Extending filament winding capabilities towards obstacle integration
M. Lossie, D. Vandepitte
Katholieke Universiteit Leuven, Department of Mechanical Engineering, Division of Production Engineering, Machine Design and Automation, PMA, Leuven, Belgium

Abstract

Although filament winding is a versatile manufacturing process, it has to cope with inherent boundary conditions which significantly restrict the tailoring potential and the integration possibilities in its products. To optimise the integration of obstacles within filament wound components, a methodology has been developed based on semi-geodesic winding. Maximum friction is applied to minimise fibre path disturbance around the obstacle, thereby integrating the obstacle in a controlled way. In this paper the obstacle integration methodology will be described and preliminary validation results discussed.

I. Introduction

A major advantage of composites over metals is their potential to tailor components to suit performance requirements. Obviously the theoretical tailoring is restricted by manufacturing imposed boundary conditions. In spite of these, composite manufacturing often allows to reduce part numbers by combining or integrating traditionally individual components into one part. However, also this second composite benefit must be put in perspective because the joints to be made usually involve locally reduced mechanical properties. In combination with the usual high stress concentration around the joints, these require special attention from both the design and the manufacturing side.
Filament winding, involving continuous fibre to be wound onto a rotating mandrel, is a versatile manufacturing process that partially answers to both composite potentials; in tubes laminate lay-up can be easily tailored by altering winding angles; in pressure vessels centric nozzles can be wound-in easily by returning the fibre path over there. However, as well the tailoring as the integration capacity of filament winding is limited due to manufacturing restrictions.

Tailoring limitations include geometry as well as laminate lay-up; geometry is preferred to be axisymmetric with additional mid-plane symmetry. Limited deviations from these requirements can be quite well dealt with [1], [2], [3]. In case of pronounced asymmetry however, as e.g. in T-connections [4], coverage becomes very complex. In general, lay-up freedom is rather poor because fibre paths must be free of slipping, and hence are limited to geodesics and semi-geodesics. Moreover, fibres should not bridge in concave mandrel areas, which imposes winding angles over there. Consequently, fibre angles cannot be chosen freely and fibre paths cannot pass wherever on the mandrel. This limited path freedom also explains why symmetry disturbing details like eccentric nozzles cause problems in terms of winding pattern and uniform coverage and hence are difficult to be wound-in.

Alternative net or near net shape manufacturing processes like braiding [5], [6], [7] and knitting [8], [9] are better suited to produce complex shapes and offer a higher integration potential than filament winding. Nevertheless, because of its advantages in terms of quality, simplicity and automation, it is worthwhile spending effort to extend filament winding capabilities.

Over the last years, PMA has developed methodologies to extend the design freedom in filament winding. Tailoring as well as integration capability are enhanced by trying to take maximum benefit from the friction available in filament winding, i.e. by using semi-geodesic paths. These methodologies have been implemented within CAWAR, a computer integrated environment around the winding process. The tailoring methodologies deal with the optimisation of axisymmetric and tubelike components, are briefly described in section 4 but discussed in [10].

In this paper the methodology is described which allows optimal obstacle integration within filament wound parts. The idea is to deviate conventional paths semi-geodesically around the obstacle in a controlled way using maximum friction. Thereby winding pattern disturbance around the obstacle can be minimised and inserts can be optimally integrated within a continuously wound lay-up. The methodology has been implemented recently within CAWAR and only preliminary validations can be presented. Although integration problems cannot be expected to be solved, validation has shown
that disturbed coverage areas around the obstacles can be significantly reduced. However, the major advantage of the methodology probably is that it allows obstacle winding to be done now in a controlled way, as well off-line as on-line.

2. State-of-the-art in obstacle integration

Filament winding offers the possibility to fairly well integrate obstacles at the component’s extremities if they are centred around the winding axis. Typical examples are the traditional centric nozzles in pressure vessel domes (figure 1a). Classical winding allows to integrate these centric nozzles but results in a significant thickness build-up on the domes. To reduce this undesired thickness increase, winding patterns based on the delta-axisymmetric method for spherical pressure vessels can be adopted [12].

Integration becomes far more difficult when eccentric nozzles are involved. Unfortunately, due to severe competition with metal vessels together with the general demand for more flexibility in connection positioning, pressure vessel winders are often asked to produce vessels with nozzles wherever on the cylinder or dome (figure 1b).

