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Slippage coefficient measurement for non-geodesic filament-winding process

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ABSTRACT

In order to calculate the winding patterns for non-geodesic filament wound products, the slippage coefficient, which represents the frictional force between the fiber tows and the mandrel surface, was introduced to find the region of possible winding patterns. This research aims to establish a method to measure the slippage coefficient. A special mandrel was proposed that has a designed meridian profile that enables a linearly proportional relation between the cross-sectional radius and the measured values of the slippage coefficient. With this mandrel, several experiments were performed corresponding to the variation of the typical filament-winding process parameters. The results indicate that the bandwidth and resin viscosity had a considerable influence on the obtained data. In contrast, the influence of the filament-winding speed and the roving tension were negligible. The results also show that the approach provides high accuracy, repeatability, low cost and simple machine control.

1. Introduction

Filament winding is currently one of the most important processes for manufacturing composite products, such as pipes, high-pressure vessels, water tanks and so on [1–5]. In this process, continuous fiber tows are successively wound on a mandrel surface along pre-designed pathways. The pathways can be divided into geodesic trajectories and non-geodesic trajectories [6,7]. The geodesic path is a curve connecting two points on a surface according to the shortest distance over this surface. A fiber tow placed along a geodesic line will not tend to slip. Hence, geodesic winding does not require any friction in order to be stable. However, geometry and winding patterns are calculated simultaneously in geodesic winding, so the mandrel shape is always determined beforehand [8]. Sometimes, it is necessary to calculate the winding patterns for pre-designed shapes, such as is done in geometric determination of non-geodesic isotension pressure vessels, the creation of smooth transitional circuits from helical pathways to hoop pathways and generation of rotational symmetric objects providing the optimal winding-angle distribution for particular load situations. The implementation of non-geodesic fiber trajectories could solve these problems and increase design space. However, this is not always achievable. The fiber tows must not slip during the non-geodesic winding because the creation of non-geodesic pathways requires a well-determined value for the available friction between the placed roving and mandrel surface. Because of this, the slippage coefficient (λ), which represents the frictional force between the fiber tows and the mandrel surface, was introduced to find the region of possible winding patterns during the design procedure of non-geodesic filament-wound products [8–13].

Early on, experiential values of the slippage coefficient were used. They ranged from 0.2 to 0.39 [8]. With these experiential values, the region of possible winding patterns could be calculated. However, it is difficult to ensure that the patterns are stable in the actual filament-winding process. Therefore, several experimental methods have been developed [9,10,13], as shown in Table 1 [9,10]. All of these methods could be used to obtain the slippage coefficient, but the experimental results would not reflect the actual situation very well. The deviations show that some actual parameters, such as resin viscosity, roving tension, winding speed and so on, must be considered during the experiments. So, the most realistic method for measuring the slippage coefficient is achieved by performing the experiments on a filament-winding machine, using a rotationally symmetric mandrel with the real filament-winding parameters. Also, the experiments should be realistic simulations of the slippage and should provide the ability to investigate the influence of the parameters.

In this paper, a method for measuring the slippage coefficient is established. It is simple and provides reliable acquisition of experimental results. In the method, a special mandrel was designed with a designed meridian profile that enables a linearly proportional relation between the cross-sectional radius and the measured values of the slippage coefficient. With this mandrel, several experiments were performed to explore the variations of the typical filament-winding process parameters. The effects of the filament-winding speed, roving tension, bandwidth and resin viscosity are discussed.

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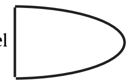
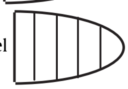
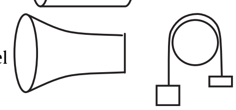
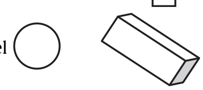
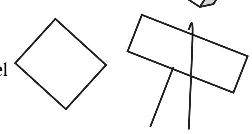
Table 1
Several methods for slippage coefficient measurement [9,10].

