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GENERIC COMPOSITE FLYWHEEL DESIGNS

R. S. Steele\*  
Greenville, South Carolina

\*Private flywheel consultant.

Fiber reinforced composites belong to a new class of materials. They allow such flexibility that free thinking individuals are encouraged to "let themselves go" with their design. The most efficient flywheel may no longer have the classic "Stodola" taper and indeed, may not even be round. Since selection of an optimum design can be the subject of a sizeable study [refs. 1 and 2], I thought that it might be instructive to review some of the flywheel designs that have been developed and comment on what NASA might learn from this experience.

Although choice of material, mounts and service requirements often dictates the final design choice for a particular application, I have chosen to classify these composite flywheels within a geometric framework. The breakdown given in figure 1 is probably not exhaustive but will suffice for today's discussion.

**NON-ROUND ROTORS**

- Bar
- Brush

**ROUND ROTORS**

Solid Disk

- Flat disk (pseudo-isotropic)
  - Alpha-ply layup
    - Without rim
    - With rim
  - Molded (sheet molding compound)
  - Plywood
- Tapered disk (constant stress)
  - Stodola
  - Modified Stodola

Pierced Disk (rims)

- Woven
  - Radial stringers
  - Helical weave
- Thin Circ Wound
  - Rollers
  - Levitated
- Thick Circ Wound
  - Single material (residual stress)
    - Single step winding
    - Multi-step winding
  - Multi-material rims
    - Circular
    - Sub-circular

Figure 1.- Classification of generic rotor designs.

Let me start with a few comments regarding non-round rotors (fig. 2). They are generally simple to construct, and in the case of the fan-brush type [ref. 3] possess a relatively benign failure mode. A major problem is their low volume efficiency. They do not fully occupy the volume in which they spin.

The bar type tends to split at the tips and take on a fan-brush character. The splitting is the result of low transverse strength in the composite. As we will see, this is usually the limiting characteristic of composites.

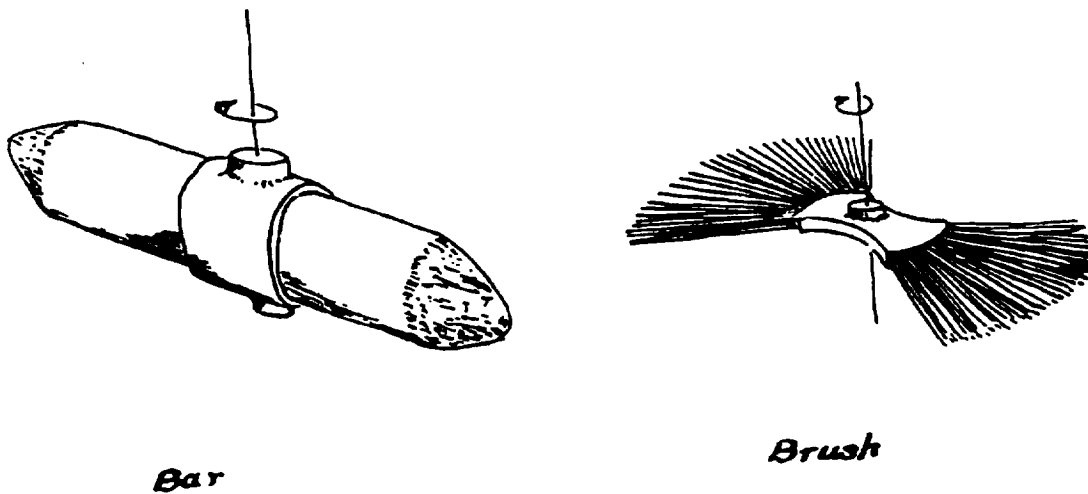


Figure 2.- Non-round rotors.

Before discussing the various perturbations of circular flywheels, we should look at a simple stress analysis of a circular disk [ref. 4]. (See fig. 3.) This analysis shows that a constant thickness disk with a small central hole can have a greater hoop stress at its center than if it did not have the hole. On the other hand, the maximum radial stress will be lower.

Now consider the two types of construction used. The first has a fiber orientation that macroscopically simulates the character of an isotropic material (metal). These were called pseudo-isotropic in the DOE program. They lean to the solid disk designs because even though their overall composite strength is lower than the unidirectional fiber composite, they can survive the high radial stresses.

