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Original

Composite flywheel material design for high-speed energy storage

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Abstract

Lamina and laminate mechanical properties of materials suitable for flywheel high-speed energy storage were investigated. Low density, low modulus and high strength composite material properties were implemented for the constant stress portion of the flywheel while higher density, higher modulus and strength were implemented for the constant thickness portion of the flywheel. Design and stress analysis were used to determine the maximum energy densities and shape factors for the flywheel. Analytical studies along with the use of the CADEC-online software were used to evaluate the lamina and laminate properties. This study found that a hybrid composite of M46J/epoxy–T1000G/epoxy for the flywheel exhibits a higher energy density when compared to known existing flywheel hybrid composite materials such as boron/epoxy–graphite/epoxy. Results from this study will contribute to further development of the flywheel that has recently re-emerged as a promising application for energy storage due to significant improvements in composite materials and technology.

Keywords: Flywheel; Energy storage; High-speed; Composites; Energy-density

1. Introduction

Energy storage technologies are becoming practical solutions for situations where energy is required to be saved for use at a different time. Today, viable energy storage technologies include flywheels and batteries. The flywheel has recently re-emerged as a promising application for energy storage due to significant improvements in materials and technology. When compared to conventional energy storage systems, the flywheel has many advantages which include high power/energy density, much less environmental problems, availability of output energy directly in mechanical form and high efficiency. Composite materials flywheel allow for much higher density than conventional steel-based flywheels due to their lower density and potentially higher tensile strength.

One of the first studies which showed that composite materials with significantly large specific strength are well suited for flywheel energy storage applications was Rabenhorst (1971). Aspects of the report on comparison of flywheel material properties indicated that the use of 70% graphite whisker/epoxy material for the flywheel leads to a factor of 17.6 improvement over maraging steel that was considered to be the highest strength isotropic material for a constant stress flywheel rotor. DeTeresa and Groves (2001) examined the performance of commercial high-performance reinforcement fibers for application to flywheel power supplies and concluded that carbon fibers are preferred for highest performance. Dems and Turant (2009) presented methods for the design of reinforced composite flywheels for maximum kinetic energy while Tzeng, Emerson, and Moy (2006) studied elastic and viscoelastic behavior of composite flywheels and proposed methodology, material characterization and test matrices for the design in order to achieve maximum performance. Clerk (1964) pointed out that a major requirement is the need to significantly increase the energy density and Janse, Petrus, Groenwold, and Wood (2013) studied some composite flywheel rotor design methods and proposed a formulation for improvement toward achieving high energy density.

Wen and Jiang (2012) reported on maximizing the energy storage capacity of a hybrid composite multi-ring flywheel. Results show that the composed rings of the hybrid flywheel

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Nomenclature

A, *B*, *D*	extension, extension-bending, bending stiffnesses respectively
E	Young's modulus
F	lamina strength
K	shape factor
KE	kinetic energy
N	force resultant; number of lamina
M	moment resultant
R	laminate strength
e	energy density
h	axial thickness of flywheel
k	integration constant; curvature
m	mass
n	number of sequence repetition
r	radius
u	displacement

Greek symbols

ε	strain
θ	LAMINA lay-up
ν	Poisson's ratio
σ	stress
ρ	density
ω	angular velocity

Subscripts

1	fiber direction
a, *b*	disk and rim respectively; outer position of disk and rim respectively
o	center of flywheel
r, θ	cylindrical coordinate directions
t, *c*	tensile and compressive
x, *y*, *z*	Cartesian coordinates directions

Superscripts

0	In-plane

rotor can nearly reach the limits of strength in both radial and circumferential directions. Ha, Kim, Nasir, and Han (2012) studied different rim design cases of hybrid composite flywheel rotor based on strength ratio optimization. The rotor was composed of four composite rims made of carbon-glass/epoxy with hoop wound reinforcements of varying volume fractions. Alexandrova and Vila Real (2009) designed composite flywheel based on the model of annular rotating disk with stress-free boundary condition while thin rim or multi-trim flywheel was reported by Post and Post (1973) where individual thin rings basically in pure uniaxial stress circumferentially were made to spin about a common axis. Wang, He, Zhao, and Li (2012) studied a multilayer rim carbon fiber/glass fiber, composite flywheel for ultimate strength requirement. Results show that selecting the layer thickness and hybrid ratio of carbon fiber to glass fiber can reduce radial strength requirement of the rim material.

Studies (Bolund, Bernhoff, & Leijon, 2007; Chang & Hirschfeld, 1978; Genta, 1985; Kirk, 1977) have found that possible flywheel shapes for energy storage include the constant stress disk, conical disk, constant thickness (pierced and unpierced) disk, disk with rim and thin rim. Metwalli, Shawki, and Sharobeam (1983) designed configurations that maximize the energy density of variable material flywheels and proposed an optimum design of a constant stress flywheel whose material density varies radially. One of the conclusions reached in the study is that a multi-element alloy flywheel will provide a higher inertia per unit mass than a flywheel made of one element with a higher specific strength. Georgian (1989) reported on the optimum design of composite flywheel consisting of inner disk of low density, high strength and low modulus of elasticity composite material and an outer disk of constant thickness with high density, high strength and high modulus of elasticity. The results show that maximum energy density was achieved using a combination boron/epoxy for the rim and high strength graphite/epoxy for the constant stress portion of the flywheel leading to the conclusion that in order to obtain high energy densities, a search for a higher strength and lower density composite for the disk is required. This present study investigated composite materials with low densities, low modulus and high strength for the constant stress portion and a higher density, higher modulus and strength for the constant thickness portion. Analytical studies along with the use of the CADEC-online software were used to evaluate the lamina and laminate properties.

2. Flywheel stress analysis

Figure 1 shows the views of the flywheel used in the study. It is a constant stress disk and a constant thickness rim flywheel with an angular velocity of ω rad/s. The sectioned annular element at a radius, r, is in equilibrium under the action of the forces shown.

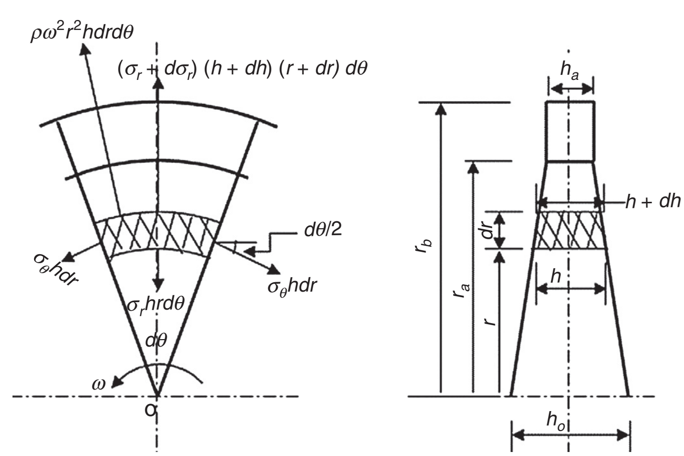

Fig. 1. Constant stress disk and constant thickness rim flywheel.