Development of High-Performance CFRP Flywheel*

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Abstract

This paper reports state of progress for development of high-performance CFRP flywheel. For the development, high specific energy density and durability are required. A new fabricating method suggested in our previous work (Mechanics of Time-Dependent Materials 2012) is employed for the CFRP flywheel. According to the method the fabricated flywheel does not have radial stress and the ultimate failure is dominated by hoop stress. A spin test is conducted for the fabricated CFRP flywheel. Strain gauge and digital image correlation methods are employed for the rotational strain measurement. The both methods verify very little rotational radial strain, which means the radial stress is also little. As a first step of the development of high-performance CFRP flywheel, the feasibility of no-radial stress flywheel fabrication is indicated by this study.

Key words: CFRP, Flywheel, Spin Test, Digital Image Correlation

1. Introduction

For the past four decades, there have been a lot of programs developing light-weight flywheel⁽¹⁾⁻⁽⁵⁾. The flywheel battery has been focused on because of the ability that can output high energy in a moment which is different from chemical battery. The mechanical battery using flywheel is superior in terms of safety, protection of environment, good repeatability etc. to a lithium ion battery, which shows good performance among the chemical batteries. NASA intended to have flywheel battery in International Space Station^{(2),(3)}. On the other hand, energy density per unit weight is prior to the lithium ion battery and long-term durability is still under discussion. High-performance carbon fiber reinforced plastic (CFRP) can be potential candidate for the material of light, durable and high-energy density flywheel.

In recent years, high-performance energy-storage system is desired to develop for the background of a global energy problem^{(4),(5)}. This is intended for reuse of energy and buffering irregularly available energy such as natural energy. Nowadays, as represented by hybrid vehicle, the energy-recycle technology has been familiar. For the hybrid vehicle, the lithium ion battery is usually used and that involves a lot of issues regarding poisonous, price, repeatability etc. When a vehicle slows down, the kinetic energy is once converted into chemical energy, and then converted into mechanical energy again when reusing the energy. This is a general mechanism of hybrid engine system using lithium ion battery.

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However, another hybrid system using mechanical battery, if it would be developed, can keep and reuse the energy in mechanical energy states; the energy is kept at the state of mechanical one thoroughly. Of course, the loss of energy when converting is less in latter hybrid system than that of former. On this sense, the development of high-performance flywheel battery will contribute to the energy saving.

The main reason that mechanical battery system is not frequently used so far is the scarcity of energy density it can store. Filament wound CFRP is superior in specific strength and stiffness in the fiber direction so that it endures large hoop stress. However, simultaneously-occurring relatively small radial stress is crucial and it leads to splitting failure (radial-directional failure) for the material. In terms of durability, this can be critical issue also. Several articles suggested press-fitted multi-ring method for eliminating the radial failure^{(4),(5)} but the method cannot eradicate the issue. The compressive stress generated at fabrication also relaxes with time and would not work in future. Even during it works, the compressive stress enhance the rotating hoop stress of outer ring so that the outer ring apparent strength reduces due to the added stress. Overcoming this kind of unexpected failures and increasing the rotational speed and durability directly promotes the development of high-performance CFRP flywheel.

In this paper, a method to design a CFRP flywheel having good durability⁽⁶⁾ is reviewed at first and spin-test results of the flywheel fabricated based on the method is presented. For a first attempt, we tested the flywheel at 18,000 rpm in which the tip speed is over ground-level sound speed. The tip speed is much less than the world-recorded fastest speed, which is more than 1000 m/s. The target of this study is obtaining the experimental evidence of tailored CFRP flywheel performance, assessing whether the flywheel is expected to fail in radial direction or not. For the measurement of strain during the spin test, strain gauge measurement and digital image correlation (DIC) method are employed. For very high-speed rotation, there is a possibility that the strain cannot be measured by strain gauge because of some damage of strain gauge induced by a large centrifugal body force. Also a number of measurement points are limited for strain gauge measurement. Since DIC does not have such problems, it might be effective but DIC for high-speed rotational object has never been tried for the meantime. Note that, for the CFRP deformation measurement during high-speed impact, DIC technique has been already employed⁽⁷⁾. This study compares the measurement results obtained by the two strain measurement ways with analytical results.

