DESIGN, FABRICATION AND TESTING OF A HYBRID COMPOSITE FLYWHEEL ROTOR & HUB

K. Hayat[1], S.J. Kim[1], Y. H. Lee[1], J. D. Kwon[1], K. T. Kim[1], D. Hockney[2], J. Arseneaux[2], S. Y. Jung[3] , and S. K. Ha[1*]
[1]Deptt. of Mech. Eng., Hanyang University,1271, Sa 3-dong, Sangnok-gu, Ansan, Kyeonggi-do, 426-791, Korea, [2]Beacon Power Corp., 65 Middlesex Road Tyngsboro, MA 01879, USA,
[3]Korea Electric Power Research Institute, 103-16, Munji-dong, Yusong-gu, Deajon, 305-380, Korea
[*]Sung Kyu Ha (Sungkha@gmail.com)

Keywords: *hybrid composites, dome-type hub, spin test, telemetry, flywheel rotor, press-fit, filament winding*

1. Abstract

This paper describes a hybrid compositeflywheel rotor designed to store 50 kWh energy at maximum rotational speed of 17,000 rpm.Design optimization and stress analysiswere carried out to acquire a hybrid composite dome-type hub geometry, thickness and fiber winding angles which provided the required stiffness to match the radial growth and axial contraction of the composite flywheel rotor during high speed rotation. Both the rotor and dome-type hub werethen fabricated by filament winding process using glass and carbon fiber reinforced composites.The hub and rotor were assembled by press-fitting techniqueto apply the necessary compression at the composite rotor inner surface, resulting in lowering of undesired radial tensile stress.During press-fit assembly process the hoop strains developed at various locations of the composite dome-type hub were measured using strain gauge sensors, which were found to be in agreement with the analytical predictions. The performance and dynamic behavior of the hybrid composite dome-type hub was verified by conducting a successful spin test of the flywheel rotor up to the target test speedof 17,000 rpm. Wireless telemetry strain measurements up to 9,700 rpm at various locations of the dome-type hub were alsoin a good agreement with analytical calculations. Moreover, the flywheel rotor temperature increment of 7.2°C (i.e. 24.5°C to 31.7°C)corresponding 1.6 mbar vacuum level was observed during the spin test.

2. Introduction

An energy storage system (ESS) is vital to use energy efficiently by storing the surplus energy from renewable resources.A flywheel energy storagesystem, a so-called mechanical battery, stores and retrieves energy from a rotating rotor. The flywheel rotor system, mostly supported by a frictionless bearing such as magnetic bearings, consists of the metallic shaft, a rotor of composite materials, and a hub connecting the rotor to the shaft[1]. The application of advanced composite flywheel rotors to store energy has recently attracted considerable attention from many investigators because of its distinctivecharacteristics of high-energystorage capability, long life and light weight[2-6].The energy is stored and retrieved from the flywheel rotor during rotation. When it rotates, stresses and strains are developed inside the composite rotor due to the centrifugal forces. Since the rotors of composite materials have very low strengths in the radial direction, therefore, radial delamination occurs which limits its energy storage capacity[7].Moreover, the rotor also tends to be detached from the metallic hub which is usually stiffer than the composite rotor.Various approaches have been utilized to increase the performance of the composite flywheel rotor, and to prevent the delamination by decreasing the radial tensile stresses. Hybrid rotors of composite materials with different stiffness and density have been used to decrease the radial tensile stresses[8-14].Several attempts to reduce the radial residual stresses developed inside therotors during the curing process are also reported in [15-17]. Interferences can be introduced between rims and hubs by press-fit or shrink-fitto generate favorable stresses in the rotor [10, 18].

The initial compressive stresses caused by interferences effectively compensate the tensile stresses developing during rotor spinning. However,

such interferences, especially between the hub and the rotor, are not sufficient due to the limited expansion or contraction. Moreover, during high speed rotation, the radial growth and axial contraction of the composite rotor usually exceeds the interference and results in the separation of the rotor from the hub.In order to overcome this problem, different types of hubs have been proposed which can expand better than the conventional solid or ring type hub[18-22].

