D16

N85 13866

FLEXIBLE MATRIX COMPOSITE LAMINATED DISK/RING FLYWHEEL

B. P. Gupta and A. J. Hannibal
Lord Corporation
Erie, Pennsylvania

PRECEDING PAGE BLANK NOT FILMED

ABSTRACT

An energy storage flywheel consisting of a quasi-isotropic composite disk overwrapped by a circumferentially wound ring made of carbon fiber and an elastomeric matrix is proposed. Through analysis it has been demonstrated that with an elastomeric matrix to relieve the radial stresses, a laminated disk/ring flywheel can be designed to store at least 80.3 Wh/kg or about 68% more than previous disk/ring designs. At the same time the simple construction is preserved.

I. INTRODUCTION

Nearly a dozen different rotor concepts have been developed over the past ten years under the auspices of the Department of Energy. (DOE). All these designs were fabricated and underwent destructive testing. From analytical studies and experimental results which included energy density at burst, identification of failure modes, dynamic stability, requirements for containment and system cost, two designs were chosen for continued development. They were Garrett-Air Research's Multi-Ring Rim Rotor and General Electric's Laminated Disk/Ring Hybrid Rotor.

Garrett's multi-ring design stored 79.4 Wh/kg at burst, the highest energy density per unit weight of any flywheel studied in the DOE's Energy Storage Program. However, in a 10,000 cycle test at a maximum energy density of roughly one-half the ultimate value, the multi-ring design failed catastrophically after 2,586 cycles [Ref. 1]. The General Electric Disk/Ring Rotor stored 52.1 Wh/kg and 68 Wh/kg in two separate tests after having successfully completed 10,000 cycles at a maximum energy density of 22.5 Wh/kg. The failure mode was circumferential rupture induced by resin failure in the radial direction.

Other factors that demonstrate the high performance of the hybrid design are its energy density per unit volume, which is roughly three times that of the multi-ring design, and the controlled manner in which it fails.

In this paper the laminated disk/ring concept is modified by replacing the epoxy matrix in the ring with a urethane elastomer. It is demonstrated analytically that the circumferential rupture mode of failure is eliminated and the energy density increased by roughly 68% when using a high strain fiber. There are several other benefits derived from this substitution. First, the ring can be made very thick, reducing the manufacturing complexity required for multi-ring configurations. Also, the disk might be eliminated altogether in lieu of a small hub, possibly metal. Second, the maximum tensile stress occurs near the outside of the ring rather than at the interface like the carbon/epoxy ring. Third, the problem of ring/disk separation is eliminated.

The laminated disk/ring concept with a high performance fiber/elastomeric ring offers the potential for the highest energy density achieved with any flywheel concept to date while maintaining simplicity in construction. (See Figure 1.)

II. ANALYSIS AND DESIGN OF DISK/RING FLYWHEELS

Three disk/ring flywheels having different ring materials were evaluated analytically. The properties of the laminated glass/epoxy disk material, which is common to all three flywheels, were taken from Reference 2 and are recorded in Table 1. S-glass, carbon and high strain carbon (1.75% elongation) were considered as candidate fibers for the ring. S-glass fibers were rejected on the basis of disk/ring separation and will not be discussed in this paper. The matrix materials were epoxy and a relatively soft urethane elastomer having a Young's modulus of 13.8 MPa. The mechanical properties of the carbon/epoxy ring were also taken from Reference 2 and are recorded in Table 2. Some of the properties of the carbon/urethane rings were calculated using the method described in Reference 3 and others were estimated based on previous experimental measurements.

The analytical method was based on the equations developed in Reference 4. They provide the stresses relating to the four major considerations when designing a disk/ring flywheel. They are: (1) maximum stress in the disk; (2) maximum radial stress in the ring; (3) maximum circumferential stress in the ring; and (4) disk/ring separation.

Table 3 records the optimum flywheel configurations considered in this study. Configuration No. 1 has a carbon/epoxy ring with a radius ratio, a/b, of 0.85. Below this value the disk/ring separates as indicated by the low value of interface pressure. Failure occurs in the disk at an energy density of 47.74 Wh/kg. Configurations No. 2 and No. 3 have a radius ratio of 0.6. Lower values are possible without the fear of disk/ring separation, but the energy densities are not increased. Configuration No. 2 fails through longitudinal fiber breakage at an energy density of 58.96 Wh/kg, 23.5% greater than Configuration No. 1. Configuration No. 3, however, with its high strain capability, increases the stored energy density at burst to 80.3 Wh/kg or 68% greater than Configuration No. 1. Its failure could be either radial ring failure or circumferential ring failure.

