THE FLYWHEEL BATTERY CONTAINMENT PROBLEM

By:

M. Pichot
J. Kramer
R. J. Hayes
R. C. Thompson
J. H. Beno

1997 SAE International Congress and Exposition, Detroit, MI, Feb 24-27, 1997.

Mechanical Engineering, vol. 18, no. 11, November 1996

PR - 225

Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

THE FLYWHEEL BATTERY CONTAINMENT PROBLEM

M.A. Pichot, R.C. Thompson, R.J. Hayes,
and J.H. Beno

The Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin TX 78712
(512) 471-4496

J.M. Kramer

Argonne National Laboratory

ABSTRACT

Flywheel energy storage systems (FESSs), commonly known as flywheel batteries, are being developed for a number of power averaging applications in the transportation industry. Most FESS designs incorporate rotors made from composite materials for which operating experience is limited and little failure data is available. Given the high energy levels inherent in these devices, a major task for the FESS designer is to provide adequate containment structures to insure safe operation in the event of flywheel failure. This paper discusses ongoing work intended to provide a better understanding of composite flywheel failure mechanisms and development of a methodology for safe containment design.

INTRODUCTION

The University of Texas at Austin Center for Electromechanics (UT-CEM) is currently under contract to develop composite FESSs for power averaging on hybrid electric transit buses and high speed locomotives. In addition, UT-CEM is participating in a Defense Advanced Research Projects Agency (DARPA) sponsored Flywheel Safety Project that seeks to investigate composite flywheel failure mechanisms and to develop systems to mitigate effects of those failures.

This paper discusses FESS principles, applications, and operating parameters. Likely failure scenarios for composite flywheels are shown, the need for containment structures is discussed, and additional information is given regarding the DARPA Flywheel Safety Project. A model to predict containment loads due to composite flywheel failures was developed by Argonne National Laboratory under contract to UT-CEM; the assumptions behind this model are discussed, and some sample calculations are presented. Results from flywheel failure testing are shown, and plans for future tests are discussed. Finally, a discussion of possible approaches to containment design is presented.

FLYWHEEL BATTERY PRINCIPLES

As the world consumption of fossil fuels has increased, so have the concerns about the environmental effects associat-

ed with our dependence on this nonrenewable resource. One result of this concern is a growing interest in electric and hybrid electric vehicles. All-electric vehicles typically use a large bank of electrochemical batteries to provide both power and energy storage and are range limited, based on the on board energy storage. Hybrid electric vehicles address the range issue by utilizing a small internal combustion prime power unit to drive an electric generator to meet the average power requirements. To address peak power requirements, an auxiliary energy storage and power conversion device (typically a FESS or a bank of electrochemical batteries) are required. In this type of hybrid system, or when used in conjunction with a bank of batteries in an all-electric vehicle, a FESS is used for power averaging.

Power averaging is accomplished primarily by storing energy generated during regenerative braking then releasing it during acceleration of the vehicle. The generation of braking energy on a vehicle is accomplished through the use of electric traction motors which operate as generators during braking. During the braking period, a motor/generator in the FESS is used to convert the electrical braking energy from the traction motors into mechanical energy in the spinning flywheel. When the vehicle accelerates, the FESS motor/generator converts energy stored in the flywheel back into electrical energy to power the drive wheels, completing the storage and recovery cycle. Because regenerative braking reduces losses, the fuel efficiency of the vehicle can be increased significantly. The peak power required of the prime power unit is reduced as well, which reduces both initial system costs and operating costs.

While both power averaging and regenerative braking have been demonstrated with electrochemical batteries and FESSs [1][2], there are significant benefits to using a FESS. Although electrochemical batteries can have high energy densities, their power densities are typically lower than those for a FESS [3][4]. Furthermore, present electrochemical battery designs require design tradeoffs between power density, energy density and system life. Because FESSs use two distinct components, the flywheel and the motor/generator, to perform the energy storage function and the power conversion function respectively, both of these key parameters can be optimized for

a specific application. Additionally, because a FESS requires little maintenance and can have a service life equivalent to that of a commercial vehicle (compared to the high maintenance requirements for a two to four year life cycle on a conventional electrochemical battery), the life cycle cost for a FESS should be less than that for a comparable electrochemical battery.