A spin test and measurements of developed strains during rotation are carried out to verify experimentally theflywheel rotor performance. Various spin tests of flywheel rotors (i.e. a subscale model of a 10MJ flywheel rotor, a molded disk and a rim-type rotor with cord-wise wrapping etc.) have been described in[18, 23]. Measurement of rotor radial growth using laser sensor, rotor displacement using optical sensors, and rotor strainswith strain gauge sensor and wireless telemetry method, and using an optoelectronic strain techniquehave also been reported in [18, 21, 24].

In this paper, design, fabrication and assembly of a hybrid composite flywheel rotor with 50 kWh energy storage capacity at 17,000 rpm will be discussed. It will be shown that the hybrid composite dome-type hub facilitatesthe required radial deformationnecessary to providecompression at the interface between the rotor and the hub, lowers the undesired radial tensile stress inside the rotor and prevents the danger of detachment at high rotational speeds. It also exhibits sufficient stiffness that might cause vibration otherwise. Then, a spin test of the composite flywheel rotor will be performed and mechanical strains will be measured using wireless telemetry system to validate the hybrid composite flywheel rotor and dome-type hub design and performance.

3. Design of hybrid composite flywheel rotor

The amount of energy stored in the flywheel rotor depends upon the mass moment of inertia and the rotational speed.

$$E = \frac{1}{2} I \omega^2 \qquad (1)$$

where E is stored energy, I is moment of inertia of the rotor and ω is rotational speed.The maximum energy density of the flywheel rotor is:

$$e = K \frac{\sigma_\theta}{\rho} \qquad (2)$$

Where e is energy density, K is a constant, σ_θ ishoop stress and ρ is density.Equations (1) and (2) show that a flywheel rotor made of the composite materials having high specific strengths(σ_θ / ρ)can acquire high rotation speed and high energy density. High rotational operating velocities, however, produce very high centrifugal forces, which generate high radial and hoop stresses in the composite rim, causing the rim to “grow”radially and “contract” axially. Therefore, design of the hub becomes as critical as the composite rotor. If a hub has high stiffness (e.g. a metallic hub)then, it might not experience the matching radial growth as the deforming composite rim. Consequently, detachment of the composite rim from the hubcan occur. On other hand, a hub with low stiffness (e.g. a composite hub) can overcome the separation between the hub and the composite rim at higher rotation speeds. However, a composite hub,due to insufficient stiffness,causesexcessive vibrations.

A hybrid composite dome-type hub was designed, and its design variables (i.e. thickness, geometry of dome and fiber angles of the hybrid composites) were optimized to get optimum stiffness needed forthe compression between the hub and the rotor, and to provide adequate radial growth to prevent the hub-rim separation at the operating rotational speed. The optimally designed hybrid composite dome-type hub has three distinctive parts: a main dome, 1st reinforcement layer and 2nd reinforcement layer. The optimized values of thickness, material composition and fiber winding angles for each part, achieved after execution of numerous numerical iterations of the hybrid composite flywheel rotor model, are shown inthe figure 1.

Detailed finite element models of the hybrid composite flywheel rotor assembly were developed to determine the strength ratio due to assembly interferencesat rest and rotational speed of 17,000 rpm, as shown in the figure 2. A steel insert ring and a carbon ring were also designed to ease in the dome-type hub and the shaft interference fit assembly by press-fitting technique.

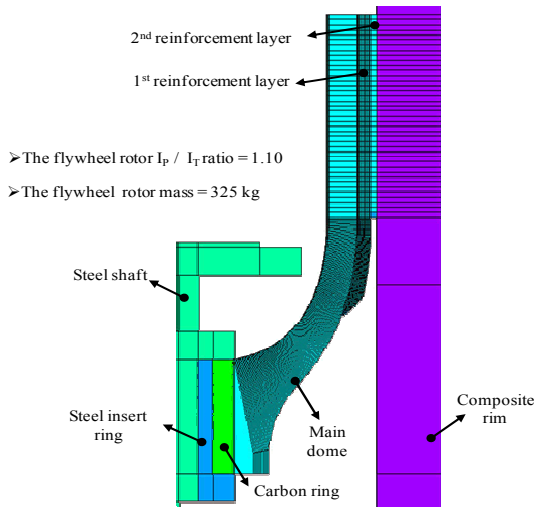


Fig.1. A hybrid composite flywheel rotor having 50 kWh energystorage capacity at 17,000 rpm, with an optimized dome-type hub

