REAL-TIME LIFE PREDICTION OF A HIGH PERFORMANCE COMPOSITE FLYWHEEL ROTOR USING A TELEMETRY SYSTEM

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ABSTRACT

This paper discusses a method for real-time life prediction of composite flywheel rotor considering material degradation. Viscoelastic material properties of Glass/Ep, Graphite/Ep and Hybrid/Ep (i.e. Glass+Graphite/Ep) were first calculated using data obtained from Dynamic Mechanical Analysis test (DMA). Based on the micromechanics of failure (MMF), real-time life prediction for a high performance 10kWh six-rim composite flywheel rotor with 50-years initial life was developed, and a real-time residual life prediction method using health monitoring system was suggested.

Keywords: Composite flywheel rotor, life prediction, fatigue load, health monitoring, telemetry system, Fiber Bragg Grating sensor

1. INTRODUCTION

Various types of flywheel energy storage systems (i.e. alternative energy) have been investigated and developed by many researchers [1]. The flywheel rotor stores energy at high rotating speed. This characteristic of high operating speed requires the safety of the flywheel rotor to be taken into account. Safety issues regarding a flywheel rotor with reference to the design margin and health monitoring are described in [2-4]. From safety point of view, the strength and initial life should be considered while designing the flywheel rotor. Moreover, due to its high-speed rotation, the damage and residual life of the flywheel rotor should also be monitored in real-time.

A composite flywheel rotor is subjected to a long-term fatigue loading due to the centrifugal forces during the charging and discharging processes. In this operation, circumferential stresses carried by fibers are more dominant than radial stresses undertaken by the matrix. However, radial stresses resulting from high rotating speed, which are affected by viscoelastic property of the composite material, are more critical than circumferential stresses. To overcome this problem, the radial stresses which are closely related to viscoelastic property of the matrix material should be determined at the stage of preliminary design.

The residual strength of a rotor is characterized by its stiffness reduction. A degradation effect of composite material occurs due to the aging of the matrix material. Recently, Jianmin Chen et al. studied time dependent material properties of the composite flywheel rotor [5]. Jerome Tzeng et al. calculated stress and displacement distributions of the composite flywheel rotor using material characterization and test matrices [6]. Ha et al. monitored local strains at multiple points on the surface of a 0.5kWh flywheel rotor at 30,000 rpm using strain gauges and wireless telemetry system [7]. However, life prediction of flywheel rotor using viscoelastic property of composite material and prediction of residual life using real-time monitoring system have never been discussed in previous works.

In this study, a 10kWh composite flywheel rotor with an estimated initial life of 50-years was designed considering the viscoelastic properties of the matrix material, and a real-time residual life prediction method was proposed. From DMA test, time-dependent material properties of Glass/Ep, Graphite/Ep and Hybrid/Ep (i.e. Glass+Graphite/Ep) were calculated, and damage fraction of the composite flywheel rotor considering the distribution of stress relaxation was shown. Finally a real-time residual life prediction method using strain signal from the telemetry system and fiber optic sensors was also suggested.

2. STRESS ANALYSIS OF THE FLYWHEEL ROTOR

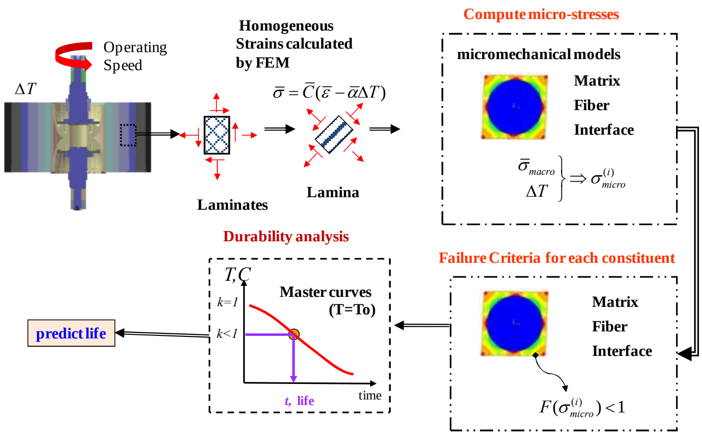


Figure 1. Procedure of the life-prediction of composite flywheel rotor.

A composite flywheel rotor is subject to a long-term fatigue load due to centrifugal forces in charging and discharging. The residual strength of a rotor is characterized by stiffness reduction, which is monitored using strain gages with a telemetry system.

The micromechanics of failure (MMF) and constituent master curves are used to predict initial strength and initial designed life of the rotor. Figure 1 shows life prediction procedure for a flywheel rotor of composite materials. Micro stress distributions in the fiber and matrix of composite flywheel rotor are calculated using stress amplification factors which correlate the macro and micro stresses.

Time to failure $t_f^{\ i}$ indicates the total working time until the damage occurs on the composite rims while stresses repeatedly act. Damage fraction, the summation of all damage indices in i-th time step, is defined in Equation (1)[8-9].

