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Design and Fabrication of Hybrid Composite Flywheel Rotor

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***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, inter hybrid, intra 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.

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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

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

Where σ_r and σ_θ are radial and circumferential stress, respectively, ρ denotes a density, and ω is the rotational angular velocity. Assuming the plane stress state, the stress-strain relationship can be written as

$$\begin{pmatrix} \sigma_\theta \\ \sigma_r \end{pmatrix} = \begin{bmatrix} Q_{11} & Q_{12} \\ Q_{21} & Q_{22} \end{bmatrix} \begin{pmatrix} \varepsilon_\theta - \alpha_\theta \Delta T \\ \varepsilon_r - \alpha_r \Delta T \end{pmatrix} \qquad (2)$$

Where ε 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 :

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_\theta \\ \varepsilon_r \end{pmatrix} = \begin{pmatrix} u_r / r \\ \partial u_r / \partial r \end{pmatrix} \qquad (3)$$

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

$$\begin{aligned} \sigma_{r_i}^{(j+1)} &= \sigma_{r_o}^{(j)} \\ u_{r_i}^{(j+1)} &= u_{r_o}^{(j)} \end{aligned} \quad (j=1, 2, 3,\ldots, N\text{-}1) \qquad (4)$$

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

$$\begin{aligned} \sigma_{r_i}^{(j+1)} &= \sigma_{r_o}^{(j)} \\ u_{r_o}^{(j)} - u_{r_i}^{(j+1)} &= \delta^{(j)} \end{aligned} \quad (j=1, 2, 3,\ldots, N\text{-}1) \qquad (5)$$

Three strength ratios are considered: R_r= σ_r(the radial stress)/Y, R_θ= σ_θ(the circumferential stress)/X

$$R_k = \begin{cases} \dfrac{\sigma_k}{X_k} & for \;\; \sigma_k \geq 0 \\ \dfrac{\sigma_k}{X_k'} & for \;\; \sigma_k < 0 \end{cases} \qquad (6)$$

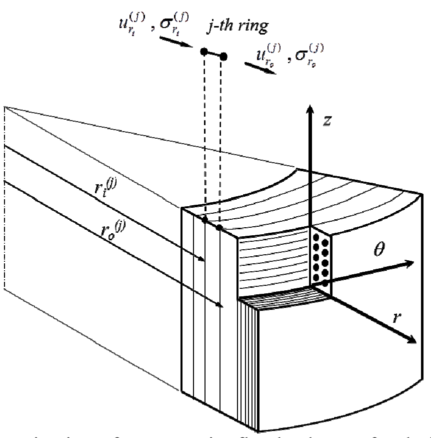

Fig. 1 Discretization of a composite flywheel rotor for derivation of the stiffness matrix of the j-th ring (j=1, 2, 3, …, N). The cylindrical coordinate (q, z, r) systems, and the radial displacement and stress components of the j-th ring are defined.

C. Advanced hybrid rotor

In order to reduce the stress along radial direction induced by the centrifugal effect during high-speed rotation, the inter-hybrid rotor is the best option because the interferences between adjacent rims can effectively decrease the radial stress. However, fabricating all the rims separately is costly and time-consuming. In this study, a new method was devised by winding every two rims together to form an intra-hybrid rim, which means the original 4-rim rotor now consists of two intra-hybrid rims, and the interference was given between two intra-hybrid rims. Although the reduction of radial stress in the rotor comprising 2 intra-hybrid rims is not as much as that in the rotor comprising 4 inter-hybrid rims, the manufacturing process was simplified considerably. Since the rotor incorporated both intra- and inter-hybridization technology, we named it Advanced Hybrid Rotor. To evaluate the stresses within such an Advanced Hybrid Rotor, three sources of stresses were considered. Fig. 2 is the schematic representation of those sources, which are the thermal residual stresses developed in each intra-hybrid rim after curing process, the stresses developed after press-fitting of two intra-hybrid rims due to the existence of interference, and the stresses generated by the centrifugal effect in high-speed rotation. The superposition of stresses from the aforementioned three sources is the stress state of the Advanced Hybrid Rotor.