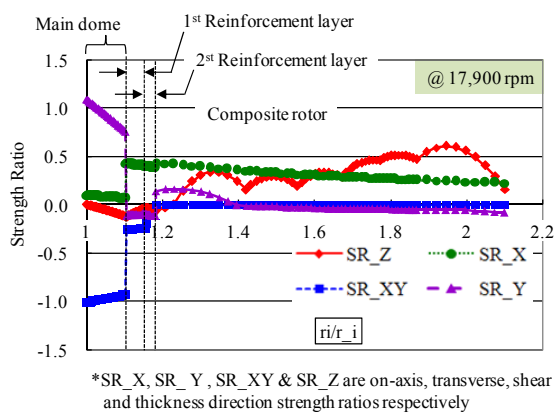


Fig.2. Stress distributionacross the hybrid composite dome-type hub, rotor and the interface

4. Fabrication and Assembly

The hybrid composite dome-type hub, carbon ring and the rotor with 460 mm inner diameter, 812 mm outer diameter, and 254 mm thicknesswere manufactured using filament-winding process. T700 (Toray, Japan), E-glass (Owens Corning, USA) and epoxy-resin werethe manufacturing materials.The shaft and insert ring were made of SCM440 steel.

To generate the favorable radial stress conditions at the inside of the hybrid composite rotor, the interference fit assembly using press-fitting technique was designed. Such interference fit assembly can cause the initial compressive radial stress which effectively offset the tensile radial stress generated during rotor spinning. The designed interference value between the steelshaft, insert ring, carbon ring, dome-type hub and the rim are shown in the figure 3.Lastly, all flywheel rotor components were machined to their final dimensions at the mating interface surfacesbefore press-fitassembly.

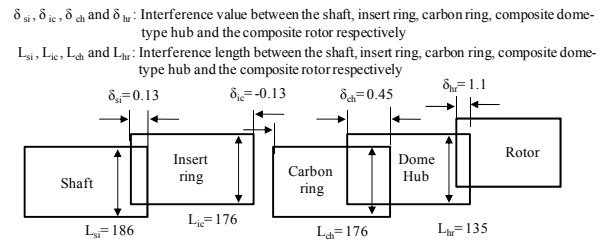
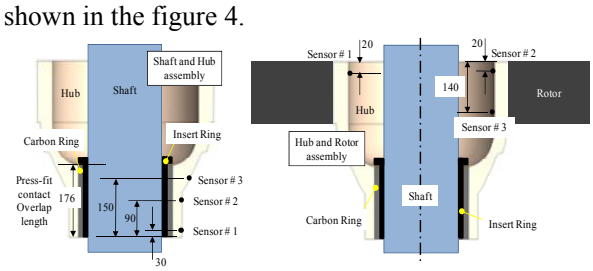
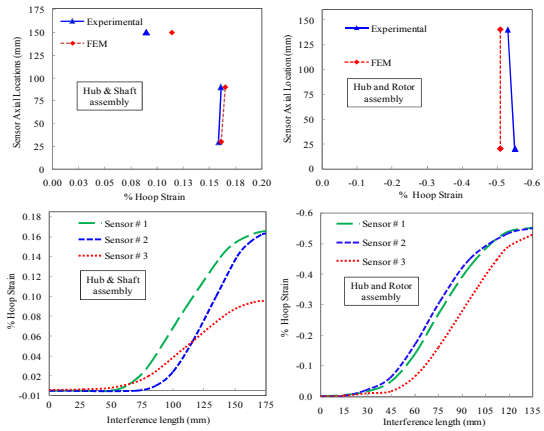


Fig.3.Interference values for press-fit assembly of the composite flywheel rotor

Since assembly of the composite parts can only be performed by press-fit method, as shrinking technique is not applicable; therefore, it was decided to measure the hoop strains of the hub developed during press-fitting. The assembly of composite flywheel rotor was carried out in two steps. In the first step, the shaft, insert ring, carbon ring and the dome-type hub were press-fitted together. In second step, the dome-type hub and the composite rim were assembled using press-fitting technique. Before press-fitting, each interface surface of matting components were coated with epoxy, which served the purpose of lubrication during press-fit and of bonding after being cured. The hybrid dome-type hub hoop strains measured during each step of press-fit assembly were compared with finite element model results and found be in good agreement, as shown in the figure 4.



