Design and Fabrication of Hybrid Composite Flywheel Rotor
Jung D. Kwon, Seong J. Kim, Sana U. Nasir, Sung K. Ha

Abstract—An advanced composite flywheel rotor consisting of intra and inter hybrid rims was designed to optimally increase the energy capacity, and was manufactured using filament winding with in-situ curing. The flywheel has recently attracted considerable attention from many investigators since it possesses great potential in many energy storage applications, including electric utilities, hybrid or electric automobiles, and space vehicles. In this investigation, a comprehensive study was conducted with the intent to implement composites in high performance flywheel applications. The inner two intra-hybrid rims (rims 1 and 2) were manufactured as a whole part through continuous filament winding under in-situ curing conditions, and so were the outer two rims (rims 3 and 4). The outer surface of rim 2 and the inner surface of rim 3 were CNC-tapered for press-fitting. Machined rims were finally press-fitted using a hydraulic press with a maximum compressive force of approximately 1000 ton.

Keywords—composite flywheel rotor, intra hybrid, inter hybrid, multi-rim, interference, in-situ cure, press-fit

I. INTRODUCTION

An advanced composite flywheel has recently been developed for various energy storage applications including electric utilities, frequency regulations, hybrid or electric vehicles and spacecraft [1-5]. The composite flywheel rotor has characteristics of distinctively high energy density, long life and lightweight. Recent efforts in development of the flywheel have been devoted to material hybridized and press-fitted multi-rim rotor to further increase the performance and insuring the safety of the flywheel [6]. The pre-stresses developed by the interference between multi-rims reduce the net stresses in the rotating rotor, and yield a higher rotating speed and higher energy storage capacity [7-9]. Filament winding with the fiber tension is a typical process of manufacturing the composite rotor, followed by the stages of heat buildup, curing, and cooling. The curing process causes tremendous amount of tensile stresses primarily due to the anisotropic thermal expansion of individual plies, which deteriorate the performance of the rotor since the inertial forces also generate the radial tensile stresses during the rotation [10].

An advanced composite flywheel rotor consisting of intra and inter hybrid rims was designed to optimally increase the energy capacity, and was manufactured using filament winding with in-situ curing. In this investigation, a comprehensive study was conducted with the intent to implement composites in high performance flywheel applications.

II. DESIGN OF THE ADVANCED FLYWHEEL ROTOR

A. Inter hybrid rotor and Intra hybrid rotor

The performance of a flywheel rotor made of composite material is always deteriorated by tensile stress in the radial direction, which is generated by both the curing process and the centrifugal force during rotation. The press-fit of multiple inter-hybrid rims ("inter-hybrid" means each rim is made of a single composite material, either CFRP or GFRP, but the material might differ from rim to rim) with interferences has been known as an effective way of reducing the radial tensile stress. However, it is relatively expensive and difficult in the viewpoint of manufacturing. On the other hand, a flywheel rotor consisting of a single intra-hybrid rim (a rim that is made of comingled composites with different carbon-glass ratio) is less costly and relatively easy to manufacture, but the radial tensile stress cannot be effectively reduced.

B. Stress analysis of a rotor

A stress analysis to calculate the deformations and the strength ratios of the multi-rim rotor with interferences as shown in Figure 1 can be found in many previous publications [10-12]. The governing equation for a rotor of rotational speed is written as

$$\frac{d\sigma_r}{dr} + \frac{\sigma_r - \sigma_0}{r} + \rho r \omega^2 = 0 \quad (1)$$

Where \(\sigma_r\) and \(\sigma_0\) are radial and circumferential stress, respectively, \(\rho\) denotes a density, and \(\omega\) is the rotational angular velocity. Assuming the plane stress state, the stress-strain relationship can be written as

$$\begin{bmatrix} \sigma_r \\ \sigma_0 \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{bmatrix} \varepsilon_r - \alpha_0 \Delta T \\ \varepsilon_0 - \alpha_r \Delta T \end{bmatrix} \quad (2)$$

Where \(\varepsilon\) and \(Q\) are the strain and the stiffness matrix in cylindrical coordinates. In the axisymmetric case, the strains are defined by the radial direction displacement \(u_r\):

$$\varepsilon = \begin{bmatrix} \varepsilon_r \\ \varepsilon_\theta \end{bmatrix} = \begin{bmatrix} u_r/r \\ \partial u_r/\partial r \end{bmatrix} \quad (3)$$

In case of Intra hybrid rotor, between rims, the following compatibility conditions should be met:

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\[ \sigma_{i}^{(j+1)} = \sigma_{i}^{(j)} \quad u_{i}^{(j+1)} = u_{i}^{(j)} \quad (j=1, 2, 3, \ldots, N-1) \]

In case of Inter hybrid rotor, Between rims, the following compatibility conditions should be met:

\[ \sigma_{i}^{(j+1)} = \sigma_{i}^{(j)} \quad u_{i}^{(j+1)} = u_{i}^{(j)} \quad (j=1, 2, 3, \ldots, N-1) \]

Three strength ratios are considered: \( R_{p} = \sigma_{i}^{(j)} \) (the radial stress)/\( Y \), \( R_{p} = \sigma_{i}^{(j)} \) (the circumferential stress)/\( X \)

\[ R_{p} = \begin{cases} \frac{\sigma_{i}}{X_{i}} & \text{for } \sigma_{i} > 0 \\ \frac{\sigma_{i}}{X_{i}'} & \text{for } \sigma_{i} < 0 \end{cases} \]

