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Development of high speed composite flywheel rotors for energy storage systems

K. TAKAHASHI*, S. KITADE and H. MORITA

Composites Laboratory, Ishikawajima-Harima Heavy Industries Co., Ltd., Shin-nakahara-cho 1, Isogo-ku, Yokohama 235-8501, Japan

Abstract—A composite flywheel rotor was developed. The rotor was designed, which was based on the finite element analysis, and fabricated to achieve the peripheral speed of 1300 m/s. The rotor consisted of a composite rim and aluminum alloy hub. The inner diameter of the rim was 340 mm, the outer diameter was 400 mm and thickness was 25 mm. The rim comprised press fitted multiple concentric rings(multi-ring) to prevent radial tensile failures at high rotational speed. Rings were fabricated by a filament winding process using high strength carbon fiber. The configuration of the hub was like a steering wheel with 4 spokes. The cross-section area of these spokes was changed to withstand a centrifugal force. Spin tests of flywheel rotors were performed, using an air turbine driven spin tester in a vacuum chamber. The rotor was spun to maximum peripheral speed at 1310 m/s, whose stored energy was 354 Wh, and the specific energy density was 195 Wh/kg.

Keywords: Flywheel; energy storage; composite material; design; spin test; filament winding.

1. INTRODUCTION

Flywheel energy storage systems offered advantages over electrochemical batteries in situations demanding high power delivery and high specific energy (energy storage per unit weight). In the 1970s and early 1980s, much composite flywheel research [1] was carried out in response to energy storage needs in daily load-leveling, space applications and automotive applications. However, the fiber strength was too low to achieve sufficient rotational speed. Recent researches on flywheels [2] have resurged because of developments of new high strength and high modulus fibers. The composite flywheel system with new fibers will be more compact and lighter weight at the same storage energy.

*To whom correspondence should be addressed.

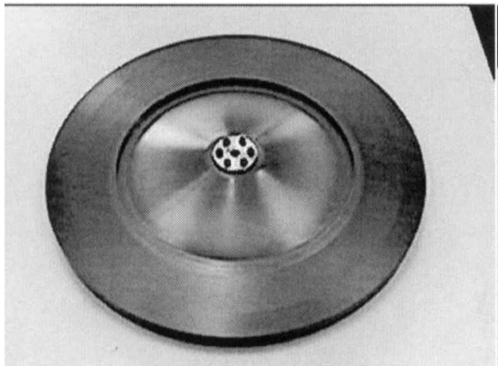

Figure 1. Composite flywheel rotor.

These authors have developed an all composite flywheel rotor [3], whose outer diameter was 400 mm (Fig. 1). The composite rotor reached a maximum peripheral speed of 1203 m/s.

In this study, the authors tried to develop a new flywheel rotor which rotated at more than 1300 m/s.

2. BASIC CONCEPT OF THE COMPOSITE FLYWHEEL ROTOR

A flywheel rotor is a rotating body consisting of a rim attached to an axis by a hub (Fig. 2). The rotor can store rotating kinetic energy by high speed rotation. The kinetic energy is proportional to weight and square of peripheral speed. The maximum energy density (energy/unit weight) is shown in equation (1).

$$e = K\frac{\sigma_\theta}{\rho}, \quad (1)$$

where e is energy density, K is a constant, σ_θ is hoop stress and ρ is density. σ_θ/ρ is specific strength. The specific strength of carbon fiber composites is much higher than metals, and a composite flywheel rotor can attain high speed rotation and high energy storage.

2.1. Composite rim

The maximum radial stress of a rotating ring depends on radius ratio between inner and outer rims (r_{in}/r_{out}), and a larger r_{in}/r_{out} causes a smaller maximum radial stress. Therefore, only thin filament wound ring can rotate at high speed because of the low transverse strength. To reduce the radial stress, a multi-ring structure is effective (Fig. 3). If a thick single ring is divided into multi rings, the maximum radial stress in each ring at rotation is lower than in the single ring, but the contact radial stress between inner and outer ring become tension (Fig. 3M). In other words, the multi-ring form cannot be maintained because each ring separates at rotation.

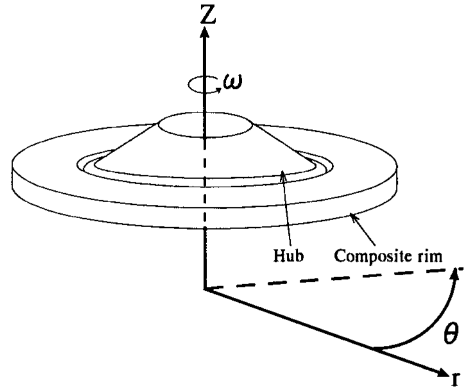

Figure 2. Configuration of the composite flywheel rotor.