2. Design for High-performance CFRP Flywheel

2.1 Time-dependent Radial Failure (Splitting Failure)

First of all, we introduce here a mechanism of time-dependent radial failure of conventional filament wound composite flywheel rotor. The radial directional failure of filament wound CFRP flywheel is typically equivalent to a transverse failure of unidirectional CFRP coupon specimen. On this assumption, the durability of flywheel in case of radial failure can be predicted. Figure 1 shows radial stress distribution when some rotation is applied. As shown in this figure, one-by-one fiber is modeled and viscoelastic analysis is performed. The fiber radius is 50 μm which is 10 times of real dimensions. But we verified that modeled fiber diameter is fine enough. In other words, if we model more precise fiber dimension, the same numerical results are obtained. For saving computational cost, we used this fiber dimension for modeling⁽⁶⁾. The constant rotational speed is applied. The fiber is assumed to be elastic body and viscoelastic property is assigned to the matrix part as in our previous study⁽⁸⁾. For the result, macro (specimen) radial stress decreases with time due to the viscoelastic behavior but micro stress governing the ultimate failure increases with time. Similar macro- and micro-stress changes with time in transverse failure of unidirectional composite are conventionally presented⁽⁸⁾. Even small macro stress causes

time-dependent increasing of micro stress and leads to ultimate failure at last. It is to say the durability regarding radial failure is much poorer than that in case when a creep stress is applied to a neat resin specimen, which is not so durable. Even though the composite flywheel once endures at some high-speed rotation, the durability is uncertain. After all, the rotational radial stress is desired to diminish.

Fig. 1 Radial stress distribution focusing on intermediate part of inner/outer edge in rotating conventional filament wound CFRP flywheel

2.2 Time-dependent Hoop Failure

The time dependent hoop directional failure of filament wound CFRP flywheel is here considered. This failure is almost equivalent to fiber directional failure in unidirectional CFRP coupon specimen. For estimation of strength of unidirectional CFRP, Simultaneous Fiber Failure (SFF) model is employed⁽⁹⁾. The SFF is semi-empirical model and can estimate reasonably various composite strengths. Also for the time-dependent strength, it has been presented that SFF can follow the strength as function of time⁽¹⁰⁾. The relationship between composite strength and time is shown in Fig. 2 in case of various assumed interface strengths. It is worthy to mention here that the initial composite strengths are different when interface strength is varied, and that the time-dependent degradation is varies with interfacial strength. If the interface strength is relatively weak, the composite strength once keeps an initial strength after that the strength starts decreasing with time. Otherwise, the composite strength starts decreasing with time at initial.

Fig. 2 SFF model deriving composite strengths with time, assuming time-independent fiber property and time-dependent matrix strength degradation, and various interface strength (IFS)

2.3 Comparison of radial and hoop failures

Here we compare radial and hoop failures which are assumed to be independent respectively. Figure 3 shows assumed matrix strength which is used for calculation of Fig. 2. In Fig. 3, transverse strength with time, considering above-mentioned micro stress increase with time⁽⁶⁾, is also depicted for which the same matrix strength vs. time is assumed. The transverse strength almost represents radial failure strength with an assumption of matrix failure dominant mode⁽⁸⁾. We hence recognize here the composite strength in Fig. 3 is time-dependent strength in radial failure and Fig. 2 is that in hoop failure of composite flywheel, respectively. Please note that we assume identical relationship between matrix strength and time for both directional failures. It is clear that the radial strength degrades with time more rapidly than hoop strength does. Especially, when we chose relatively weak interface strength (IFS = 10MPa), the hoop strength is kept up to 10⁹ hours, but the radial strength becomes very low at the time. We should design a flywheel as hoop failure is dominant.