UT-CEM and its industrial partners (AVCON Inc. and AlliedSignal Aerospace Equipment Systems) are developing two FESSs for power averaging in hybrid electric drive trains. The first of these is a 2 kWh, 150 kW, 40,000 rpm device for a 13,600 kg transit bus; this device is illustrated in figure 1. In this system, the primary benefits of the FESS are to facilitate the use of a smaller prime power unit, reduce fuel consumption, and reduce emissions. The second system is a 165 kWh, 3 MW, 15,000 rpm system for a high speed locomotive where a load leveling flywheel is required for faster acceleration and reduced emissions. The combination of a flywheel with a hybrid drive train provides the locomotive with the additional benefits of regenerative braking and improved performance without the additional infrastructure expense normally required for all-electric trains [5]. At present, for these two transit applications, where the vehicle is frequently stopping and starting and where fuel costs are a large part of the operating costs, a flywheel battery appears to have a reasonable payback period. Other potential near term uses for flywheel systems are in passenger cars and as uninterruptable power supplies in stationary and mobile applications.

THE NEED FOR CONTAINMENT

A flywheel's energy storage potential is proportional to its mass moment of inertia and the square of the rotational speed. For a specific configuration, speed is limited by the material strength-to-density ratio. In terms of performance, high strength composite materials are currently the preferred flywheel material [6]. Furthermore, while metal wheels may provide a lower cost, albeit heavier, alternative for small stationary applications, composite flywheels will be required to meet the weight requirements for mobile applications. It is also apparent that to maximize energy storage in composite flywheels, they must operate with stresses near their yield strength.

Based on a long history of operating experience, a great deal is known about the failure modes of metallic flywheels and the public has grown accustomed to using them in many everyday applications. This includes their use as power smoothing devices in manual transmission passenger cars, where the flywheel resides in close proximity to both the driver and passenger. This is of no concern to the average driver, and because metallic wheel failure mechanisms are well characterized, there is little reason for concern. Very little data, however, has been published about the failure modes of composite flywheels. What is known is that these failure modes (described later in this paper) are very different from the well characterized behavior of metallic wheels. It is also known that they are both design and material dependent, so accepted design rules have not yet been established. Additionally, catastrophic burst failures during overspeed of certain flywheel designs have been demonstrated during failure testing [7][8][9][10]. Based on the potential for a catastrophic failure and the lack of operating experience with composite flywheels, it is prudent to incorporate containment structures to mitigate the effects of a failure in near-term vehicular FESSs. While this is the approach taken by the U.S. FESS industry, it should be noted that low stress vehicular flywheels have been successfully operated without dedicated containment systems in Germany for many years, with no serious accidents reported.

DARPA FLYWHEEL SAFETY PROJECT

To address the aforementioned concerns, DARPA has funded a Flywheel Safety Project to both determine the effects of typical composite flywheel failures and develop systems to mitigate those failures. The objectives of this project are to develop burst test technology; conduct a combined theoretical and experimental program to gain a fundamental phenomenological understanding of composite flywheel failures; and devise a basic methodology for design of containment structures and systems. The program is fully integrated with Department of Energy efforts in composite flywheel containment and emphasizes technology sharing within the U.S. flywheel battery community. A major outcome of the project will be a final report documenting test results and development of containment design procedures for the U.S. flywheel battery community.

The project couples the major commercial U.S. flywheel spin-test facility, Test Devices, Inc., with a powerful group of competing flywheel battery developers: UT-CEM, Trinity

Figure 1. Transit bus flywheel battery

Flywheels Inc., and U.S. Flywheels Inc. The genesis of this project and the enthusiasm for mutual cooperation stems from the belief that flywheel safety is a problem of such importance and difficulty that it transcends normal competitions. The group membership was developed to pool resources and assemble a combined expertise, representing a suitable variety of flywheel battery design approaches, so that a relatively general approach for design of composite flywheel containment systems could be developed. The commitment to share intermediate test results, interim progress, and final project results stems from altruistic concerns about personnel safety as well as concerns about public perception and the overall health of the flywheel battery market potential. Although the project is relatively new, some results (specifically, results of a detailed literature search) are already available on the internet at the Southern Coalition for Advanced Transportation site, www.advtrans.org.