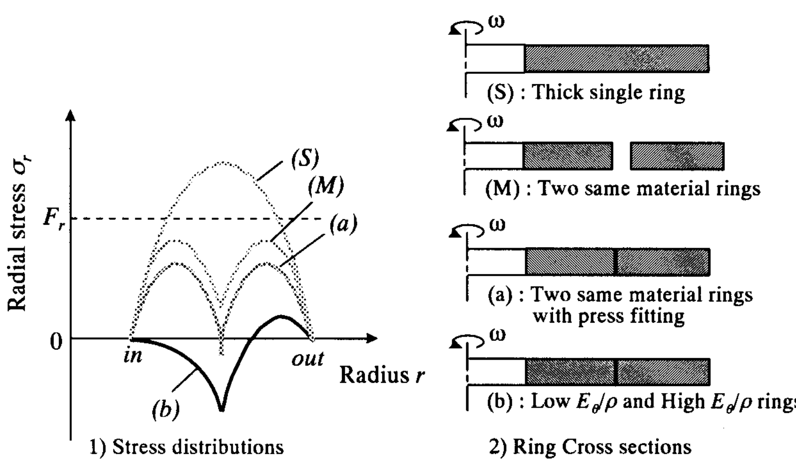

Figure 3. Reduction of the radial stress by multi-ring configuration.

To maintain the multi-ring form, contact radial stress between inner and outer ring should be a compression in the rotating area. Therefore, the multi-ring design approaches are: (a) the rim consists of press fitted multiple rings (Fig. 3a) and (b) the inner rings are denser and/or less stiff than outer rings (Fig. 3b). In method (a), the initial compressive stress field caused by press-fitting could reduce radial stress. In method (b), expanding of denser and/or softer inner ring under rotation presented compressive stress in the composite rim, and it resulted in the reduction of radial stress.

The rim of the all-composite rotor [3], which the present authors have developed, has been designed using both these approaches, (a) and (b). The outer ring was made of a high modulus fiber (Toray M40J) and the inner rotor was made of standard modulus fiber (Toray T300). All rings were press fitted. This rotor failed at a peripheral speed of 1203 m/s.

Table 1.
Mechanical properties of fibers (T300, M40J, T1000G)

	Strength (MPa)	Elastic modulus (GPa)	Density (g/cm^3)
T300	4210	230	1.78
M40J	4400	377	1.77
T1000G	6370	294	1.80

In this study, the target speed was set at higher than the peripheral speed of 1300 m/s. The strength of a thin single ring, which was made of M40J and had an outer diameter of 400 mm, was too low for the ring to spin at over 1300 m/s. Therefore, Toray T1000G, which had higher strength than M40J, was applied to the outer ring. But the modulus of T1000G is lower than M40J. In the case of a T300 ring inside a T1000G ring, the effect (b) could be obtained, but the inner radius of the rim had too large a deformation at over 1300 m/s because T1000G had less modulus than M40J. Therefore, it was difficult to design a hub, which had to expand according to the elongation of the composite rim. As a result, only effect (a) was used with all T1000G rings. The strength and modulus of T300, M40J and T1000G are shown in Table 1.

2.2. Hub

Under rotational loading, the hub had to expand according to the elongation of the composite rim, and the contact stress between the hub and the rim should be compressive to prevent separation. Therefore, the material of the hub needed to have high strain of failure and relatively low modulus. The material also needed to have stable deformation behavior until the high strain (over 1.5%) region to predict precise deformation field in design work.

The hub of the all-composite rotor [3], which the present authors have developed, was made of glass fiber composite because of its high strain of failure and low elasticity to expand with rotational speed. However, the glass fiber composite hub was damaged with delamination and fiber/matrix debonding at low speed. The deformation behavior of the glass fiber composite hub was unstable, and it was concluded that the design of a glass fiber composite hub for the new 1300 m/s class rotor was difficult.

In this study, high strength aluminum alloy (7075) was selected for the hub. The aluminum alloy had adequate ultimate strength and modulus like glass fiber composite to rotate at a peripheral speed of 1300 m/s, and the deformation behavior was stable. Under the high speed rotation, the strain of the aluminum alloy hub was beyond the elastic region. Therefore, plastic deformation of the hub was considered in design work. The hub was inserted after cooling with liquid nitrogen, to obtain initial contact stress to fit the hub with the rim.

3. FLYWHEEL DESIGN

3.1. Configuration of the flywheel rotor

The basic configuration of the flywheel rotor in this study is shown in Fig. 4. The rim was 400 mm in outer diameter, 340 mm in inner diameter and 25 mm in axial thickness. The ultimate peripheral speed in the design was 1350 m/s.