Fig. 3 Assumed matrix strength with time and transverse composite strength with time

2.4 Design Concept

Based on above investigation, a fabrication of flywheel which fails in hoop direction not radial direction is necessary. In other words, it is better that radial rotational stress does not occur. We design the CFRP flywheel as follows. We assume that the flywheel consists of many of thin rings. For each ring, there is a relationship between radial directional displacement u , material density ρ , hoop directional modulus E_θ , rotational speed ω and ring radius r ,

$$u \propto (\rho / E_\theta) \omega^2 r^3 \quad (1)$$

When the displacement of each ring is the same, the rings do not interfere each other mechanically. That can be identified as there is no radial stress. That means this flywheel has no radial rotational stress. Actually, since there is an effect regarding Poisson's contraction, the thickness of each ring shrinks. When we assume the Poisson's ratio of the materials is 0.3, following equation satisfies that there is no radial rotational stress⁽⁶⁾.

$$E_\theta / \rho \propto r^{3.3} \quad (2)$$

In order to satisfy the above equation, low modulus material is adopted inner parts and high modulus material is done outer parts of the flywheel. In other words, increase of fiber modulus from inner edge toward outer edge can makes the radial stress zero. From inside to outside, the modulus should be in proportion to radius to the power of 3.3. It is verified that hoop directional rotational stress almost remains unchanged nevertheless the radial stress vanishes by this method⁽⁶⁾. This method has the merit without any significant demerits. Consequently, our previous work⁽⁶⁾ suggests that the rotational radial stress is diminished by above tailored-design and relatively weak interface is applied to make the durability better in order to fabricate high-performance CFRP flywheel.

3. Spin test

3.1 Specimen

A CFRP flywheel is fabricated based on the design concept mentioned above. The dimensions of our flywheel are shown in Fig. 4. Inner radius is 150mm, outer radius is 200mm, and height is 10mm. Due to cost constraint, the prepreg laminate fabrication is chosen not filament winding method. Fiber volume fraction is 52%. Used prepregs, their properties, and their applied locations are shown in Table 1. 450 numbers of plies are laminated and the thickness is 50mm. Each prepreg thickness is determined based on the above mentioned tailor-design so that rotational radial stress is expected to be very low. The cure condition is 2 hours at 120°C. At first the specimen height is 60mm and then it is sliced into 10 mm height after curing. Fig. 5 plots radial and hoop stress distributions at 18,000 rpm rotating state calculated by finite element method (FEM). The thermal residual stress is small enough so that this study ignores the effect of thermal residual stress. For the calculated results, it is verified that the radial stress is very low and almost only hoop stress exists. Note that we do not control the interface strength of the prepregs. As mentioned in previous section, the two implementations are required for the high-performance CFRP flywheel fabrication. One is material modulus control and another is interface strength control. For the purpose of this study, as a first step, we evaluate that the present flywheel does not have rotational radial stress. The present study does not examine the failure rotational speed. This is a subsequent study which will be done in near future.

Table 1 Materials and their properties of CFRP flywheel

Materials	Hoop modulus GPa	Density g/cm ³	Inner radius mm	Thickness mm
T300	120	1.76	150	7.5
T800	153	1.73	157.5	10
M35	178	1.75	167.5	7
M40	196	1.75	174.5	5.4
M40 and M60	251	1.84	179.9	9
M60	306	1.93	188.9	4
XN60	306	1.98	192.9	7.1

3.2 Test procedure

The tester is air turbine type and the maximum rotation speed is 100,000rpm. The test was conducted at vacuumed condition. For the strain measurement, the strain gauge method and digital image correlation (DIC) method are attempted. The position of strain gauge is 15,

Fig. 4 Dimensions of fabricated CFRP flywheel

Fig. 5 Numerically-obtained radial and hoop stress distributions in fabricated flywheel

25, 35, 45mm, which are from inside edge of the specimen. We refer them as strain gauge number 1, 2, 3, 4, respectively. Via slip ring, the strain gauge is connected to the bridge. The rotational radial and hoop strains are measured. The rotational speed is added gradually by approximately 10 minutes. In this test, the maximum rotational speed is 18,000rpm, which corresponds to 377m/s of tip speed, greater than ground-level sound speed. Photograph of attached specimen is shown in Fig. 6, indicating that the strain gauges are mounted on the specimen surface. On the surface, white and black painting for DIC is implemented. The photographs of the painted surface are shown in section 4.