TABLE 1 -

PROPERTIES OF S2-GLASS/EPOXY DISK

PROPERTIES	VALUE
Elastic Modulus, E_d	20.0 GPa (2.9×10^6 psi)
Poissons Ratio, ν_d	0.3
Density, γ_d	1.805 g/cm^3 (0.065 lb/in.^{3})
Ultimate Strength, σ_{ud}	386 MPa (56,000 psi)

In Figure 2 the maximum normalized stress factor (SD) in the disk is observed to be nearly the same for all three configurations over the entire range of a/b. For thicker annular rings, which are possible with configurations No 2. and No. 3, the stress in the disk is reduced and therefore becomes less of a concern.

The maximum tangential stress factor (SLT) for the ring is also presented in Figure 2. Below a radius ratio of about 0.77 the carbon/urethane configurations (No. 2 and No. 3) pay a penalty in higher tangential stress. SLT for the carbon/epoxy configuration (No. 1) minimizes at 0.56 while configurations No. 2 and No. 3 minimize at an SLT of 0.858. This difference is fairly constant for all a/b ratios less than 0.56.

The higher tangential stress factors for the carbon/urethane configurations are more than offset by the advantage gained in the radial stress factor (SLR) of the ring as illustrated in Figure 3. Clearly for all radius ratios below 0.85 the carbon/urethane configurations have a dramatic advantage over a carbon/epoxy ring. For a radius ratio below about 0.8, SLR is constant for configurations No. 2 and No. 3, allowing a ring of arbitrary annular thickness without an increase in radial stress. This is clearly not the case for configuration No. 1.

In Figure 4 the interface pressure (PL) versus radius ratio is presented. A negative value of PL indicates disk/ring separation. For configuration No. 1 separation would exist for all values of radius ratios below 0.85, although this value can be lowered somewhat by applying a precompression during assembly. Configurations No. 2 and No. 3, on the other hand, show no sign of separation at any radius ratio.

Figures 5 through 8 present the stresses along the radius of the flywheels. The interface of the disk and the ring is indicated by a vertical line. The maximum circumferential stress in the ring is at the interface in configuration No. 1, but near the outside of the ring for configuration No. 3. If failure should occur in the circumferential direction in configuration No. 3, a more benign failure mode would be expected. The compressive radial stress at the interface shown in Figure 8 for configuration No. 3 indicates the absence of separation.

TABLE 2 - PROPERTIES OF RING MATERIALS
(V_f = 60%)

Flywheel Configuration No.	1	2	3
Composite Material	Carbon/Epoxy	Carbon/Urethane	High Strain Carbon/Urethane
Density, γ_h g/cm^3 (lb/in.^{3})	1.509 (0.0545)	1.467 (0.053)	1.467 (0.053)
Poisson's Ratio, ν_h	0.33	0.39	0.39
Tangential Modulus, E_θ GPa (psi)	126.2 (18.3 x 10^6)	126.2 (18.3 x 10^6)	126.2 (18.3 x 10^6)
Radial Modulus, E_r GPa (psi)	9.59 (1.39 x 10^6)	0.38 (54,800)	0.38 (54,800)
Tangential Strength, $\sigma_{u\theta}$ MPa (psi)	1124.1 (163,000)	1124.1 (163,000)	1575.2 (228,400)
Radial Strength, σ_{ur} MPa (psi)	12.4 (1,800)	12.4 (1800)	12.4 (1,800)
Ratio, $N = E_\theta/E_d$	6.31	6.31	6.31
Ratio, $K^2 = E_\theta/E_r$	13.17	334	334
Ratio, $R = \gamma_d/\gamma_h$	1.195	1.222	1.226