(a)



(b)

Fig.4. (a) shows strain gauge locations on the hub for measuring hoop strains during press-fitting; (b) top row: shows comparison of experimentally measured and FEM calculated hoop strains; and bottom row: shows the hoop strains increment during press-fit assembly process

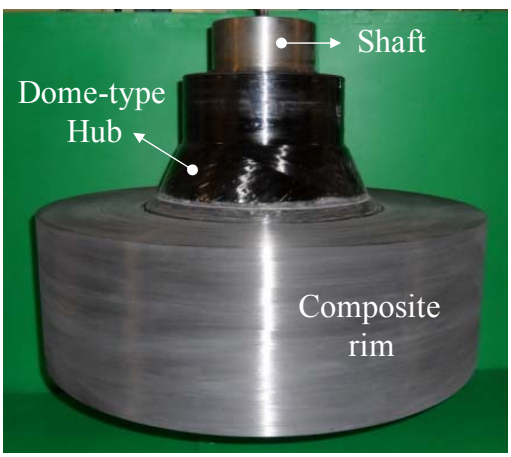


Fig.5. Assembled hybrid compositeflywheel rotor

5. Spin Test

A spin test of the composite flywheel rotor was carried out to observe the dynamic behavior of the dome-type hub and to measure mechanical strains (see figure 7) at the target test speed of 17,000 rpm. An arbor was machined from SCM440 steel to make bolt-connection between the spin-tester motor quilland the flywheel rotor shaft. Strain gauge sensors and wireless telemetry system were used to measure mechanical strains of the hub and rotor during the spin test, as shown in figure6.

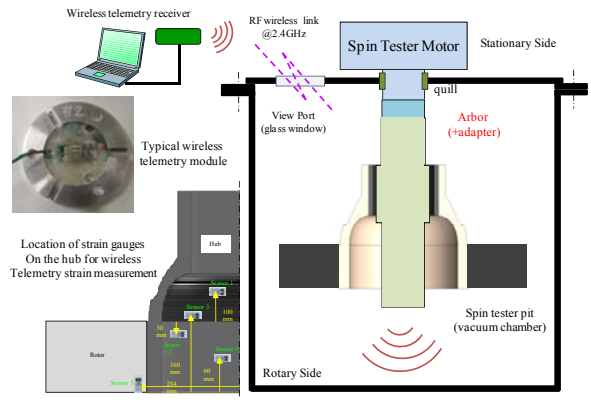


Fig.6. Wireless telemetry strain measurements at various locations on the hybrid composite dome-type hub and rotor

All strain gauge sensors and wiring was securely glued, and 05 wireless telemetry modules (each fixed on an Aluminum disk) along with a battery were fitted inside the bored steel shaft as shown in figure6. Before the spin-test, the balancing of the flywheel rotor with fitted wireless telemetry modules and attached arbor was carried out at 403 rpm. The unbalance values recorded were 429 gmm and 261 gmm at the end of two-plane balancing process.

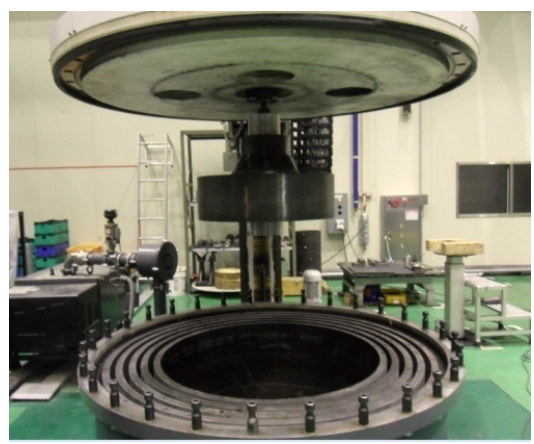


Fig.7. Spin testing setup (SCHENCK Co. [25])

The rotation speed of the composite flywheel rotor, measured radial vibration level at spin-tester motor quilland associated vacuum level inside the spin-test chamber during spin test can be seen in the figure 8.