3.3 Test Result

Experimentally-obtained relationship between strains and rotational speed is shown in Fig. 7. The four biaxial strain gauges are mounted on the specimen surface and they are named 1 to 4 from inner to outer. Several strains cannot be measured due to probably some damage during high-speed rotation so that the corresponding strain data is removed in Fig. 7. Two flywheels are spin-tested and several strain gauges also dropped out due to some damage in another test. Also in Fig. 7, the numerical results of two locations, which correspond to strain gauge number 1 and 4, are depicted in solid curves. The numbers of legend are strain gauge number, attached alphabet *r* means radial, *h* means hoop.

Fig. 6 Photograph of CFRP flywheel placed on the spin tester

Fig. 7 Relationship between rotational speed and strains obtained from experiments and numerical analysis.
(In legend, number is strain gauge number, *r* and *h* means radial and hoop directions respectively, solid curves are FEM results, and symbols are experimental results)

In order to satisfy rotational radial stress to be zero, the radial strain should be actually small and negative values as shown in analytical results in Fig. 7 because of the effect of Poisson's contraction of composites. Comparing the experimental and analytical results, there are slight gaps between the experiments and analyses. Regarding hoop strain of strain gauge number 4, the gap between experimental and analytical is relatively large. When fabricating this flywheel, the prepregs are wound from inner parts toward outer parts so that laminating defect attributed to wrinkle etc accumulates as laminate becomes thick. If the hoop modulus of a part (ring in shape) is less than that expected, the ring expands more in hoop direction and pushes outer neighboring ring. The outer ring then bears more stresses and expands as well and strain gap is thus aggregated toward outer part. However, analyses

and experiments indicate thoroughly close values. It is confirmed that this flywheel has no or little rotational radial stress, which is important validation for the purpose of this study.

4. Digital image correlation (DIC)

4.1 Basic principle of DIC

Although 5 points of strain could be measured in this study as mentioned before, if the rotational speed increases more, feasibility of strain gauge measurement would be losing. The present study attempts the applicability of Digital image correlation technique. The DIC concept is presented by Yoneyama et al⁽¹¹⁾. In two-dimensional digital image correlation, displacements are directly detected from digital images of the surface of an object (specimen). The plane surface of an object is observed usually by a CCD camera with an imaging lens. The images on the surface of the object, one before and another after deformation, are recorded, digitized and stored in a computer as digital images. These images are compared to detect displacements by searching a matched point from one image to another. Because it is almost impossible to find the matched point using a single pixel, an area with multiple pixel points (such as 20×20 pixels) is used to perform the matching process. This area, usually referred as subset, has a unique light intensity (gray level) distribution inside the subset itself. The light intensity distribution basically remains unchanged during deformation. Figure 8 shows the part of the digital images before and after deformation. The displacement of the subset on the image before deformation is found in the image after deformation by searching the area of same light intensity distribution with the subset. Once the location of this subset in the deformed image is found, the displacement of this subset is determined. Strain distribution is then derived from taking differentiation of the displacement distribution. In order to perform this process, the surface of the object must have a feature that allows matching the subset. If no feature is observed on the surface of the object, an artificial random pattern must be applied. A typical example of the random pattern on the surface of an object produced by spraying paint is shown in Fig. 9, shown in following.

Fig. 8 DIC basic concept for determining displacement

4.2 DIC Results

Photographs taken for DIC are shown in Fig. 9. The alphabets on the specimen surface are intended for identification of position. Figure 9 shows observed images at static and 18,000 rpm rotations for two locations. In the present study, the DIC is conducted for the two locations, which are referred as *9k* and *M* hereafter. The photographs are taken by high-speed video camera. The image acquisition rate is 1/1,000,000 sec. Since the tip speed of this test is 377m/s, during one image acquisition, the specimen moves 0.377mm. As long

as seeing this photograph, the movement during shutter exposure does not remarkably affect on the quality of digital image.

Obtained displacement distribution in x and y directions (in the photograph coordinate) are shown in Fig. 10. For this state, they are depicted in x - y coordinate not in r - θ one. For this result, similar to typical rigid rotation body displacements are obtained. That is just due to the difference in rotational position at the moments the photographs are taken. Implementing differentiation of these displacement distributions and then coordinate is converted from x - y plane into r - θ plane, the r - θ strain distributions are obtained and shown in Fig. 11. As shown in Fig. 11, obtained strain distributions are not clear. That might be influenced by the movement during shutter exposure or white and black patterning on specimen surface might not be appropriate. The rougher pattern might be better. Hence, in the present study, we take average value of strain in whole distributions at first. The average values are listed in Table 2. In Table 2, even rough, strain values obtained from the strain gauges and FEM are also listed.

