriented according to the angle α_t. If it is impossible to meet the target values, a solution, which is the closest one to the desired parameters, will be obtained. The definition of the closest solution depends of the parameters a, c and b, which are called weights. Based on the importance of certain winding parameter for a structure, the weights can be increased. Hence this parameter will be closest to the target value and the others have a lower priority.

3 DIGITAL CORRELATION

3.1 Experimental Validation

With the mathematical background presented in the previous chapter, the algorithm was implemented in Matlab®. As an input, an STL file of the desired mandrel geometry is used. Based on the machine used, the machine controls can be output. Triangular mesh is required for the calculation of the fibre trajectory. The density of mesh dictates the steering angle of the fibre. This is an important parameter in complex structures and places where there is a higher possibility of fibre slippage. Very dense mesh results in longer calculation time.

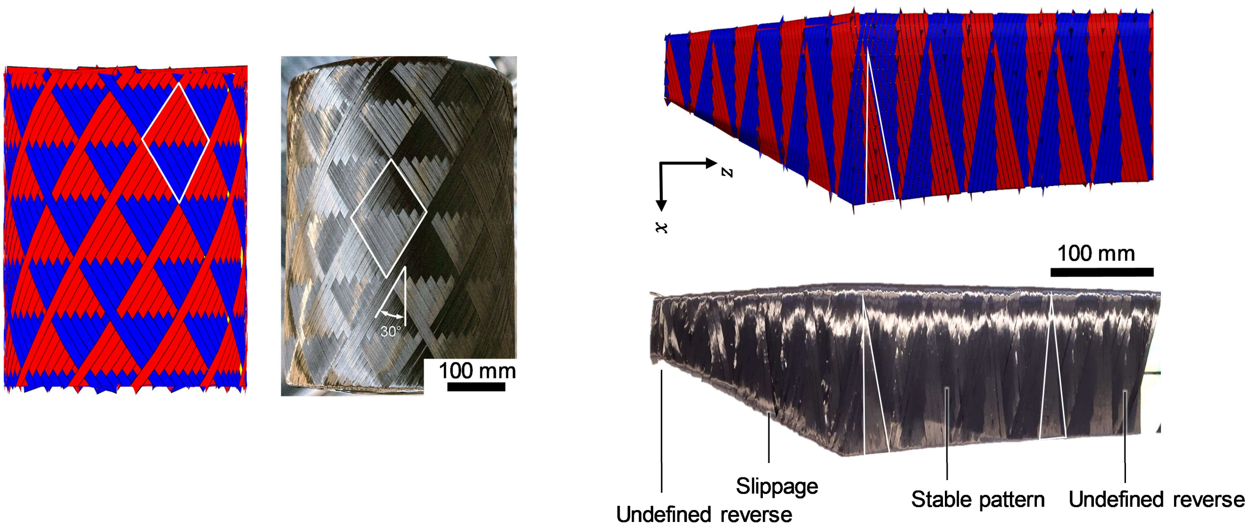

Figure 3: Comparison between simulated and fabricated laminate; Cylinder (left); Propeller blade (right).

The tool was experimentally validated initially on a simple tubular structure, see Fig. 3. In this case, the fibres were wound over the edge of the cylinder. The winding angle and the fibre layup can be compared between the tool and the actual winding. Some fibre slippage was noticed at the ends of the cylinder. Since at this stage of development the friction parameter was not implemented, small slippages like this were neglected.

To extend the boundaries of this tool, complex and non-rotation symmetric component like a propeller blade was chosen, see Fig. 3. The results of winding are shown in the next section. With use of suitable camera and sensor systems, the data from the experiment can be evaluated and the deviation from the desired winding pattern can be obtained.

3.1 Digital Correlation

In ideal case of industrial production, it is strived to keep the variation in the machine and material parameters as low as possible to minimize or eliminate the need for additional analysis. Each addition step costs money. However, this approach does not work well for prototype production and initial set-up of machine. Even today, this is done manually and requires highly experienced engineers and technicians to obtain a good result in a reasonable time. Additionally, in the case of safety critical structures and components which are produced in low numbers, like rocket storage tanks, the cost of this analysis is only a small fraction of the whole component itself. In these situations, a constant digital correlation is meaningful.

A digital shadow of the winding pattern is possible through feedback loop. The machine data during the winding process is captured and a digital object is developed. Tools like HPC-V-3D from Hexagon AB scanner were used for measurement of the actual object. The deviation between the digital and actual model is calculated. Further analysis is carried out on the digital model to quantify the influence of these deviations on the structural properties of the component.

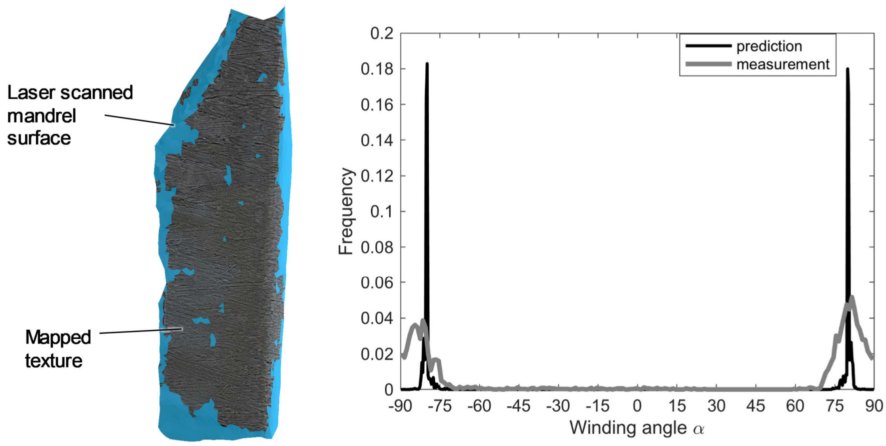

Figure 4: Comparison of the texture image (left); Diagram of the predicted and measured winding angle (right)

4 CONCLUSIONS

In this paper, a novel approach for the design of filament wound components was presented. Firstly, the mathematical formulation was briefly introduced, followed by experimental validation and digital correlation. The approach provides a reasonably stable calculation for complex geometries, like propeller blade. The prediction from the winding tool was compared to the experimental winding angle. For the prototyping, including initial machine set-up and manufacturing of complex structures, this approach provides an edge over the conventional techniques. Additionally, the ease of coupling different machines and sensors makes the tool suitable for various applications.

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