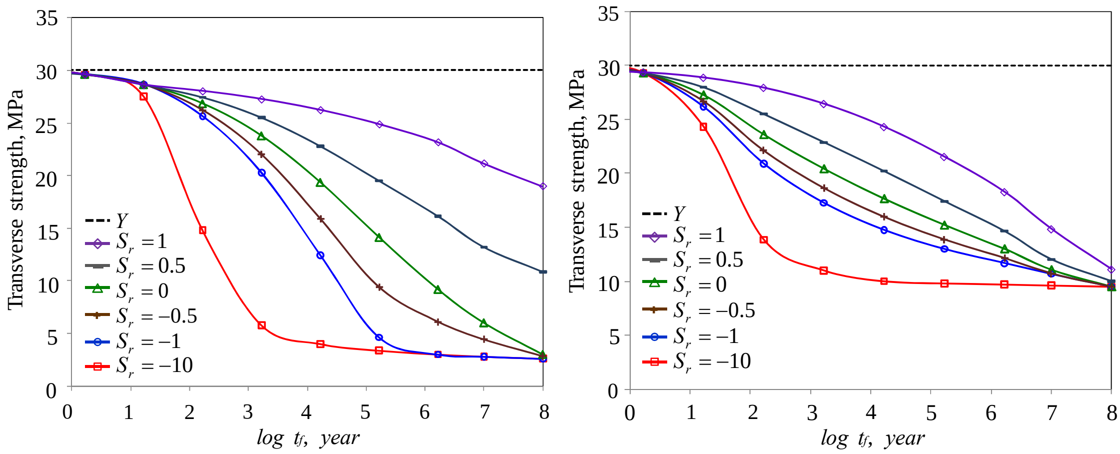
$$D(t_i) = D(t_{i-1}) + \frac{\Delta t_i}{t_f^{\ i}} \tag{1}$$

where $D(t_i)$ and $D(t_{i-1})$ are damage fractions at the i-th and (i-1)-th step, respectively.

The useful life of a flywheel rotor lasts until the damage fraction of total time steps $D(t_i)$ reaches 1 from the beginning of its operation.

3. NUMERIAL RESULTS

A six-rim composite flywheel rotor with the capacity of 10kWh, the lifespan of 50 years, and an operating speed of 24,300 rpm, was designed. The rotor comprises two Glass/Ep rims, one Hybrid/Ep (Glass[50]:Graphite[50]) rim, one Hybrid/Ep (Glass[30]:Graphite[70]) rim, and two Graphite/Ep. Rims



(a) Glass/Ep (b) Graphite/Ep

Figure 2. Fatigue master curves with respect to stress ratio for a cycle of 2 times a day.

To predict the initial life of the composite flywheel rotor considering the radial stress, the fatigue mater curves of Glass/Ep, Graphite/Ep and Hybrid/Ep were predicted. Figure 2 shows fatigue master curves of Glass/Ep and Graphite/Ep with respect to stress ratio. In the case of Hybrid/Ep, the transverse strengths of Glass/Ep & Graphite/Ep are compared and the lowest one was selected.

Damage fraction of the six-rim flywheel rotor was calculated using the distributed radial stress relaxation, ATM and micromechanical calculation. As shown in figure 3, damage fraction of 3rd rim which is made of Hybrid/Ep(Glass[50]:Graphite[50]) reaches 1 after 50 years. Accordingly, the life span of six-rim composite flywheel rotor was taken as 50 years and 3rd rim could be first damaged.

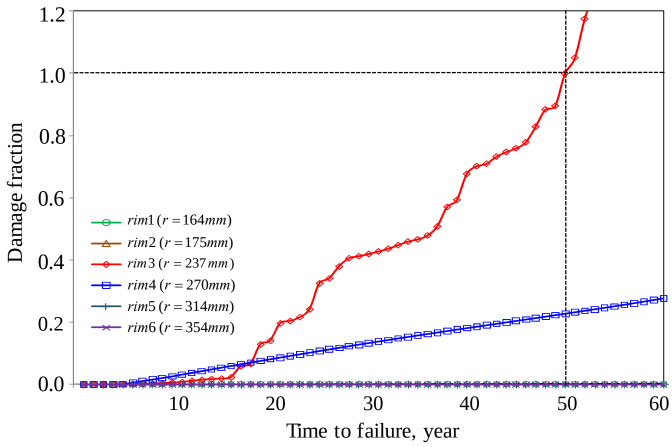


Figure 3. Damage fraction of composite flywheel rotor using viscoelastic material.

The calculated dimensions and specifications of the six-rim flywheel rotor are listed in Table 1. The values of inner radius, outer radius, length, and maximum rotational speed are given as 138 mm, 366 mm, 320 mm, and 24,300 rpm, respectively. Based on these results, the 10kWh composite rotor which has 50-years life was manufactured.

Table 1. Specifications of 6-rim composite rotor

Specifications	Symbol	Value	Unit
Usable Energy	E_{usable}	10	kWh
Maximum rotation speed	ω_{max}	24,300	r.p.m
Burst speed	ω_{burst}	32,000	r.p.m
Inner radius	r_i	138	mm
Outer radius	r_o	366	mm
Rotor height	h	320	mm
Mass	M	197	kg
SED_Burst	SED_{burst}	66	Wh/kg

4. REAL-TIME PREDICTION

To measure the mechanical strain on the surface of the rotor, we are now proposing 2 kinds of monitoring methods. The 1st method is utilizing strain gauge and wireless telemetry system. This method was already applied in previous research [7] and mechanical strain data from rotor were successfully measured up to 30,000rpm using an in-house developed telemetry system. The 2nd method is utilizing optical fiber Bragg grating (FBG) sensor and rotary optical coupler [1]. Application of the monitoring method using FBG sensor and rotary optical coupler is currently under development.

5. CONCLUSIONS

In this study, a 10kWh six-rim composite flywheel rotor which has 50-years initial life was designed considering the viscoelastic properties of the composite material, and a real-time residual life prediction method by measuring strain using monitoring system (i.e. wireless telemetry, rotary optical coupler) was suggested.

A method for prediction of residual life of the designed rotor during operation was suggested. Measured strain from the monitoring system was utilized for back-calculation of the storage modulus curve of pure epoxy. From the strain measured time, residual life can be updated by adopting same procedure.

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