Fig. 9 Photographs of specimen at 0 (a), (c) and 18000 rpm (b), (d) for two locations ($9k$ and M)

Table 2 Comparison radial and hoop strains obtained from DIC, strain gauges, and FEM

	DIC		Strain gauge	FEM
Location	$9k$	M	-	-
Radial strain $\times 10^{-6}$	160	730	0	-200
Hoop strain $\times 10^{-6}$	1300	1200	1200	1000

The DIC shows relatively close strain values compared with the results obtained from strain gauges and FEM, except for the radial strain of location M . Especially, strain values experimentally-obtained by both DIC and strain gauge are very close. Regarding location $9k$, it can be verified also from DIC that radial strain is much less than hoop strain, which means little radial stress occurs. However, that is a problem that the radial strain of location M deviates apparently compared with other cases. The problem cannot be found from test results of strain gauges but DIC can find because it obtain global strain distribution. In the following section, we describe what is happening at location M .

Fig. 10 Displacement distributions: (a), (b) are location 9k, (c), (d) are location M. (a), (c) are x-direction, (b), (d) are y-direction

Fig. 11 Strain distributions: (a), (b) are location 9k, (c), (d) are location M. (a), (c) are radial strain, (b), (d) are hoop strain

4.3 Discussion and Future Work

We remove the white and black painting at corresponding parts, $9k$ and M , shown in Fig. 12 (a) and (b). From the specimen surface of $9k$, there appears no significant defect as shown in Fig. 12 (a). However, at the location M , it is found two defects as shown in (b) with inside circles. They seem to be fiber waviness; the carbon fibers are not arcs. In Fig. 12 (c), the corresponding regions of photograph (b) are duplicated on the strain distributions for location M by dotted curves with the two highlighting circles. Especially for the radial strain distribution, the radial strain is large around the defects. This is possible reason that radial strain of M is deviates in Table 2. That region hence has relatively large radial stress. It is confirmed that zero radial stress design is not accomplished where the inherent specimen defects exist. Of course this kind of defects should be eliminated for the high-performance flywheel.

As an aside, by DIC method, we can check fabricated flywheel is success or failure due to such as above examinations. Applying DIC for high-speed rotor is effective. In order to make the DIC measurement better, following aspects are required: appropriate patterning of black and white, shortening of shutter exposure time for high-quality digital image, and strong light involved by the shutter speed shortening. When these aspects are available, the strain of object which rotates much higher speed can be measured by DIC, even strain gauge cannot work.

The specimen used in the present study is not so good because there are some defects as described above. However, almost zero rotational radial stress in the present flywheel is confirmed where significant defects do not exist. In near future, more high quality flywheel is fabricated employing filament winding method and it is spin-tested until ultimate failure. In order to enhance the maximum rotating speed, the interface strength is controlled. Moreover, to discuss its durability, accelerated testing methodology by elevated temperature is implemented. Thus, the development high-performance CFRP flywheel proceeds.

5. Conclusion

In the present study, a flywheel is fabricated based on the concept that no rotational radial stress occurs. This is because CFRP rotor is neither strong nor durable in radial direction so that the radial stress conventionally hinders the development of high-performance CFRP flywheel. A spin test is conducted for the fabricated flywheel at 18,000 rpm. The strain is measured by strain gauge and digital image correlation (DIC) methods. Especially, applying DIC for high-speed rotor is novel trial. The both measurements verify that almost zero rotational radial stress occurs in the present flywheel, basically. The DIC finds unexpected strain distribution where a defect exists in the flywheel. The present study indicates, as a first step for the development of high-performance CFRP, the feasibility of no-radial-stress flywheel fabrication and mentions future prospective for the development.

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Fig. 12 Specimen surface photograph of 9k (a) and M (b) and its correspondence in strain distributions (c).

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