The other is characterized by a highly structured (usually orthogonal) fiber orientation that places the strength of the fiber in the direction of the major principal stress component. This allows the composite structure to survive a very high major principal stress so long as the minor principal stress does not exceed the transverse strength of the composite.

The favorite structured orientation is a hoop wound cylinder which naturally possesses a central hole. The limiting factors have been either the low strength transverse to the fibers or items independent of the rim. The larger the diameter of the hole, the lower the transverse stress. Thus the designer is faced with balancing his desire for a thick, high energy rim with the maximum transverse stress his material can stand.

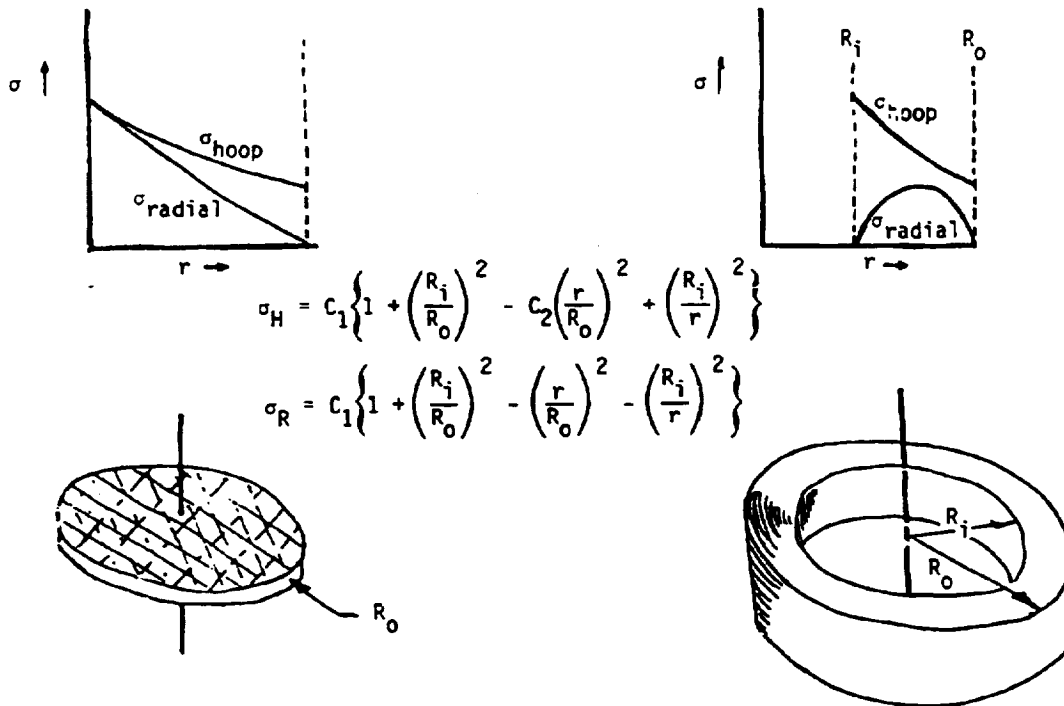


Figure 3.- Stress analysis of spinning circular disk.

Let me review some of our experience with actual rotors. I will rely upon my own experience with the Department of Energy's Mechanical Energy program as test director at the Oak Ridge Y-12 Plant's Flywheel Evaluation Laboratory.

Pseudo-isotropic flywheels demonstrated lower energy densities but also had relatively low fabrication cost. They also demonstrated a higher level of durability than their competition. One type was built using an alpha-ply [ref. 5] layup in which sheets of unidirectional fibers in an epoxy matrix were stacked at various angles until the desired thickness was reached. Circular disks were machined from the cured plates and, in some cases, tapered to simulate the constant stress shape [ref. 6] used in high performance metal flywheels.

A pseudo-isotropic flywheel (fig. 4) survived our only 10,000 cycle fatigue test. The graphite version of the modified Stodola flywheel achieved close to 1000 m/s tip speed, giving it the top speed in our record book.

Two problems persisted [ref. 7]. An elastomeric interface is required between the the metallic arbor mount and the composite surface. Unless the metallic arbor and the disk mass centers both lie on the spin axis (a very remote possibility), the distance between them will vary with speed. This adds complexity to the suspension system. The fatigue stresses at the bonded interface are also found to be detrimental to the life of the rotor.

