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Mechanics analysis on the composite flywheel stacked from circular twill woven fabric rings

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ABSTRACT

The filament wound composite flywheel had a deficiency of being fragile along the radial direction because there is no reinforcing phase distribution. The failure along the radial direction due to delamination may happen when the thick cylinder composite flywheel rotate at high speed. A new way to solve the low radial strength problem of the composite flywheel is to use woven fabric material. The 2D woven fabric composite in the form of a circular ring has fibers in both the circumferential and radial directions to bear the stress. This structure features the combination of the typical two-dimensional orthogonal textile fabric and the classic axial laminations, performing new characters in mechanics. Samples of composite disks with 2D woven fabric material were designed and fabricated for spinning test, and the mechanics analysis on the thin woven composite disk was carried out for the first time. With the introduction of micromechanics methods, the elastic constants of the unit cell model of periodic volume representing the whole fabric were extracted from geometrical simplification and homogenization theories. The stiffness and strength of orthogonal twill woven fabric were predicted to evaluate the failure spinning speed of the fabric composite disks. The theoretical maximum spin speed of the woven flywheel could reach 1261 rps with energy density of 53 W h/kg. The tension test data on samples of twill woven fabric composite helped with the prediction of failure of disk samples. The spinning tests confirmed that the tail weakness of the stacked configuration and the stiffness degradation from defects in composite contributed greatly to the stable running of flywheel spin.

1. Introduction

Energy storage is essential to electrical utilities and customers. Energy storage technology mainly includes pumped hydro storage, compressed air energy storage, flywheel energy storage (FES), battery energy storage system, capacitor and super-capacitor energy storage [1]. The modern flywheel-energy-storage performance was greatly enhanced with the use of advanced fiber composites for higher speed, magnetic bearing for lower friction loss and new power conversion for greater efficiency [2]. FES is adequate for interchanging energy in high powers (kW to MW) during short periods (seconds) with high energy efficiency (in the range of 90–95%) and long lifetime (20 years). Flywheel technologies may be used in different applications such as uninterruptible power system (UPS) [3], power quality [4], kinetic or potential energy regenerating, grid frequency leveling and wind power smoothing [5,6].

The kinetic energy stored in a flywheel is proportional to the inertia and the square of its rotating speed. The maximum stored energy is ultimately limited by the tensile strength of the flywheel material. Until now, most composite flywheels were made from circumferentially wound fibers pulled through a wet bath of resin [7,8]. However, filament-wound-composite-rings flywheels have one weakness of being fragile on the radial direction because the fibers are placed parallel to each other in the hoop direction with no reinforcement in the radial direction. To overcome this weakness, the multi-rings flywheel and stacked-ply flywheel techniques were evaluated [9,10].

Ha et al. derived a symmetric ring's stiffness matrix for the analysis of a multi-ring composite flywheel and assembled it into a symmetric global matrix satisfying the continuity equations at each interface with the assumption of plain strain and axial symmetry [11]. Arnold presented an analytical model capable of performing an elastic stress analysis for single/multiple, annular/solid, anisotropic/isotropic disk systems, subjected to pressure surface tractions, body forces and interfacial misfits [12]. Thielman and Fabien designed a flywheel from alternating plies of purely

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circumferential and purely radial reinforcement (see Fig. 1) [13]. Classical Lamination Theory was used to the equations that determined the stress and strain in the stack-ply composite disk [14].

To solve the problem of lack of radial reinforcement of composite flywheel, a new method is to employ the profile modeling weaving technique in which fibers are woven along both circumferential and radial direction to form a circular ring fabric for flywheels. The new continuous spiral weaving sector rings were stacked into a disk and composited with epoxy resin to obtain a thin disk flywheel using vacuum assisted resin infiltrate molding (VARIM) process.

Woven fabrics are used as reinforcements for composites to get better properties in mutually directions and obtain more applications such as automotive, architecture, and aerospace engineering. 2D woven fabrics including plain, twill, and stain weave style are obtained by interlacing two sets of yarns in the weaving machine [15,16]. In a twill, the fill tows are interlaced in a pattern of "m under–n over", with at least one of m, n greater than 1. The main characteristic of the twill weave is its improved drapability as compared to plain weave.

The mechanical properties such as elasticity, strength of the woven composites are essential data for the design and application in engineering. Angioni et al. gave a review of homogenization methods for 2D woven composites [17]. Onal and Adanur reviewed the modeling of elastic, thermal and strength/failure analysis of 2D woven composites [18]. Admumitroaie and Barbero proposed a general approach for the geometrical modeling and the new formulation for mechanical analysis of 2D orthogonal woven fabric reinforcements for composite materials [19,20].