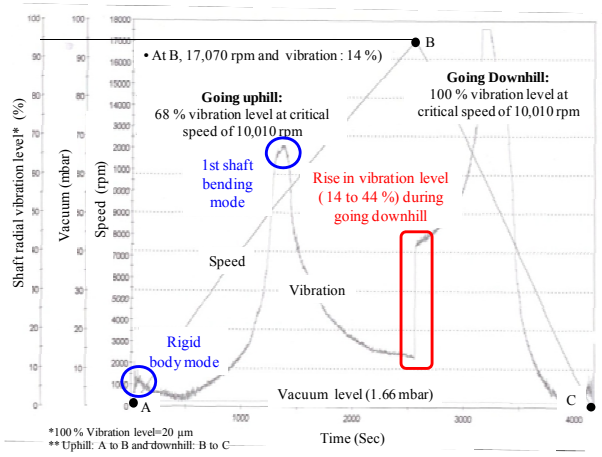


Fig.8. Spin test result

The rigid body mode was observed around 300 rpm (the prediction was 134 rpm). But first shaft bending mode was recorded at the critical speed of 10,010 rpm (the prediction was 2,490 rpm), and corresponding radial vibration levelwas 68 %. Later investigation showed thatincorrect boundary conditions atspin tester motor quillwere taken into account during rotordynamics analysis,which caused the deviation of the critical speed from the prediction.The vibration level dropped to 14% at the target test speed of 17,070rpm. Unexpected rise in radial vibrations was observed during going downhill. Approximately 100% vibration level was recorded while passing through the critical speed.The rise in radial vibration during going downhill was attributed to the bolt-connection and loose clearance fit between the arbor and the quill of spin-tester motor. The reverse torque due to deceleration might have caused the re-adjustment of bolt-connection, causing relocation of the rotational axis, resulting increased radial vibration.

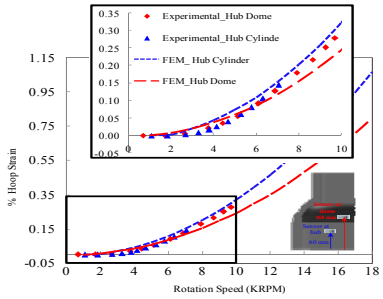


Fig.9. Comparison of the measured hoop strains with the calculated hoop strains

When spin test started, only two out of five wireless telemetry channels survived (one lasted up to 7,057 rpm and other one to 9,700 rpm) The measured strains were found to be in agreement with analytical calculations, as shown in figure 9.

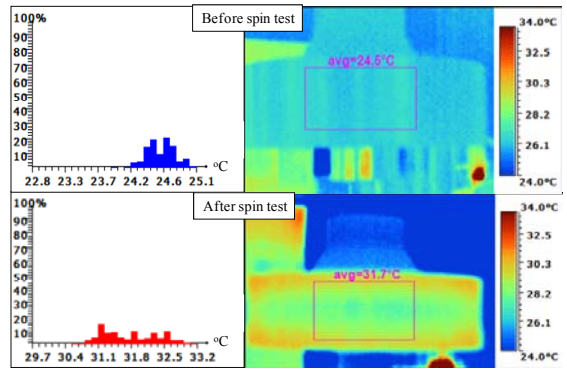


Fig.10. The flywheel rotor temperature measured before and after completion of spin test

The temperature of flywheel rotor was also recorded with infrared thermal camera (MobIRM8) before and just after spin test completion. The temperature increment of 7.2°C (i.e. 24.5°C to 31.7°C) corresponding 1.6 mbar vacuum level was observed, as shown in figure 10, showing the relaxed vacuum level requirement at the real world flywheel rotor applications.

6. Conclusions

A hybrid composite dome-type hub and rotor have been designed, fabricated and testedto build a hybrid composite flywheel rotor to store 50 kWh energy at maximum rotational speed of 17,000 rpm.Successful spin test at the target speed of 17,000 rpm has shown that the dome-type hub provides necessary radial expansion to match the radial growth of the composite rotor. It also exhibits sufficient stiffness to apply required compression at the rotor inner surface to prevent the separation and to overcomethe problem of excessive vibration at high speed rotation. The mechanical strains measured during press-fitting and spin-testing process validate the designprocedure. The designed hybrid composite flywheel rotor with dome-type hubis a successful step towards the development of high speed, high energy storage capacity composite flywheel rotor.