The other problem is the severe failure modes. The constant thickness disks usually failed at the drive shaft interface. This allowed the entire disk to roll around inside our containment, setting up severe vibratory stresses in the containment for several seconds. A "lightweight" containment vessel would not stand the failure. The tapered disk performed such that it disintegrated in an explosion that sent chunks of graphite composite into our containment ring. What we must learn is that the pseudo-isotropic rotor can produce the full range of failure problems, thus making containment development difficult and expensive.

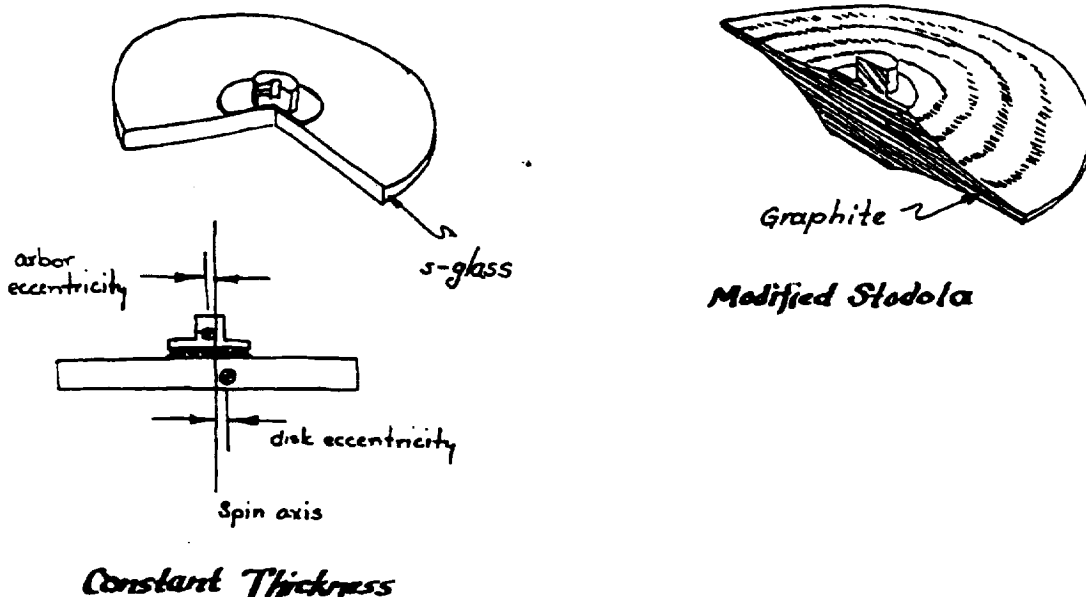


Figure 4.- Pseudo-isotropic disk.

A second method of accomplishing isotropy was demonstrated by the molded, chopped fiberglass rotors [ref. 8]. They required a hoop wound support ring to achieve the highest energy density. A similar arbor attachment was used and the same balance problems were encountered. The failure mode was consistent [ref. 9]. The hoop supports usually burst, leaving the disk no longer able to support itself. The entire rotor broke into small fibrous wads of mass, fairly uniformly distributed in the chamber.

Finally, a very inexpensive flywheel was proposed and built from hexagonal, birch plywood [ref. 10]. (See fig. 5.) Successful testing was reported with respectable energy densities for the cost involved.

However, since NASA will place more importance upon performance than cost, it is unlikely that a solid disk from any composite will be chosen for space applications.

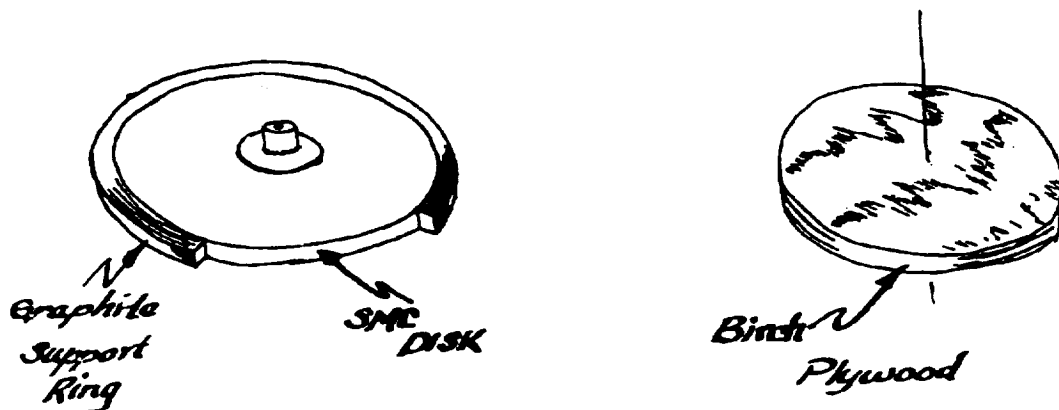


Figure 5.- Lower cost pseudo-isotropic disk.

