Composite Structures 107 (2014) 19–29

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Design and fabrication of hybrid composite hubs for a multi-rim flywheel energy storage system

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ARTICLE INFO

Article history:
Available online 18 July 2013

Keywords:
Hybrid composites
Press-fit interference
Finite element analysis
Filament winding

ABSTRACT

A composite hub was successfully designed and fabricated for a flywheel rotor of 51 kWh energy storage capacities. To be compatible with a rotor, designed to expand by 1% hoop strain at a maximum rotational speed of 15,000 rpm, the hub was flexible enough in the radial direction to deform together with the inner rotor surface. This hub is also stiff in the conical deformation mode to increase the vibration frequency for high rotational speed. A dome type hub of carbon-glass/epoxy has been developed to be press-fitted into the rotor with interference in order to offset the hoop strain. A series of parametric study were sequentially performed to determine fiber fractions, layer thickness, winding angles, interference, and the shape of the geodesic dome contour. A safety factor of two was secured in the final design to take into consideration a long term fatigue life of the hub. The hub was fabricated by wet filament winding-process, followed by press-fitting into a surrogated rotor, which has the same inner and outer diameters and stress states as those of original rotor except height. The strains were measured during the press-fit and found to be in agreement with the stress analysis results.

1. Introduction

Flywheels have been developed for energy storage and retrieval in various applications, including frequency regulation, uninterruptible power supplies, hybrid electric vehicles, and space stations [1,2]. When compared to other energy storage devices (e.g., electrochemical batteries), flywheels can be viable alternatives due to a high power density, no degradation during the entire design life, and superior energy discharge rates [1,2]. A flywheel rotor system consists of a metallic shaft, a rotor, and a hub. The rotors of these flywheels are made of composite materials since they usually operate at high speeds, whereas conventional metals (steel or aluminum) are seldom applicable. Low weight, high strength and stiffness, longevity, and anisotropy are characteristics of the composite materials, which often make them excellent candidates for the fabrication of flywheel rotors for energy storage [3–6]. A flywheel rotor system is levitated mostly by magnetic bearings [7–9], which offer very low friction, enabling low internal losses and a long service life.

The rotor is connected to the metallic shaft by a hub, which transmits torque between the rotor and the shaft during the flywheel operation. During the rotation, the hub is subjected to stresses due to the centrifugal forces and differential growth of the metallic shaft and composite rotor in the radial direction. As the rotational velocity increases, the hub can be subjected to the resonant frequencies. Thus, the hub should be stiff enough to overcome the critical speeds. Moreover, the hub should be tightly connected to the metallic shaft, which is very stiff, and the outer surface of the hub that is attached to the rotor should be flexible enough to expand and hold onto the inner surface of the rotor. The flexible hub is intended to facilitate the radial deformations of the hub while securely attaching the rotor to the shaft. Such radial deformations cause compression at the interface between the rotor and the hub, lowering the radial tensile stresses [4].

Several investigations have been performed regarding the design and material of the hub [3,4,10–14]. Xingjian et al. [3] designed and performed tests on a prototype flywheel system with an aluminum alloy hub formed by a thin plate and shell, where the low rigidity of the hub developed flexible modes at a lower frequency than the rated frequency, requiring complex methods to control the nonsynchronous vibrations of the flywheel system. Ha et al. [4] determined the effect of the hub expansion on the rotor performance using both conventional ring-type and newly introduced split type aluminum alloy hubs. Though the strength ratios were decreased using the split type hub, the hub weight may increase significantly for large capacity flywheels due to the high density ofaluminum. Herbst et al. [10] performed spin tests on a sub-scale model of a 10 MJ rotor with a conical steel alloy hub, and measured the rotor growth and strains; a complex structure comprised of a composite arbor, a conical metallic hub, and a metallic sleeve was deployed, which connected the composite rotor with the metallic shaft.

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0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.07.032

The use of metallic hubs in a flywheel rotor system can be limited due to the structural and stability constraints. Due primarily to its high density, a metallic hub inevitably increases the total mass of the flywheel system, and thus a high force is required for levitation support. The hub mass also barely contributes to the stored energy of the flywheel rotor system [11], so it should be as low as possible. In addition, it is not easy to manufacture large metallic hubs for large flywheel rotors. Due to the dissimilar expansion behaviors of the metallic hub and the composite rotor, it is difficult to maintain the bond at the hub–rotor interface at high rotational speeds. The metallic hub also limits the composite rotor from reaching its maximum capability of a higher operating speed [12].

In addition to the metallic hubs, Xin [11] investigated a composite domed hub by employing a design optimization procedure to modify the hub shape, increased the maximum shear stress, and deformation in the limited space. The research represented the crack investigation results on a composite disk type hub; however, it did not explain the fabrication procedure and the experimental results of the composite domed hub. Spears et al. [12] also proposed a composite hub made of prepreg tapes, preferably made using a hand lay-up process. Though the prepreg allows better control of the resin content, hand lay-up is a manual, slow, and labor-consuming process. Moreover, the nature of the hand lay-up process may also result in inconsistent reinforcement orientations. Perez et al. [13] analyzed the effect of nylon andurethane hubs on the displacements, stresses, and failure factors of the flywheel. The nylon hub was detrimental as the strength ratio exceeded the value 1, while the urethane hub had an aging constraint under fatigue loads. Genta [14] found that disk type polyamide and plywood hubs performed well during spin tests on prototype flywheels. However, the study indicated that the shaft–hub interface problem persisted, and no data represented the fatigue behavior of the hubs.