7. References

[1] G. Genta, *Kinetic Energy Storage*. London: Butterworth & Co. Ltd, 1985.

[2] www.beaconpower.com

[3] U.S. Department of Energy (DOE), "Energ storage_Program planning document," 2011.

[4] B. G. Anerdi G, "Technology potential of flywheel storage and application impact on electric vehicles," *12th Internal Electric Vehicle Symposium (EVS-12),* vol. 1, p. 10, 1994.

[5] D. A. Christopher and C. Donet, "Flywheel technology and potential benefits for aerospace applications," 1998, pp. 159-166 vol. 1.

[6] G. Rodriguez, *et al.*, "Assessment of flywheel energy storage for spacecraft power systems," National Aeronautics and Space Administration, Greenbelt, MD (USA). Goddard Space Flight Center1983.

[7] H. L. Wettergren, "Delamination in composite rotors," *Composites Part A,* vol. 28A, p. 4, 1997.

[8] E. L. Danfelt, *et al.*, "Optimization of composite flywheel design," *International Journal of Mechanical Sciences,* vol. 19, pp. 69-78, 1977.

[9] N. D. Ebrahimi, "Optimum design of flywheels," *Computers & structures,* vol. 29, pp. 681-686, 1988.

[10] S. K. Ha, *et al.*, "Optimum design of thick-walled composite rings for an energy storage system," *Journal of Composite Materials,* vol. 32, p. 851, 1998.

[11] S. K. Ha, *et al.*, "Effects of material properties on the total stored energy of a hybrid flywheel rotor," *Archive of Applied Mechanics,* vol. 70, pp. 571-584, 2000.

[12] S. K. Ha, *et al.*, "Optimum design of multi-ring composite flywheel rotor using a modified generalized plane strain assumption," *International Journal of Mechanical Sciences,* vol. 43, pp. 993-1007, 2001.

[13] G. C. Pardoen, *et al.*, "Achieving desirable stress states in thick rim rotating disks," *International Journal of Mechanical Sciences,* vol. 23, pp. 367-382, 1981.

[14] P. M. Wild and G. W. Vickers, "Analysis of filament-wound cylindrical shells under combined centrifugal, pressure and axial loading," *Composites Part A: Applied Science and Manufacturing,* vol. 28, pp. 47-55, 1997.

[15] C. W. Gabrys and C. E. Bakis, "Simplified analysis of residual stresses in in-situ cured hoop-wound rings," *Journal of composite materials,* vol. 32, p. 1325, 1998.

[16] S. K. Ha, *et al.*, "Effects of rotor sizes and epoxy system on the process-induced residual strains within multi-ring composite rotors," *Journal of Composite Materials,* vol. 38, p. 871, 2004.

[17] S. K. Ha, *et al.*, "Measurement and prediction of process-induced residual strains in thick wound composite rings," *Journal of Composite Materials,* vol. 37, p. 1223, 2003.

[18] J. D. Herbst, *et al.*, "Design, Fabrication, and Testing of 10 MJ Composite Flywheel Energy Storage Rotors," 1998, pp. 235-244.

[19] D. Bakholdin, *et al.*, "Flywheel rotor with conical hub and methods of manufacture therefor," 1997.

[20] R. C. Flanagan and J. J. Wong, "Energy storage rotor with flexible rim hub," 1989.

[21] S. K. Ha, *et al.*, "Design and spin test of a hybrid composite flywheel rotor with a split type hub," *Journal of Composite Materials,* vol. 40, p. 2113, 2006.

[22] D. W. Swett, "Flywheel with self-expanding hub," 2000.

[23] I. M. Zaitsev, *et al.*, "Spin-tests of composite flywheels. A review," *Mechanics of composite materials,* vol. 33, pp. 356-370, 1997.

[24] R. P. Emerson and C. E. Bakis, "Optoelectronic strain measurement for flywheels," *Experimental mechanics,* vol. 42, pp. 237-246, 2002.

[25] Schenck-Ro Tech. GmbH, "Technical documentation Spint Test Stand B15U," ed, 1999.