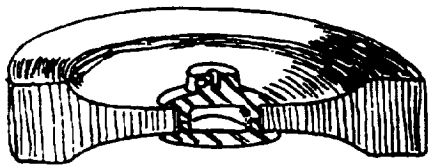
If you are going to use a composite flywheel, it will be a disk with a hole. Should it have a big hole or a little hole? I know of at least one composite flywheel that was circumferentially wound around a 25-mm spindle with an outer diameter of about 1 mm. When tested, it failed at a very low speed due to transverse cracking. (See fig. 3.) The smaller the hole relative to the overall diameter, the greater the transverse stress. Thus the limiting material factor in thick, orthogonal composite rings is the transverse composite strength.

You have two problems: how to make the rim as thick as possible so it will be volume efficient and how to attach it to the outside world.

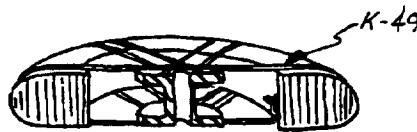
Several attempts have been made to wind a residual stress state into the flywheel so that the inner circumference is in compression at rest. This allows a thicker rim at a given speed.

I am familiar with two flywheels that use this technique. In the one pictured in figure 6(a), carbon fibers were used in a polysulfone matrix [ref. 11] that was cured during winding. The design speed was not achieved because the transverse strength of the composite with this matrix was lower than the designer had expected. The one in figure 6(b) used 14 wind-cure steps to produce the rim. The band-wrap [ref. 12] technique was used to attach the rim to a central shaft. Pre-stressing did result in an improvement upon an earlier non-pre-stressed wheel. However, the ultimate speed was limited by the band-wraps.

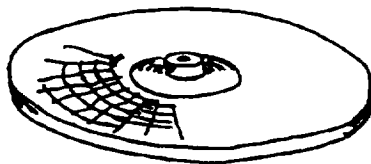
Another method to increase the thickness of a rim is to place radial reinforcements in the rotor [ref. 13]. (See fig. 6(c).) These rotors were fairly successful but suffered interface problems with the drive shaft.



(a) Continuous winding with residual stress.



(b) Step winding with residual stress.



(c) Radial stringers or bidirectional weave.

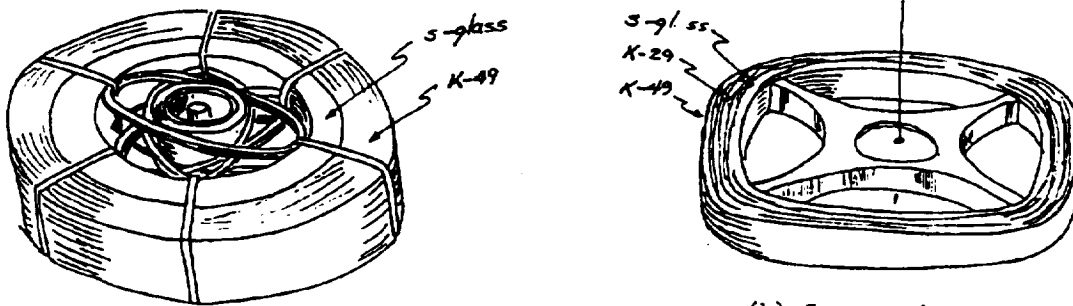
Figure 6.- Thick rims.

Another successful and less expensive method is to wind the rim from several materials. An inner material with a lower modulus/density ratio will grow radially, with speed, into the higher modulus/density rings [ref. 14]. This creates compressive radial stresses at the interface between the layers. To my knowledge, no one has yet been able to create a hoop failure in such a flywheel. Failures in the attachment system always come first.