In this study, we propose a new filament-wound dome type hub of hybrid composites meeting strength and deformation design requirement. It features press-fit interference to induce the pre-compression in order to reduce the radial tensile stresses at the shaft–hub and hub–rotor interfaces. The stiffness of the hub varies from the inner surface to the outer surface, ensuring contact with the shaft and rotor when rotating at the maximum speed. This variation in stiffness is achieved by material hybridization and the proper selection of the winding angles. The shape of the dome section, the winding angles and press-fit interference are determined by sequential parametric studies using a finite element analysis. In the fabrication procedure, two hubs are simultaneously wound on a mandrel due to the nature of the filament winding process, and the hubs are cut into two pieces after curing. A surrogate rotor with the same radial dimension as the full scale rotor was fabricated to check the assembly procedure and to perform the spin test of the hub together with the rotor: the metallic shaft is press-fitted into one of the hubs, and the shaft–hub assembly is then press-fitted into the rotor. The surrogate hub would experience the same deformation and stresses as in the full rotor. Only difference is that the full rotor would need two identical hubs press-fitted at the top and bottom of the rotor. The strains are measured during the press-fit assembly procedure to verify deformation predicted by the FEA.

2. Design procedure for a hybrid composite rotor and dome hub

2.1. Multi-rim hybrid composite rotor

The energy stored in a flywheel is given as [1,2]:

$$E = \frac{1}{2} I \omega^2, \tag{1}$$

where I and ω are the moment of inertia and the angular velocity of the rotating components, respectively. It can be deduced from Eq. (1) that the most efficient way to increase the stored energy is to increase the speed of the flywheel. However, the speed is mostly limited by the centrifugal forces of the flywheel rotor. Therefore, fiber-reinforced composite materials are being utilized in the fabrication of flywheel rotors in order to maximize the speed limit. These rotors are strong in the hoop direction, but weak in the radial direction, causing radial delaminations, and subsequently limiting the energy storage capability of the flywheels. The radial delaminations can be prevented by minimizing the radial tensile stresses using material hybridization and interference [15–17]. In hybrid rotors, softer and heavier reinforcements are placed at the inner side of the rotor, whereas stiffer and lighter reinforcements are placed at the outer side. Such an arrangement of reinforcements produces favorable compressive stresses, which reduces the radial tensile stresses in the rotor during the flywheel operation. The interference fit is also an effective way to reduce the radial tensile stresses, because it generates primary compressive stresses that considerably offset the radial tensile stresses during the flywheel operation [18,19].

The composite rotor used in this study is made of six hybrid rims of carbon fiber, glass fiber, and epoxy resin. The carbon fiber volume ratio increases from the inner rim to the outer rim. Consequently, the rotor has more radial growth at the inner surface than at the outer surface generated by the hybrid rims during the spinning of the rotor. Ha et al. [19] described the design and manufacturing procedure of the rotor, considered in this study, in a separate investigation.

2.2. Composite dome hub

During rotation, a rotor radially “expands” and axially “contracts” due to the centrifugal force, and the hoop strain (ε_θ) at the rotor inner surface increases. For a given composite rotor with an anticipated radial growth, the designed hub should be flexible enough and must not fail during compensation of the radial deformation of the rotor at high rotation speeds.

Fig. 1 illustrates the strategy used in this paper in order to offset the radial growth of the inner rim of the composite rotor using a flexible composite dome type hub. Prior to the assembly, a stress-free hub is shown in Fig. 1a. The compressive stresses are then generated at the hub–rotor interface during press-fit assembly of the rotor and the hub. Since the rotor is not rotating, there is no radial growth in the rotor as shown in Fig. 1b. However, ε_θ occurs when rotor rotates at the maximum speed (ω_{max}) as shown in Fig. 1c. The hub will detach from the rotor, if ε_θ exceeds the compressive strain at the hub–rotor interface produced by the radial interference (δ_t) during rotation at ω_{max}. To overcome this problem, we introduce the radial hub expansion (δ_h) at the hub–rotor interface while rotating at ω_{max} using a flexible hub. Consequently, ε_θ is cumulatively offset by the δ_t and δ_h at ω_{max}. It should be noted that δ_t and δ_h do not affect the rotor, because the rotor is stiff enough to respond such deformations.

2.3. Stress analysis of a composite dome hub

Three coordinate systems are defined for a composite dome hub: a local on-axis coordinate system (x, y, z), a local off-axis (loading axis) coordinate system (x_1, x_2, x_3), and a global coordinate system (θ, r, z), where x, y, and z denote, respectively, the axis parallel to the fiber direction, the axis perpendicular to the fiber direction, and the axis perpendicular to the x–y plane, and x_1, x_2, and x_3, are the axis parallel to the loading direction, the axis perpendicular to the loading direction, and the axis perpendicular to the x_1–x_2 plane, respectively, while θ, r, and z denote, respectively, the circumferential (hoop), radial, and axial directions. The local on-axis