TABLE 3 - OPTIMUM DESIGNS OF FLYWHEELS

Configuration No.	1	2	3
Composite Material	Carbon/Epoxy	Carbon/Urethane	High Strain Carbon/Urethane
Radius Ratio ($c = a/b$)	0.85	0.6	0.6
Interface Pressure Ratio ($PL = p/\rho_h\omega^2 b^2$)	0.0012	0.0021	0.0021
Maximum Stress Factors			
SLT	0.956	0.8577	0.8577
SLR	0.0082	0.00695	0.00695
SD	0.355	0.180	0.180
Maximum Stress Strength Ratios 10^{-6}/MPa (10^{-6}/psi)			
SLT/$\sigma_{u\theta}$	850.5 (5.86)	763.4 (5.26)*	545.7 (3.76)
SLR/σ_{ur}	660.4 (4.55)	560.4 (3.861)	560.4 (3.861)*
SD/σ_{ud}	920.2 (6.34)*	466.5 (3.214)	466.5 (3.214)
Maximum Energy Wh/kg (Wh/lb)	47.74 (21.7)	58.96 (26.8)	80.3 (36.5)
Failure Speed, RPM **	36,000	40,160	46,900

* Indicates the failed part and the mode of failure.

** Radius b of the flywheel is 22.48 cm (8.85 in.).

Figure 9 presents the maximum energy densities per unit weight for all three configurations as a function of the radius ratio a/b. The failure mode changes for different values of the radius ratio. It can be observed that failure occurs in the disk for all three configurations when the ring is thin. For thicker rings, the mode of failure shifts to circumferential rupture (radial stress) for the carbon/epoxy configuration. The energy density decreases rapidly at this point for a small increase in ring annular thickness. For a radius ratio less than 0.77, the failure mode of configuration No. 2 is a tangential stress failure with a constant energy density of about 58.3 Wh/kg. Configuration No. 3 (high strain carbon fiber) has the same characteristic for radius ratios less than 0.65. Its energy density is constant at 82.5 Wh/kg or 68% higher than the carbon/epoxy configuration.

III. RESIDUAL STRESSES CAUSED BY MANUFACTURING PROCESSES

The manufacturing processes involved in fabricating a filament wound composite ring can create residual stresses in the flywheels. These stresses will have a detrimental effect on the performance of the flywheels if they are tensile in nature. Table 4 records the residual stresses in two carbon/epoxy rings and two carbon/urethane rings based on the calculations published in Reference 5.

It can be observed from Table 4 that as the thickness increases, the residual stresses also increase. In terms of ultimate strength it appears the radial stress is more harmful than the tangential stress. Even though analysis indicates a single ring having a small a/b ratio is feasible, manufacturing induced stresses may preclude this possibility. If so, it seems that two or three relatively thick rings with precompression will reduce the problem to a manageable level.

TABLE 4 - RESIDUAL STRESSES

Ring Number	Dimensions, cm (in.) OD	ID	Thickness	Material (V_f)	Residual Stresses MPa (psi) (σ_θ) inside	(σ_θ) outside	(σ_r) middle
1(a)	53.34 (21.0)	50.8 (20.0)	1.27 (0.5)	Carbon/Epoxy (60%)	41.0 (5,940)	-39.6 (-5,750)	0.475 (69.0)
1(b)	53.34 (21.0)	50.8 (20.0)	1.27 (0.5)	Carbon/Urethane (46%)	31.7 (4,600)	-31.3 (-4,540)	0.455 (66.0)
2(a)	40.3 (15.87)	27.94 (11.0)	6.18 (2.44)	Carbon/Epoxy (60%)	87.7 (12,730)	-69.8 (-10,130)	6.7 (970.0)
2(b)	35.6 (14.0)	27.94 (11.0)	3.81 (1.50)	Carbon/Urethane (50%)	80.7 (11,710)	-70.4 (-10,210)	4.0 (580.0)

IV. FUTURE WORK

In this paper the performance improvement of a laminated disk/ring flywheel with a carbon/urethane ring over a flywheel with a carbon/epoxy ring has been demonstrated. There is, however, still a great deal of work to be done, such as:

- Optimum design of a disk/ring flywheel with a few rings assembled with an interference fit and possibly having different fibers and different resins at different fiber fractions (Figure 10).
- Materials data studies to determine the most suitable resin and fiber combination.
- Fiber sizing studies to optimize fiber/resin adhesion.
- Dynamic stability study.
- Spin test to burst.
- NDT evaluation.
- Deep cycle fatigue.