Mandrel shape measurement		Measurement
1. Bullet shape mandrel		Widing with angle $\alpha \approx$ constant till the fiber tows slips
2. Coaxial cones mandrel		Hoop winding, tangent of the cone angle gives the friction coefficient
3. Cylindrical shape mandrel		Widing with angle α changed till the fiber tows slips
4. Trumpet shape mandrel		Two different forces, increase on till fiber twos slips
5. Arbitrary shape mandrel		Block with roving on the underside will slip at a certain inclination angle
6. Plane shape mandrel		One fiber tow will slip at a certain inclination angle

2. Theoretical aspects

2.1. The special mandrel design

As shown in Fig. 1, during the filament-winding process, the fiber tows are subjected to tension $\vec{f}_t$. The roving tension $\vec{f}_t$ will lead to a force $\vec{f}_r$ per unit length on the mandrel surface, which is directed towards the center of curvature of the fiber path. The resultant force $\vec{f}_r$ can be split into two components: the normal force $\vec{f}_n$, which is perpendicular to the surface, and the lateral force $\vec{f}_s$, which is tangential to the mandrel surface. The slippage tendency λ represents the slippage tendency of the fiber tows wound on the mandrel surface and is defined as the ratio of the lateral force $\vec{f}_s$ and the normal force $\vec{f}_n$:

$$\lambda = |\vec{f}_s|/|\vec{f}_n|, \tag{1}$$

where λ is slippage coefficient, $\vec{f}_s$ and $\vec{f}_n$ denote lateral force and normal force, respectively. Combined with the geometric relationships, Eq. (1) can be changed into

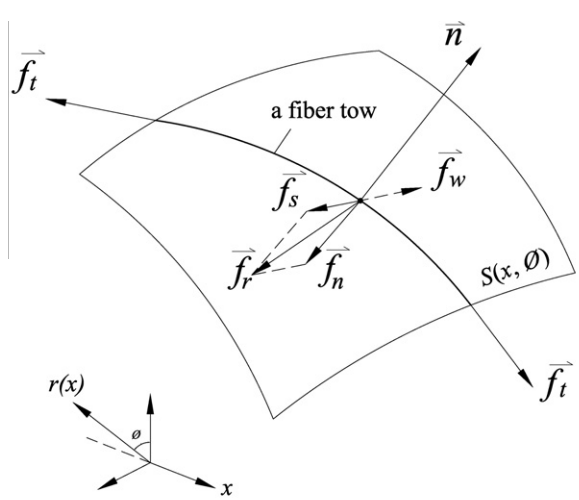


Fig. 1. Stress analysis of a fiber tow on an arbitrary convex surface.

$$\lambda = |k_g|/|k_n|, \tag{2}$$

where k_g and k_n denote geodesic curvature and normal curvature, respectively.

The detailed derivation of Eq. (2) can be found in [15,16].

In addition, an arbitrary convex surface of revolution about the x-axis is defined as $\vec{S}(x, \phi)$ in Fig. 1:

$$\vec{S}(x,\phi) = [x \quad r(x)\cos\phi \quad r(x)\sin\phi]^T, \tag{3}$$

where x and φ denote the axial coordinate and the circumferential coordinate, respectively, and $r(x)$ stands for the radial distance.

The first fundamental form of $\vec{S}(x, \phi)$ is as follows [17]:

$$E = r(x)^2, \quad F = 0, \quad G = 1 + r'(x)^2, \tag{4}$$

where $r'(x)$ is the first derivative of $r(x)$ with respect to x, E, F, G are the coefficients of the first fundamental forms. Substitution of Eq. (4) into the ***Liouville*** formula [17] leads to the expression for the geodesic curvature k_g:

$$k_g = \frac{\cos\alpha}{\sqrt{1 + r'^2(x)}} \cdot \frac{d\alpha}{dx} + \frac{r'(x)}{r(x) \cdot \sqrt{1 + r'^2(x)}} \sin\alpha, \tag{5}$$

where α is the angle between the roving path and the meridian direction, i.e., the filament-winding angle.

According to the ***Euler*** formula [17], the normal curvature k_n can be expressed in terms of the main curvatures in the meridian and parallel directions. Therefore,

$$k_n = \frac{r(x)r''(x)\cos^2\alpha - \left(1 + r'^2(x)\right)\sin^2\alpha}{r(x)\left(1 + r'^2(x)\right)^{3/2}}, \tag{6}$$

where $r''(x)$ is the second derivative of $r(x)$ with respect to x. By substituting Eqs. (5) and (6) into Eq. (2), the slippage coefficient λ can be expressed as

$$\lambda = -\frac{r'^2(x)\left(1 + r'^2(x)\right)\sin\alpha + r(x)\left(1 + r'^2(x)\right)\cos\alpha(d\alpha/dx)}{\left(1 + r'^2(x)\right)\sin^2\alpha - r(x)r''(x)\cos^2\alpha}. \tag{7}$$

Eq. (7) shows that the slippage coefficient λ is a function of $r(x)$, $r'(x)$, $r''(x)$ and α. So, if $r(x)$ and α are determined, the slippage coefficient λ will be obtained. Two boundary conditions are introduced.

The first boundary condition is as follows: the winding angle α equals $\pi/2$, i.e., hoop filament winding.