Figure 1a: Centric nozzles
Figure 1b: Eccentric nozzles

Eccentric nozzles are currently introduced, either by drilling after winding, either by manually assisted integration during winding. This integration is however done in a non-controlled and non-optimised way. Because of a lack of calculation and control capacities, the classical fibre paths are adopted and critical fibres are guided around the obstacle by means of human intervention. This intervention requires a person to be watching the complete winding process and handling the fibre tows where necessary. The “tears” which traditionally appear in front and behind the obstacle, i.e. triangular areas with no or only partial coverage, are usually reinforced by means of fabrics which are hand laid-up in between the filament wound layers. This artisan’s approach is unpredictable, only allows poor “on-line” control, results in poor repeatability and hence detracts from all main filament winding advantages.

Consequently, a methodology was to be developed to integrate obstacles in a controlled way without human intervention, by deviating the critical paths around the obstacle using maximum friction. This would allow off-line
feasibility control and optimisation, yielding minimum winding pattern disturbance, minimum tear size and hence minimum additional required fabric reinforcement.

3. Semi-geodesic winding as tool to extend fibre path freedom

A fibre can be wound onto a mandrel in several ways, a major condition being the path should be stable and free of slipping. Best known fibre paths are geodesics which connect 2 points on a surface along the shortest distance over the surface. While following a geodesic line, a fibre will not show any tendency to slip when being pulled. Hence geodesic winding does not require any friction to be stable.

For surfaces of revolution, the geodesic equation can be expressed by the law of Clairaut: \( r \sin(\alpha) = \text{constant} \), with \( r \) being the radius in the particular point on the mandrel and \( \alpha \) the angle between the fibre path and the meridian through that point.

However, a path must not be strictly geodesic to be stable. Also by semi-geodesic winding, i.e. by deviating slightly from the geodesic, stable winding patterns can be realised if enough friction is available. When a fibre deviates from its geodesic path on a curved surface (figure 2), the tensile force \( \vec{T} \) in the fibre exhibits, beside a normal component \( \vec{f}_n \) (required for proper compacting), also a transversal component \( \vec{f}_b \). This transversal component can make the fibre slip and must be compensated through friction.

\[
|\lambda| = \frac{\vec{f}_b}{\vec{f}_n}
\]

Figure 2: Force system in semi-geodesic winding.

In winding terminology, \( \lambda \) or slippage tendency has been introduced and defined as:
To be stable, slippage tendency should remain smaller than the maximum available friction coefficient:

$$|\lambda| \leq \mu_s$$

This condition should be fulfilled all along the complete fibre path and hence limits the trajectory freedom of the fibre; winding angles cannot be chosen free and one and the same winding cannot pass wherever on the mandrel. Nevertheless, compared to the even more restrictive geodesic winding, semi-geodesic winding offers an important design freedom which one should exploit as much as possible.

4. CAWAR, a filament winding design tool

In the past, PMA has developed software, called CAWAR, to compute fibre paths and winding patterns on complex surfaces. Originally, CAWAR, which stands for Computer Aided Winding of Asymmetrical parts using Robots, was created for winding T-connections [4]. Appropriate fibre paths were calculated and translated into robot paths, taking feasibility and collision avoidance into account. While previously main emphasis was on manufacturing, CAWAR has recently been extended from the design side. New modules have been implemented to gain maximum benefit from semi-geodesic winding for optimisation purposes as well as to extend winding capability.

Figure 3 shows CAWAR's actual design capabilities. These allow general filament wound lay-up optimisation for a given geometry, making maximum use of available friction. Optimisation can be considered on 3 levels: fibre, layer and laminate level. For axisymmetric geometry's and loading, fibre path optimisation is performed using semi-geodesic winding. One representative fibre path is optimised as to yield an as uniform as possible safety factor all over the component [10] [11]. A two-way link to FEA is provided to assist optimisation from both laminate analysis and laminate updating side. The lay-up is generated by repeating the optimised path along the circumference. If necessary, fibre path optimisation can be restricted to well-defined areas, thereby avoiding that critical areas, which might be locally reinforced by additional windings, will dominantly limit the overall optimisation. For slightly asymmetrical but tubelike parts, optimisation is performed on a layer level. One representative path is sub-optimised and then shifted along the circumference counting on friction, until the complete surface is uniformly covered. This coverage optimisation can be done for multiple layers as to yield an appropriate global lay-up.
Concerning the third level, no particular methodology has been developed and the user must on his own initiative use CAWAR's capabilities to propose, calculate, assemble, analyse and update the filament wound lay-up.