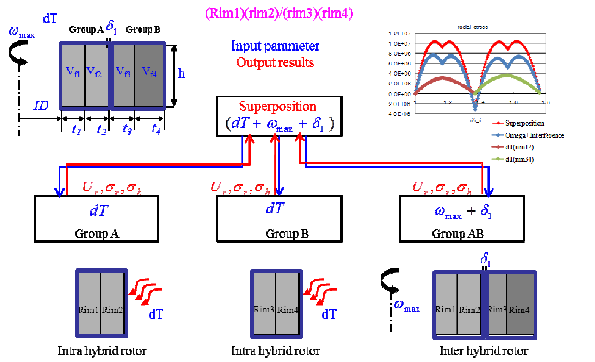

Fig. 2 Superposition of stress of multi rim rotor

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 Ip/It (the ratio between polar moment of inertia Ip and transverse moment of inertia It), 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.

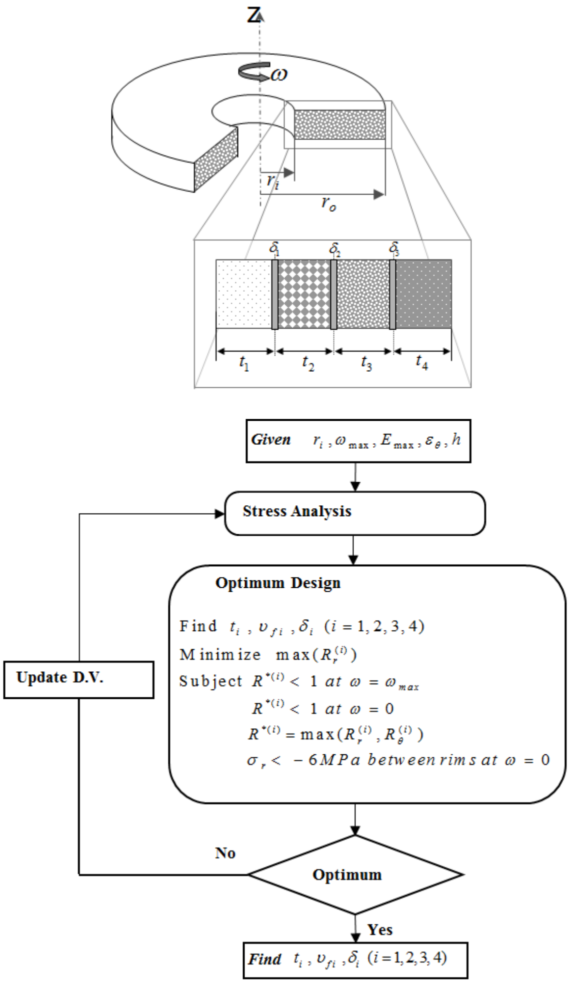

Fig. 3 Optimization of multi-rim hybrid rotor

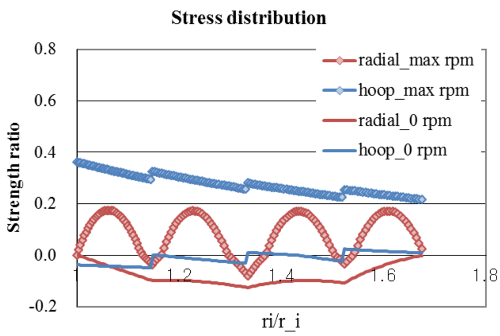

Fig. 4 (a) Stress distribution of Inter hybrid rotor

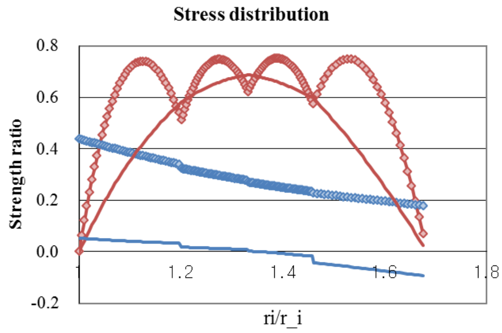

Fig. 4 (b) Stress distribution of Intra hybrid rotor

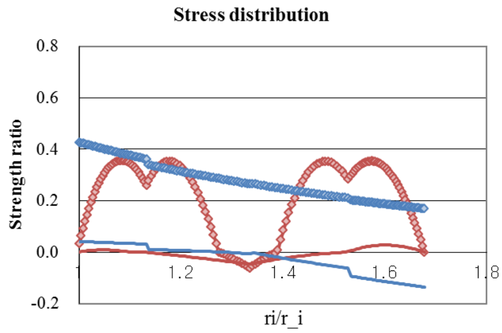

Fig. 4 (c) Stress distribution of Advanced hybrid rotor

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 carbon-glass volume fraction ratio is 11, 30, 79, and 100%, 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]

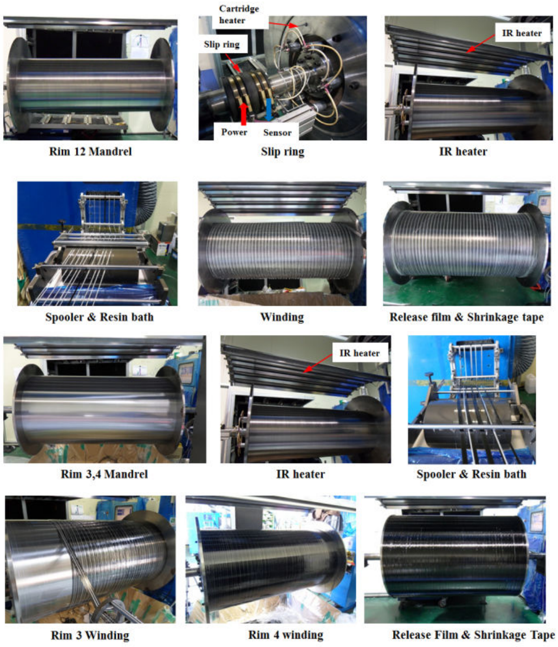