The rim had a multi-ring structure with 4 rings which were made of the high strength fiber (T1000G). The material of the hub was aluminum alloy (7075). The configuration of the hub was like a steering wheel with 4 spokes. The cross-section area of these spokes was changed to withstand a centrifugal force. The detailed configuration was adjusted analytically.

3.2. Analytical method

The flywheel rotor was designed with a finite element analysis. The model of the analysis is shown in Fig. 5. The model was one-eighth of circle and one-half of the thickness of the rotor, assuming symmetry for the circle and the thickness. The model consisted of 3D elastic-plastic elements, and the effects of contact among each rings and aluminum hub was examined.

The criteria for the flywheel rotor design were as follows;

(a) Hoop stress limitation in the rim was the ultimate strength of the composite which was made of T1000G. The ultimate stress by a NOL ring test was 3.5 GPa.

(b) Radial stress limitation in the rim was under 10 MPa.

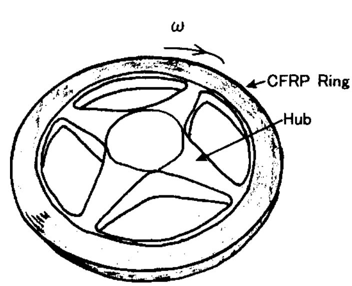

Figure 4. Configuration of the flywheel.

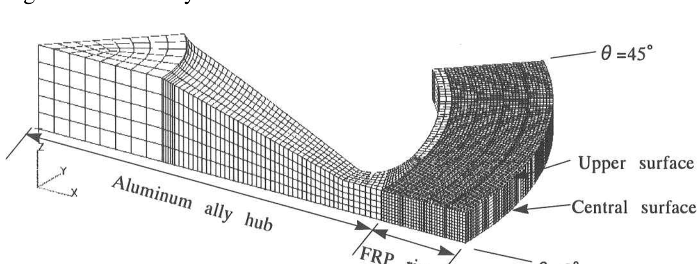

Figure 5. FEM model for composite flywheel.

(c) Contact radial stress between each rings should be compressive (under 0 MPa). Contact radial stress between the rim and the hub should be compressive (under 0 MPa).

(d) Von-Mises stress limitation in the hub was 570 MPa.

3.3. The result of the analysis

The radial and hoop stress distribution of the composite rim at 1350 m/s are shown in Figs. 6 and 7. The radial stress of the composite rim was compressive in all regions, and the rim satisfied the radial stress criteria (b) and (c). In Fig. 7, the bold line shows failure stress. Hoop stress was under failure stress, and it satisfied the hoop stress criterion (a).

The stress distribution in the hub is shown in Fig. 8. To reduce the stress by centrifugal force, the cross-sectional area of the spoke was decreased according to the outside of the spoke. Therefore, von-Mises stress distribution in the spoke was almost uniform. The maximum stress in the hub occurred in the root of the spoke (indicated in Fig. 8). The relation between maximum stress and peripheral speed

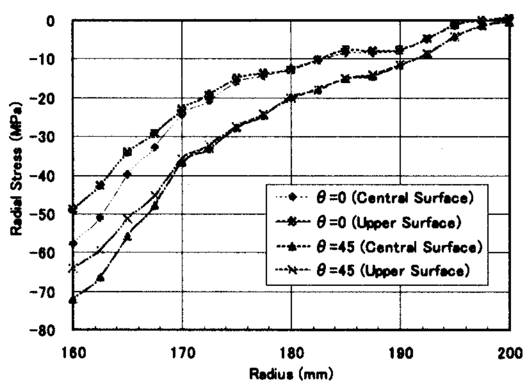

Figure 6. Radial stress distribution of the rim at 1350 m/s.

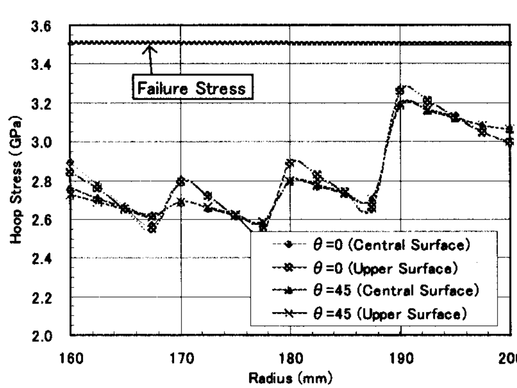

Figure 7. Hoop stress distribution of the rim at 1350 m/s.