![Diagram](https://example.com/diagram.png)

Figure 3: CAWAR's design facilities

### 5. Obstacle integration methodology

For optimal obstacle integration, following methodology has been developed and implemented within CAWAR (figure 4). The obstacle and its base surface are represented by means of trimmed surfaces, the obstacle surface being considered as filling surface. First a set of fibre paths is assembled as if no obstacle was present, i.e. for axisymmetrical parts by repeating 2 basic paths, a $[+\alpha]$ and a $[-\alpha]$ one, along the circumference, for tubelike shapes by shifting both basic paths along the circumference within friction limits.
Then all paths which somehow cross the obstacle (and hence the filling surface) are grouped and for each of them the begin- and end cross points are stored. For each crossing path, the points before the begin cross point, increasing in reverse direction, are iteratively recomputed forwards with maximum friction until the new begin cross point does not cross but meet the obstacle. Similar calculations are done for the end cross point; recomputation is done here backwards while the number of points taken along in the calculation increases in the forward direction until the fibre path meets the obstacle. Finally, both raccording path parts are linked together by means of a path following the obstacle border. By applying maximum friction over a minimum number of points in front of and behind the obstacle, fibre path disturbance and hence tear formation are minimised. Original paths are restored as soon as possible, thereby avoiding winding strategy problems. Winding strategy is computed by linking $[+\alpha]$ with $[-\alpha]$ paths so that overall connection length is minimised.

![Figure 4: Strategy for obstacle integration](image-url)
6. Validation

The methodology has been preliminary validated on a tube of diameter φ 81.5mm with a φ 20mm obstacle. Uniform coverage with a 1200 Tex glass fibre of 4mm width at a winding angle of ± 45° requires 46 winding cycles along the circumference. 46 [+45] paths and 46 [-45] paths were computed from which 5 [+ ] and 5 [- ] paths originally crossed the obstacle. These 10 paths were optimised within a slippage limit of \( \lambda = \pm 0.2 \), to minimally avoid and hence maximally integrate the obstacle. Figure 5 shows a part of the developed cylinder with the 10 obstacle avoiding paths.

![Figure 5: Optimal obstacle integration in cylinder wall](image)

7. Conclusion

This paper has dealt with component integration in filament wound structures. Current filament winding design and manufacturing know-how do not allow to integrate eccentric obstacles in a controlled way. Therefore PMA has recently extended its filament winding design software to cope with optimal obstacle integration. A methodology has been developed in which maximum friction is used to deviate conventional paths semi-geodesically around the obstacle. Thereby winding pattern disturbance around the obstacle can be minimised and inserts can be optimally integrated within a continuously wound lay-up. The developed methodology has been presented within this paper. Although coverage disturbance around the obstacle remains due to only limited friction, preliminary validation has shown that it can be significantly reduced. Nevertheless, the major benefit of the methodology will probably be the tool it offers for controlled obstacle winding, on-line as well as off-line. Future obstacle integration developments will have to concentrate on optimising the additionally required tear reinforcement by means of FEA.
8. References

[1] Lloyd-Thomas, D.G., Eckold, G.C., Wells, G.M.,
Asymmetric filament winding,
2nd International Conference on Automated Composites 88, P.R.I.,
pp 12/1-12/12, Noordwijkerhout, Holland, September 1988.

Developments in non-axisymmetric filament winding,
2nd International Conference on Automated Composites 88, P.R.I.,

[3] Di Vita, G., Marchetti, M., Moroni, P., Perugini, P.,
Designing complex shape filament wound structures,

[4] Scholliers, J., Van Brussel, H.,
Computer integrated filament winding: computer integrated design,
robotic filament winding and robotic quality control,

[5] Michaeli, W., Rosenbaum, U.,
Structural braiding of complex FRP parts - A new approach for higher productivity,

[6] Ko, F. K.,
Braiding,
Engineered Materials Handbook, vol. 1, Composites, ASM International,
1987, pp 519-528.

Fabrication and mechanical properties of a braided composite truss joint,

[8] Raz, S.,
Advanced knitted structures for composites: an outlook,
2nd International Symposium on New Textiles for Composites:

[9] Raz, S.,
Three-dimensional knitted structures for technical uses,