V. SYMBOLS AND ABBREVIATIONS

a	radius of disk
b	radius of flywheel
c	ratio of disk radius to flywheel radius
E_d	elastic modulus of disk material
E_r	radial modulus of ring material
E_θ	tangential modulus of ring material
ID	inside diameter
K^2	ratio of tangential to radial modulus of ring material
M	E_θ/E_d
N	speed of flywheel, RPM
OD	outside diameter
PL	interface pressure, nondimensional; $PL = p/\rho_h\omega^2b^2$
p	interface pressure,
R	σ_d/σ_h
r	radius
SD	maximum normalized stress factor
SLR	radial stress factor
SLT	maximum tangential stress factor
V_f	fiber volume section
γ_d	density of disk material
γ_h	weight of ring material
θ	arbitrary position along circumference of ring
ν_d	Poisson's ratio for disk material
ν_h	Poisson's ratio for ring material
ρ_d	density of disk material
ρ_h	density of ring material
σ_r	radial stress in ring material
σ_{ud}	ultimate tensile strength of disk material
σ_{ur}	ultimate tensile strength of ring material in radial direction
$\sigma_{u\theta}$	ultimate tensile strength of ring material in tangential direction
σ_θ	tangential stress in ring material
ω	angular speed, rad/sec

Subscript:

max	maximum

VI. REFERENCES

1. Coppa, A.P. and Kulkarni, S.V.: Composite Flywheels Status and Performance Assessment and Projections, Proceedings of the Second European Symposium on Flywheel Energy Storage, Polytechnic of Tuon Turn, Italy, May 9 - 13, 1983

2. Nimmer, R. P., Torossian, K., and Wilkening, W. W.: Laminated Composite Disc Flywheel Development, Fourth Interim Report by General Electric Co., for Lawrence Livermore Laboratory, No. UCRL-15383, January 1981.

3. Gupta, B. P.: Elastic Constants of a Uniaxial Composite by Finite Element Energy Method, 19th Annual Meeting of the Society of Engineering Science, Inc. (University of Missouri-Rolla, Rolla, Missouri), October 1982.

4. Gupta, B. P. and Lewis: A. F.: Optimization of Hoop/Disk Composite Flywheel Rotor Designs. 1977 Flywheel Technology Symposium Proceedings, San Francisco, California, March 1978.

5. Dewey, B. R., and Knight, C. E., Jr.: Experimental and Theoretical Determination of Residual Stresses in Filament-Wound Rings, Rep. No. Y-1701, Union Carbide Corp., Oak Ridge, TN, 1970. (Available from NTIS.)

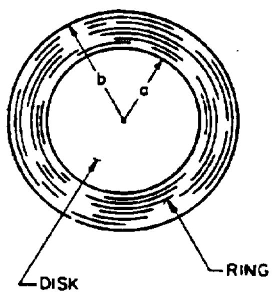

Figure 1.- Laminated disk/ring flywheel. Disk is solid and is made of an isotropic material, such as a laminated S2-glass/epoxy composite. A ring made of high-modulus high-strength fiber and flexible matrix composite is wound onto the disk. The fibers in the ring are directed circumferentially.

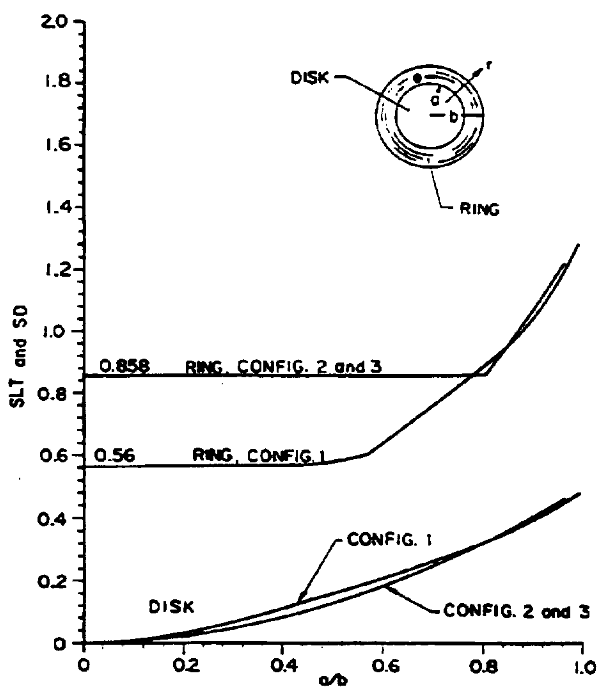

Figure 2.- Maximum tangential stress factors.

