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Unified approach of filament winding applied to complex shape mandrels

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ABSTRACT

The filament winding process faces up limiting fabrication inconveniences when designing complex geometries of composite structures. Even the complete coverage of a cylindrical mandrel requires introducing deviation from geodesic trajectories. As a consequence, models for non-geodesic paths have been developed. The present research aims to establish, to solve and to validate a generic mathematical model that contributes either to wind complex shapes, or to solve common filament winding disadvantages, on the basis of an integrated strategy. This so-called unified approach leads to benefit of composite structures made by filament winding despite the limitations of the manufacturing process. Based on the mathematical description of the mandrel geometry, the theory of surfaces leads to express the local curvatures. Considering the slippage tendency of the fiber tow over the surface, a local stability criterion involving mathematical parameters of the mandrel surface is established, and a general fiber path equation can be formulated. A numerical tool is developed and applied to predict the evolution of the filament winding angle of the fiber tow placed over the surface of two axisymmetric geometries: a convex and a concave one. Experimental validation is carried out by manufacturing these geometries using a four axis filament winding machine.

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1. Introduction

This research is motivated by the need to investigate the development of complex geometries in composite materials made by winding filament, i.e. non-cylindrical and non-symmetric objects. Certain industries such as automotive, aeronautical, or naval require specific solutions that go beyond the classical geometries such as cylinders, hemispheres or ellipsoids. In this respect, the HYPE [1] project (réservoir HYdrogène haute PrEssion – High pressure hydrogen reservoir), promoted by the French automotive industry, aimed to solve some of the drawbacks of hydrogen compressed storage technology for automotive applications like bulkiness, customer acceptance and cost, i.e. safety related issues to hydrogen behavior and high pressure. Considering these criteria, a new generation of reservoirs aims to take advantage of empty spaces in a car, to be as light as possible and not expensive. The main result was the development of form-fitted tanks as a geometrical evolution of type III (composite overwrapped metal liner) and IV (composite overwrapped polymer liner) tanks [2], see Fig. 1.

Concerning other high performing solutions fabricated with the filament winding process, recent aeronautical solutions have constructed closed-shape structures [3,4], such as single-piece fuselages whose advantages include lower cost, lighter weight, improved integration, safety, improved performance, noise reduction, improved aerodynamics, and styling flexibility. For a one-piece fuselage, either metal or composite materials may be used. Metal has certain disadvantages due to the inability to fabricate all components of the fuselage in a single step; therefore composite materials are more advantageous for the fabrication of a one-piece fuselage because they can be fabricated simultaneously.

Filament winding structures have been achieved mostly using geodesic (friction-free) and non-geodesic paths. Geodesic winding paths are to be considered as natural fiber paths, i.e. the tension in the fiber tow causes the filament path to be geodesic regardless of the desired fiber path. The use of geodesic paths simplifies the calculation of fiber paths but is much more restrictive. The fiber trajectory is perfectly defined in so far as the initial position and the starting angle have been selected. Consequently, geodesic paths lead to an obstacle to optimization of the composite lay-up [5]. However, the filament path can be changed by altering the friction between the mandrel and the filament using some shrewdness

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Nomenclature

F	fiber tension force	(u, v)	generalized curvilinear orthogonal coordinates; parallel and meridian, respectively
f_b, f_f, f_n	lateral force, friction force, normal force	X_u	derivative of fundamental coefficient X with respect to u
k_g, k_m, k_n, k_p	geodesic, meridian, normal, parallel curvatures	z	machine rotating axis
L_f	curve length (deposited fiber length); length of mandrel	α	curve orientation with respect to meridians (filament winding angle)
L_c	length of concave and convex geometries	(φ, θ)	generalized curvilinear spherical–polar coordinates, parallel and meridian, respectively
L_m	length of the mandrel	$\boldsymbol{\Gamma}$	curve; vector function describing a curve onto the mandrel
$\boldsymbol{P}$	point of analysis on $\boldsymbol{\Gamma}$ curve	λ	slippage tendency
$\boldsymbol{M}$	centre of normal curvature	μ	static friction coefficient
$\boldsymbol{N}$	centre of geodesic curvature	ccv	concave
$\boldsymbol{n}_u\boldsymbol{n}_v$	derivatives in u- and v-direction of the unit normal vector to the surface	cvx	convex
$\boldsymbol{O}$	centre of curvature	cyl	cylinder
R	cylindrical part radius		
s	length of the arc segment		
$\mathbf{S}$	surface; vector function describing the surface of the mandrel		
$\mathbf{S}_u, \mathbf{S}_v$	derivatives in u- and v-direction of the surface function		