In this paper, the profile modeling weaving is introduced to manufacture the spiral twill woven fabric rings as shown in Fig. 1. In the simplified analysis, the spiral twill fabric was spread to a twill flat plate with orthogonal warp and fill (or weft) yarns along the circumferential direction. The spindle-shaped section was used to describe the geometry configuration of the yarns in the twill unit cell. Elastic properties of the twill woven composite plate in volume averaging method were obtained and compared to the experimental results. Samples of composite disks with 2D woven fabric materials were designed and fabricated for spinning test, and the mechanical analysis on the thin woven composite disk was carried out unprecedentedly to predict the maximum rotational speed of the woven fabric composite flywheel.

2. Properties of 2D-woven fabric composite flywheel

2.1. Profile molding weaving of composite flywheel

The 2D-woven fabric composite flywheel is unfolded into a continuous circular ring as shown in Fig. 2. The warp filament bears the circumferential stress, and the fill yarn enhances the strength along the radial direction of the flywheel.

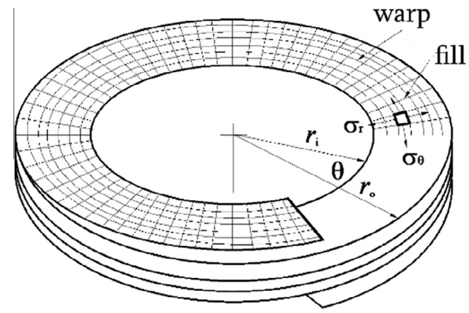


Fig. 2. Disk stacked from 2D woven fabric in sector shape.

The continuous circular ring fabric was manufactured by the profile modeling weaving method. The weaving process is shown in Fig. 3 and the fabric parameters are illustrated in Table 1. In the woven circular plate processing, the warp yarns with different length twined along the circular direction, and the fill yarn twined along the radial direction. The warp yarns were drawn from the bobbins on the creel and set into up and down ends forming the shed which the shuttle passed through. The beating up mechanism made the fabric woven from warp and fill yarns after the shuttle finished filling insertion. The key point in fabricating circular plate was to control the different warp yarns and the length of the warp yarn at particular positions interweaving to the fill yarn.

The circular fabric rings in spiral continuity were stacked to form a disk and then cured with epoxide resin by VARIM process. The cured woven composite disk samples were ready for spin burst test.

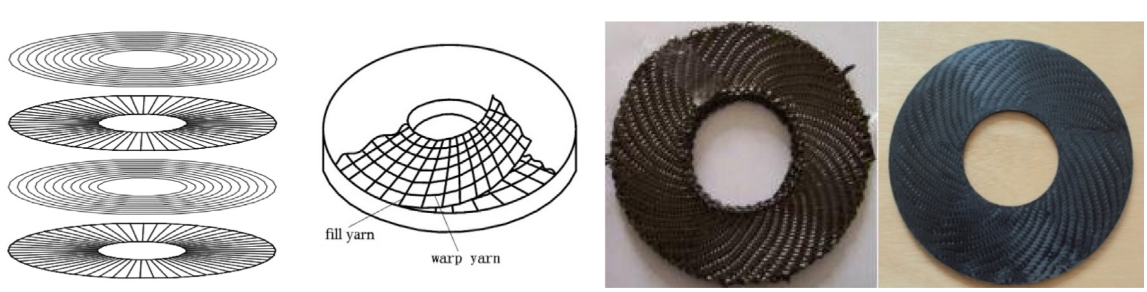
The twill weaving process determines that the flywheel has the following special properties. The warp yarn along circumferential direction was curved axially unlike the circumferential wound flywheel. The fill yarn radiates straight along the radial direction. However, the fiber density becomes lower as the radius increasing. The analytic mechanics solution became difficult because of the warp yarn curving and the fiber non-uniformity in the radial direction. Analytical models with some simplification or finite element numerical analysis may be used to solve the mechanical behavior of fabric reinforced composites.

In the following work, the curving twill spiral sector in fan-shaped Respective Unit Cell (RUC) was simplified to straight twill flat plate in orthogonal flat RUC to get the elastics properties of woven composites, which made the analytical approximate mechanics solution easily and rapidly obtained.

2.2. Mechanical properties of the twill woven flat plate

2.2.1. Geometry configuration of twill unit cell

The spindle-shaped section was assumed as a lenticular area of intersection of two circles (see Fig. 4). If we define the cross-sectional shape factor, a_f, as the fill yarn width divided by the yarn



(a) Circumferential and raidal ply (b) Spiral twill woven fabric and stacked composites disk

Fig. 1. Radial reinforcement of fiber composites flywheel.