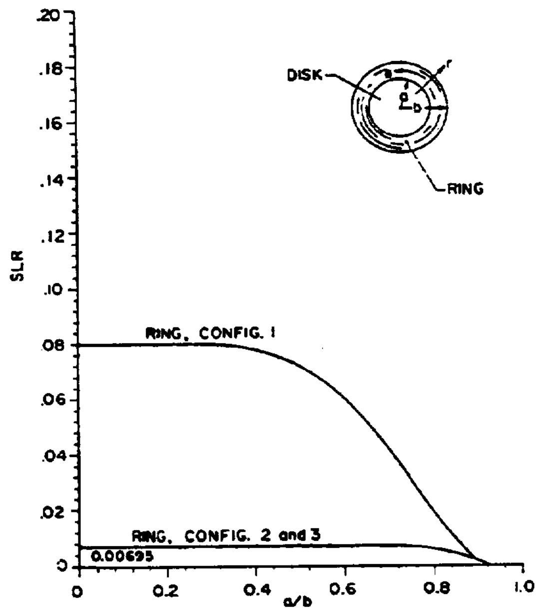

Figure 3.- Maximum radial stress factors.

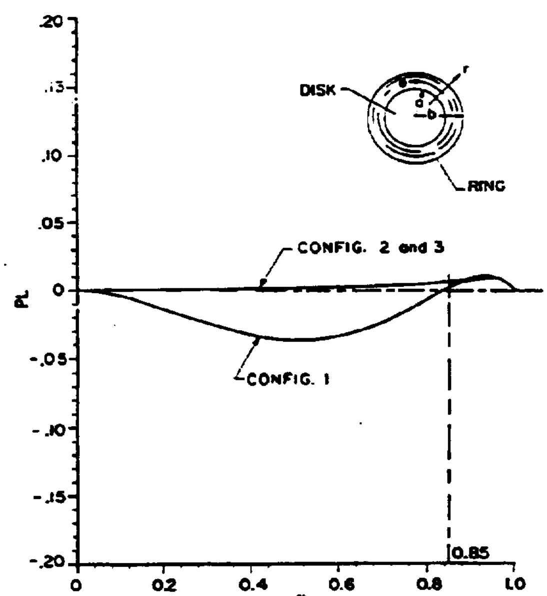

Figure 4.- Interface pressure factors.

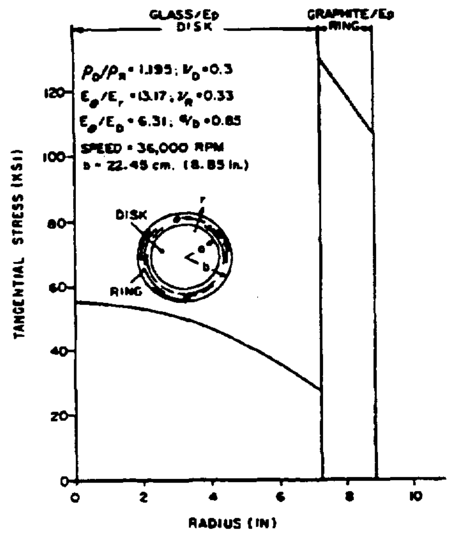

Figure 5.- Tangential stress along radius of flywheel. Configuration 1.

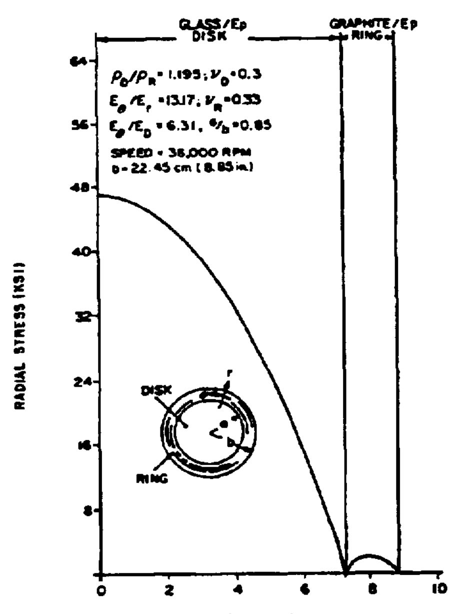

Figure 6.- Radial stress. Configuration 1.