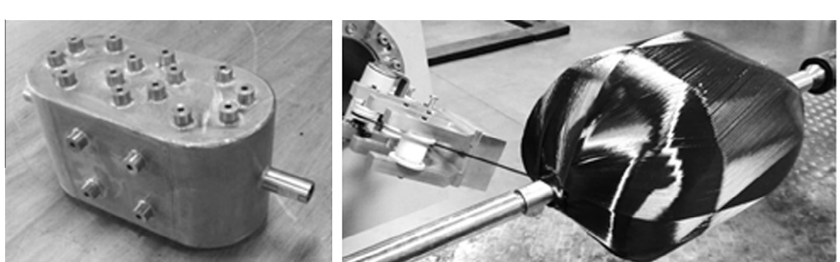
such as putting dressmaker pins, or applying high tack resin that keeps the filaments in place until a return crossing filament locks the previous ones as desired [4]. Other methods can be implemented such as using non-geodesic trajectories in which after following an initial rotation, no additional steps are taken to secure the tow of filaments at the desired angle [5–7].

But even the fabrication of simple geometries does not mean that the desired filament winding patterns are suitable, as demonstrated by [8]. In this case the geometrical parameters of a type III tank are dictated by the geometrical constraints of the liner rather than from a mechanical behavior calculation or optimization. Considering that the tank being analyzed by this author was a cylinder with ellipsoidal ends (or oblate spheroids) and taking into account mechanical strength of the structure, the desired winding angle of a helicoidally geodesic path over the cylindrical body should be 55°. Nevertheless, based on a sequential analysis of the filament winding process and considering a geodesic path, a 42° angle is obtained on the cylindrical part as shown in Fig. 2a; or 43.92° angle when the path is non-geodesic as shown in Fig. 2b. This is mainly due to the angle discontinuity of the transition between trajectories along the cylinder and the ellipsoids, as shown in Fig. 2c, so a non-geodesic transition should be considered. Furthermore, the dimension of the neck of the bottle imposes an entry angle (azimuth angle, A_{z_0}) of the fiber tow into the ellipsoids which also conditions the desired filament winding angle of the fiber placed over the cylinder. Therefore, in the previous analysis, the geometry of the supporting liner imposes the final geometrical description of the reinforcement.

The scope of the present paper is to develop a numerical computing tool which will allow us to simulate the filament winding process whatever the mandrel geometry is, even if an axisymmetric mandrel is more suitable regarding the manufacturing process. By doing so, we contribute to the development of filament wound structures by designing, simulating and fabricating two axisymmetric geometries using a generic winding model that permits either to wind complex shapes, or to solve common filament winding disadvantages. To achieve this goal, a convex and a concave geometry are studied in an effort to propose more complex shapes, beyond traditional cylinders, or semi-spheres. Both shapes are described mathematically, so that the geodesic and the non-geodesic trajectories can be defined and solved. Then by means of a filament winding machine the previous complex geometries are roved and the numerical predictions are validated, allowing to corroborate the ability of the previous analysis to ensure that the referred mandrels can be overwrapped as desired. This work makes part of a more complete investigation which aims to define an optimization methodology: starting from the mathematical description of the mandrel, and knowing the mechanical loading, one should be able to suggest one or more suitable stacking sequences allowing to fulfill both objectives, a reduced weight and a high mechanical strength.

2. Mathematical procedure

The correct establishment of the stability condition of the fiber over the surface of the mandrel is the key to obtain the governing



(a) (b)

Fig. 1. Form-fitted tank (a) stainless steel liner. (b) Filament winding manufacturing [2].

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