Fig. 5 Each rim manufacture using filament winding

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]

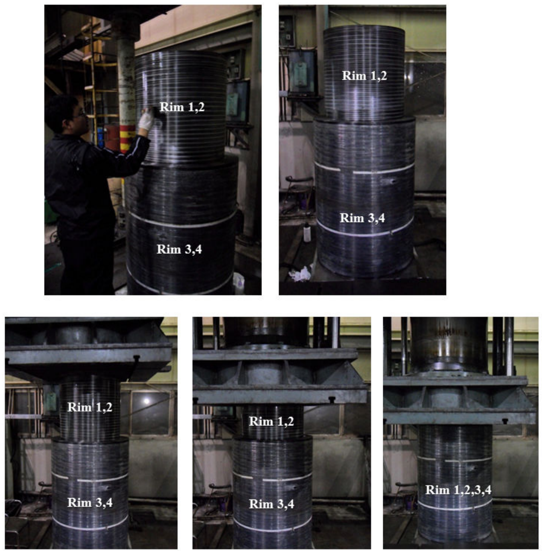

Fig. 6 Each rim assembly using Press-fit

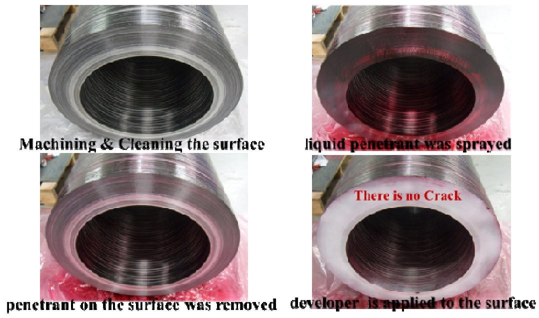

Fig. 7 Well cured and press-fitted

IV. Conclusion

In this paper, the advanced rotor which is constituted with the inter hybrid rotor and intra hybris rotor is suggested. The optimization of the inter hybrid rotor , intra hybrid rotor, and advanced hybrid rotor was performed respectively in order to compare both the performance and the fabrication cost of the rotor.

By using insitu-cure the rim 1,2 and rim 3,4 were wound. The outer surface of rim 1,2 and the inner surface of rin 3,4 were tapered and then pressed together to fabricate the advanced hybrid rotor.

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	$

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