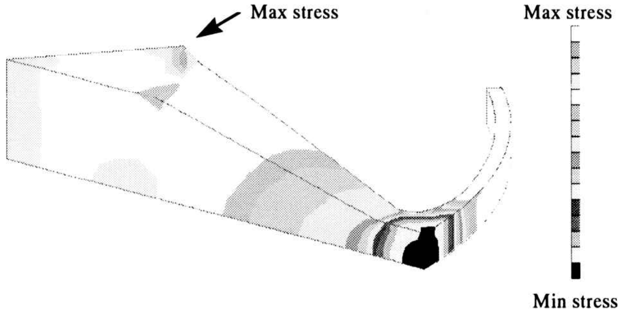

Figure 8. The von-Mises stress distribution in the hub.

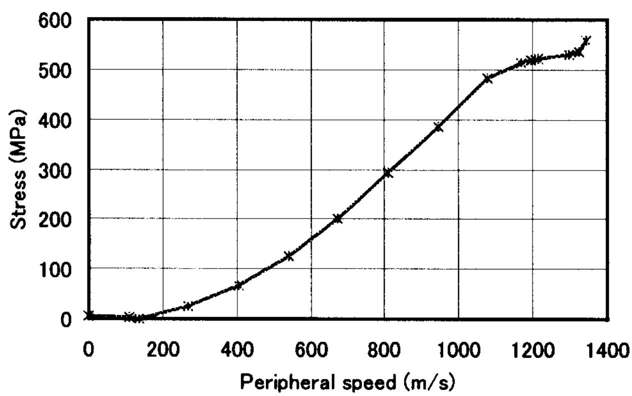

Figure 9. Peripheral speed dependence of the maximum stress in the hub.

is shown in Fig. 9. The stress rose in proportion to peripheral speed. At about peripheral speed of 1100 m/s, plastic deformation of aluminum alloy occurred. Beyond about 1300 m/s, the stress rapidly rose, and the stress almost reached the ultimate limitation at 1350 m/s.

From the design work, it was found that the most critical stress of the rotor was the maximum stress of the aluminum alloy hub.

4. FABRICATION AND SPIN TEST

Composite rings were fabricated by filament winding process using T1000G fiber and epoxy resin. After the winding, the outer diameter of each ring was machined and the multi-ring was assembled by press fitting. After the hub was cooled by liquid nitrogen, the hub was fitted into the rim. The flywheel rotor is shown in Fig. 10.

The test of the flywheel rotor was performed using a spin-tester which drove rotors with an air turbine in a vacuum chamber.

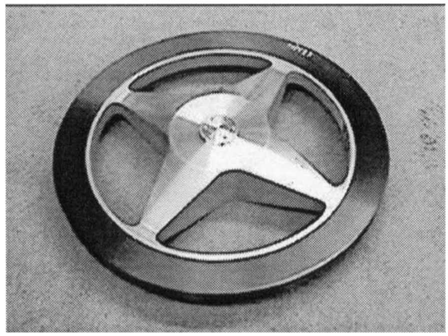

Figure 10. Composite flywheel.

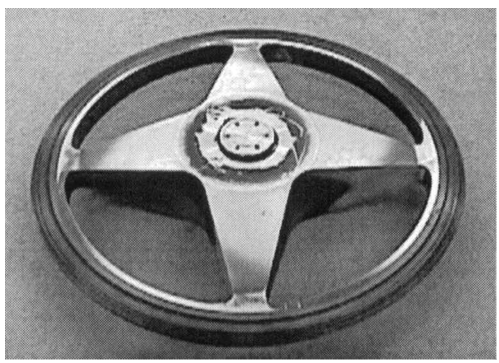

Figure 11. Burst flywheel rotor with machined outer diameter.

4.1. Machined rotor

The flywheel rotor, of which the outer circumference of the rim machined, burst at peripheral speed of only 1220 m/s. The rotor after the spin test is shown in Fig. 11. There was no damage in the hub, and the outer part of the composite rim was broken. The result of the test was unexpected from the design because the composite rim was designed without failure up to peripheral speed of over 1300 m/s. To observe the failure process, another machined rotor was cyclic-tested at 1000 m/s level.

After the first cycle, whose speed was 1080 m/s, the fiber of length 50 mm and width 1.0 mm was peeled at one spot on the surface of the outer circumference of the rim. The windage loss by the rotation made the rotor warm.

The second cycle, whose speed was 1020 m/s, was performed to check the temperature of the rotor during the rotation using a thermo-seal. The temperature of the rotor rose up to 45°C, and other fiber peeling occurred.