Attaching a rim to the outside world is not simple. The primary problem is to accommodate the radial growth of the rim without having such a "soft" system that the flywheel would have resonant frequencies in the operating range.

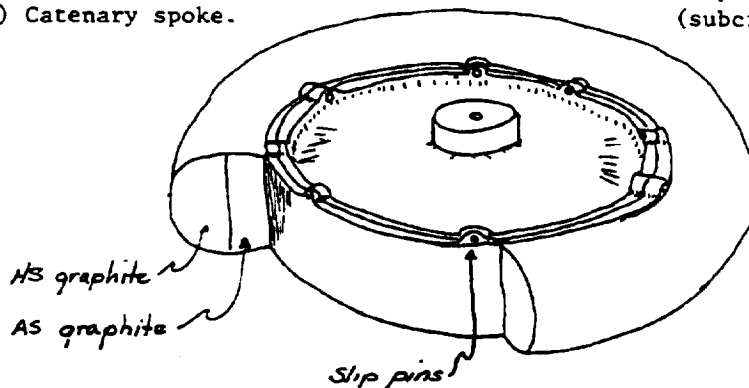
The most successful design with the rim/shaft interface in tension used rotational catenary spokes [ref. 15]. (See fig. 7(a).) These were carefully designed to grow with the rim.

The other successful approach used compressive spokes and a sub-circular rim [ref. 16]. (See fig. 7(b).) This required a rim made of multiple, concentric, thin rings held together at rest by a small interference fit. The spokes remained in compression until the rim grew circular. The rim failures that have occurred in this type resulted from overheating and fatigue. The outer layers are most susceptible, and if the rest of the rim can be supported by the shaft and spoke system, the containment problems are minimized. The designer of the flywheel shown in figure 7(c) needed a very rugged flywheel [ref. 17] for his intended application and used aluminum plates in the center of the rim with 16 slip-pins to accommodate the differential radial growth. Unfortunately, the tolerance on the slip-pins was insufficient to maintain adequate balance. We were unable to confirm its 4 kWh potential energy storage capability.



(a) Catenary spoke.

(b) Compressive spokes (subcircular).



(c) Rim with aluminum plates.

Figure 7.- Multi-material rims.



Finally we come to the rim without a central shaft. I know of two basic designs. The first is a thin ring supported on rollers. Power I/O was through a rack and pinion system on its inside surface. The proposed rim was 1 meter thick, 2 meters tall, and 1 kilometer in diameter. The composite material was steel reinforced concrete. That rim was never built.

The other is also a thin ring but is magnetically levitated and functions as the rotor of a motor/generator. The test results I have seen regarding this design involve control and power studies. I know of no test results concerning the life or performance characteristics of these rotor designs. It strikes me, though, that since a 1-meter-diameter rotor will have about 5 mm radial growth at operating speed (2% graphite operating with a 50% knockdown factor), the electrical coupling could be severely degraded at maximum speed. An inefficient coupling may lead to high temperatures at the highly stressed inner surface of the rotor and thus reduce life.

Only testing under these specific conditions will provide the confidence needed in the lifetime for one of these units.

A rim type rotor can be built that will have an energy density suitable to NASA's requirements. The levitated rim type appears structurally attractive if the electronic coupling doesn't suffer too much from radial growth.

I am concerned that two areas might be neglected. The containment problems are not trivial. A composite flywheel does not simply break up into fluff. It loses a lot of energy as it stops. If it attempts to stop too suddenly, you have a containment problem. For instance, a rim contained in a small cavity will tend to jam suddenly, creating a tremendous torque [refs. 18, 19, and 20]. The severity of the problem is known to vary with materials, but the test results needed for accurate design optimization do not exist.

Neither does good data exist for my other concern, which is the effect of long term exposure to sustained high stress in vacuum. Composite properties, and in particular matrix properties, will change with time. Very little data exists to estimate what the material characteristics will be after one to five years of operation.

I have touched on many different topics that have been addressed in the development of composite flywheels. My final words are to encourage NASA to approach composite flywheels cautiously and with a healthy respect for the energies involved (fig. 8).

**\* Containment Development will NOT be Trivial**

- . Remember total energy involved
- . Look for fast stops

**\* Long Term Effects Need Assessment**

- . Sustained stress
- . Continuous vacuum
- . Radiation

Figure 8.- Concerns needing study,

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