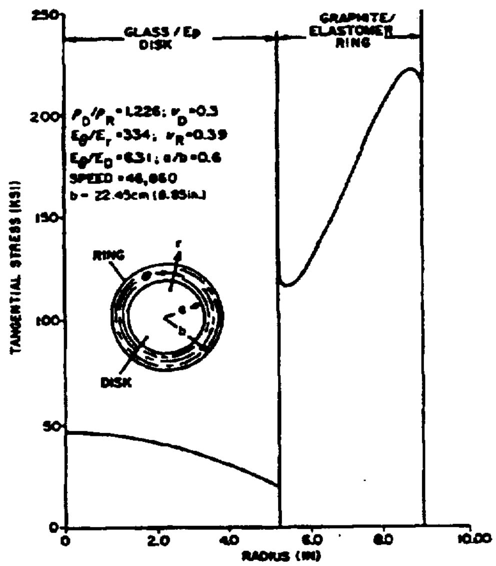

Figure 7.- Tangential stress. Configuration 3.

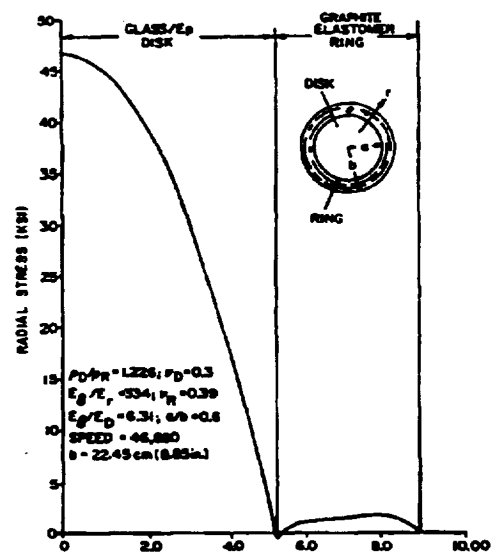

Figure 8.- Radial stress. Configuration 3.

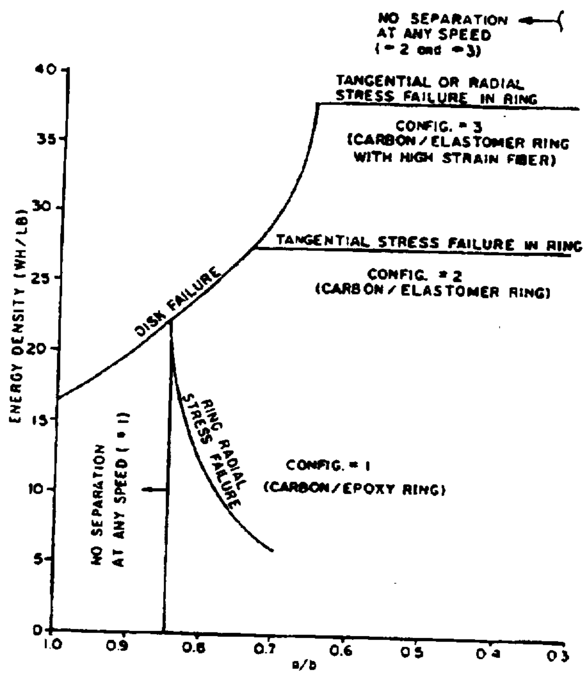

Figure 9.- Maximum energy densities and failure.

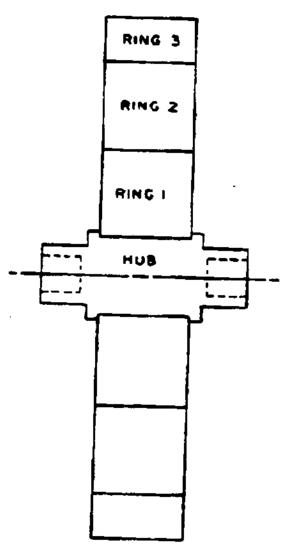

Figure 10.- Proposed flywheel construction.