At the third cycle, the rotation was stopped at 1000 m/s because of a noise from the spin tester. After the rotation, the outer part of the rim, whose thickness was 2 mm, was peeled (Fig. 12) but other damage could not be found.

From these results, the initial damage of the rotor was the fiber peeling of the outer circumference at low rotating speed of 1000–1100 m/s. It was considered that the

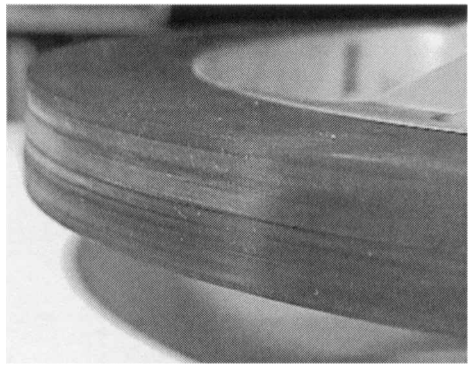

Figure 12. Peeled rim of machined outer diameter.

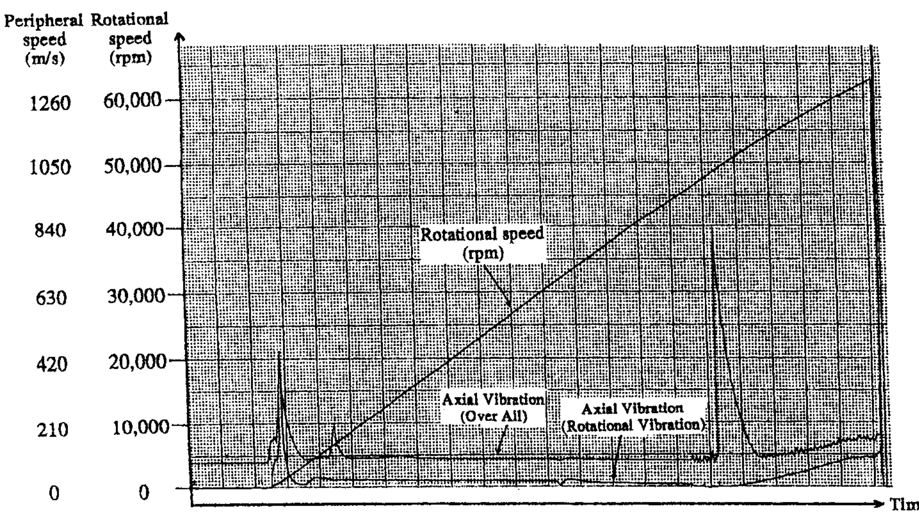

Figure 13. Result of the spin test.

machining process shortened the carbon fibers at the outer circumference of the rim and decreased its strength.

4.2. Re-wound rotor

To prevent initial peeling damage, a new flywheel rotor, whose outer circumference of the rim was re-wound with a few plies after machining, was fabricated and tested. The rotor burst at peripheral speed of 1310 m/s. Figure 13 shows the result of a spin test which was the relation between rotational speed and axial vibration. The axial vibration gradually increased from the peripheral speed of 1050 m/s (rotational speed 5000 rpm) to 1300 m/s (6200 rpm). When the speed was beyond 1300 m/s (6200 rpm), the axial vibration rapidly increased, and the rotor burst at the peripheral speed of 1310 m/s. This phenomenon could be explained using the aluminum alloy hub stress prediction as shown in Fig. 9. The flywheel rotor might stably rotate until about 1100 m/s. Beyond this speed, axial vibration rose because plastic deformation of the aluminum alloy caused unbalance of the rotational axis. Beyond about 1300 m/s, the hub burst because plastic deformation increased until the ultimate strength of aluminum alloy. It was considered that the vibration in the spin test indicated good agreement with the stress behavior in the analysis. The fragments of the broken hub were blocks. The fragments of the broken rim were in pieces.

The composite flywheel rotor stored energy of 354 Wh, and the specific energy density of the ring was 195 Wh/kg at maximum peripheral speed of 1310 m/s.

5. CONCLUSION

A flywheel rotor was designed, fabricated and tested. The rim, which was a multi-ring structure, consisted of 4 rings made of high strength fiber (T1000G). The configuration of the hub made of aluminum alloy (7075) was like a steering wheel with 4 spokes. The cross-sectional area of these spokes was changed to withstand a centrifugal force.

The rotor, whose outer circumference of the rim was machined, burst at 1220 m/s. The rotor, whose outer circumference was re-wound, burst at a peripheral speed of 1310 m/s. The rotor stored energy of 354 Wh, and the specific energy density of the ring was 195 Wh/kg at 1310 m/s. The vibration in the spin test indicated good agreement with the stress in the analysis.

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