D. Design of hybrid rotor

The design of the Advanced Hybrid Rotor was optimized with respect to internal stress distribution and manufacturing cost. The predetermined specifications of the rotor are listed as following: usable energy 35kWh, maximum rotating speed 15,000 rpm, inner diameter 539.5mm, length 1340mm, maximum hoop-directional strain of the inner surface during rotation 0.8%. Three different designs satisfying those given conditions and possessing the same value of \( \frac{I_{p}}{I_{t}} \) (the ratio between polar moment of inertia \( I_{p} \) and transverse moment of inertia \( I_{t} \)), mass, and specific energy density (SED), were compared. Those designs were the inter-hybrid rotor which consists of 4 separately wound rims, the intra-hybrid rotor which consists of 4 rims wound at the same time, and the Advanced Hybrid Rotor. To avoid excessive radial compressive stress applied to the inner intra-hybrid rim during the press-fitting of the Advanced Hybrid Rotor, the interference between two rims was calculated such that the radial compressive stress was limited to below 6 MPa. Comparing the radial stress within each rotor during rotation, it was discovered that the following inequality held: Inter < Advanced < Intra, while in terms of manufacturing cost, the reverse order held: Inter > Advanced > Intra. Fig. 4 shows the radial and hoop strength ratio along the radial direction of the rotor corresponding to 0 rpm and 15,000 rpm. It can be seen from Fig. 4(a) that for the inter-hybrid design, the hoop strength ratio is lower than the radial one in most region along the radial direction when the rotor is at rest; when the rotor is rotating at the maximum speed, the hoop strength ratio is always higher than the radial one, and the maximum value of the hoop strength ratio is always below 0.4, which means the safety.
factor is more than 2. For the intra-hybrid design, as shown in Fig. 4(b), the situation is much worse than the previous one: the maximum radial strength ratio approaches 0.8 when the rotor is rotating at full-speed. For the Advanced Hybrid Rotor, both the radial and hoop strength ratios are below 0.4 in most of zone along radial direction, and thus the balance between performance and cost was achieved with this design.

In this study, the design of a 35 kWh press-fitted flywheel rotor consisting of four intra-hybrid rims and working at 15,000 rpm was optimized to minimize the maximum radial tensile stress as well as to reduce the cost and simplify the manufacturing process. Design variables include thickness of each rim, carbon-glass volume fraction ratio in each rim, and interference between two adjacent rims. Three situations were considered in the optimization process: cured rims with residual stresses prior to press-fitting; a stationary rotor after press-fitting, and a rotor at the maximum rotating speed. The rule of mixture was used to calculate effective properties of the hybrid materials. The optimized rotor has a mass of 1005 kg, an inner diameter of 539.5 mm, and a height of 1340 mm. Starting from the innermost rim to the outermost one, the thickness of each rim is 36.8, 55.0, 52.0, and 40.0 mm, respectively; the interference between the second and the third rim is 0.2 mm. The estimated maximum tensile and compressive stresses in both radial and circumferential directions under the aforementioned three situations are always below material strengths.

III. FABRICATION OF THE ADVANCED FLYWHEEL ROTOR

The inner two intra-hybrid rims (rims 1 and 2) were manufactured as a whole part through continuous filament winding under in-situ curing conditions, and so were the outer two rims (rims 3 and 4). The outer surface of rim 2 and the inner surface of rim 3 were CNC-tapered for press-fitting. [Fig. 5]
Machined rims were finally press-fitted using a hydraulic press with a maximum compressive force of approximately 1000 ton. [Fig. 6]

These pictures show how to check the rotor after curing and pressing. Penetrant testing is therefore best adapted to inspection of all types of surface cracks, porosity, laminations, and lack of bond at exposed edges of joined materials, and of leaks in tubing, tanks, welds and the like.

First a liquid penetrant is applied to the surface of a part. It is permitted to remain on the surface for a period of time, during which it penetrates into any defects open at the surface. After the penetrating period, the excess penetrant that remains on the surface is removed. Then an absorbent, light colored, powdered material called a developer is applied to the surface. This developer acts as a blotter and draws out a portion of the penetrant which has previously seeped into the surface openings. As the penetrant is drawn out, into diffuse into the coating of the developer, forming indications that are much wider than the surface openings with which they are associated. An inspector then views the part and looks for these colored indications against the background of the developing powder. [Fig. 7]
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REFERENCES


| TABLE I | OPTIMAL RESULT OF 4RIM HYBRID ROTORS |
|-------------------|-------------------|-------------------|-------------------|-------------------|
| Specification | Inter hybrid | Intra hybrid | Advanced hybrid | Unit |
| Usable Energy | 35 | kWh |
| Rotational speed | 15,000 | rpm |
| Inner Diameter | 539.5 | mm |
| height | 1340 | mm |
| Ir/(Ip/It) | 0.62 | - |
| Mass | 1005 | kg |
| Inner strain | 0.8 | % |
| Max Strength ratio | 0.17 | 0.75 | 0.35 | - |
| Manufacturing cost | 44,000 | 25,000 | 31,000 | $ |