TECHNICAL BACKGROUND

COMPOSITE FLYWHEEL FAILURE SCENARIOS - Different composite flywheel designs possess a propensity for different types of failures. However, the reader should also be aware that similar designs can experience different failure modes if operating conditions or fabrication techniques are varied. If failure does occur, the more likely scenarios are:

- delamination (i.e., radial separation of layers of composite windings),
- burst, and
- transverse epoxy matrix failure.

These scenarios with causes and effects are listed in table 1. Order of presentation in the table is in the "plane of action" of the event based upon a cylindrical coordinate system.

Table 1. Summary of failure scenarios

Failure Scenario	Cause	Effects of Failure
<i>In the Radial (R) Plane</i>		
Delamination: Ring radial separation	<ul style="list-style-type: none"> • Over speed • Epoxy matrix degradation and/or shifting of imbedded fibers (creep) • Elevated temperature 	Maybe benign for some designs: Produces imbalance due to mass shift requiring flywheel shutdown
<i>In the Theta (θ) Plane</i>		
Burst: Hoop fiber crack	<ul style="list-style-type: none"> • Over Speed • Fatigue 	Catastrophic with significant energy release
<i>In the Axial (Z) Plane</i>		
Matrix crack transverse to hoop fibers	<ul style="list-style-type: none"> • Induced by high axial tensile stress from Poisson effects 	Benign in limited occurrences. May produce imbalance

Mass loaded flywheels, i.e. flywheels with radially increasing specific modulus, generate radial compression with increasing speed. Generally, this design can be more susceptible to burst, especially if loss of the outer ring results in hoop failure of all the inner rings. A burst is a failure of fibers in the hoop direction. Figures 2 and 3 show different views of a graphite composite ring which underwent a burst type failure in static tests. Bursts can be caused by overspeed, fatigue, or fabrication flaws, which either exceed or compromise fiber hoop strength resulting in significant kinetic energy release.

Preloaded flywheel designs, by contrast, exhibit constant or near constant specific modulus. They are characterized by a tendency to delaminate before experiencing a burst, especially when employing lower modulus graphite composites. Delamination is a physical separation of a localized portion of the flywheel due to loss of radial compression, leading to a debond between hoop fiber layers. Causes include high spin loads due to overspeed. Debonds can also be initiated by creep of the epoxy matrix or matrix degradation due to elevated temperature. Polar woven flywheel designs are resistant to delaminations due to the inclusion of radially oriented fibers.

S 8301.0093 bw

Figure 2. Burst of a composite ring

S 8301.0098 bw

Figure 3. End view of the burst of a composite ring

Figures 4 and 5 show views of a delaminated composite ring. Delamination of this ring was caused by a fabrication anomaly. However, the pictured radial separation is representative of a delamination during flywheel operation.

Spin tests conducted at Oak Ridge National Laboratory [11] demonstrated a particular preloaded flywheel design which delaminates during overspeed conditions. This flywheel design failed in a benign mode referred to as a mechanical fuse. At a specific speed, significantly less than burst speed, the delamination event produced a slight mass imbalance which was detected by shaft displacement probes. The flywheel was safely shut down, avoiding a large energy release associated with a flywheel burst.

It should be emphasized that both mass loaded and preloaded flywheels can be designed to delaminate. In addition, not all delaminating flywheel designs possess a benign failure mode. An abrupt, fast acting delamination can result in significant imbalance forces quickly overcoming bearing load capacity. The result is a loss of control of the flywheel leading to flywheel failure.

Figure 4. Delaminated composite ring

Figure 5. End view of delaminated composite ring

Another noted failure scenario [11] is cracking of the epoxy matrix transverse to hoop fibers. This is usually induced by high axial stresses from Poisson effects due to radial growth. According to the literature, this failure usually produces mild imbalances permitting safe flywheel shutdown.

CONTAINMENT LOADING ESTIMATES - The initial containment loading estimates have focused on the flywheel burst mode of failure, because it is generally agreed that this type of failure would represent the most extreme challenge to the containment. The burst mode of failure is characterized as a sudden failure of the rotor fibers in the hoop direction. For a partial burst, it is assumed that only the most highly-stressed outer rings of the rotor fail. For a complete burst, the entire rotor is assumed to fail instantaneously.

The size and shape of the fragments that are ejected from a flywheel burst are currently being investigated experimentally. If the fragments are large, they can have a sizable component of rotational kinetic energy in addition to their translational kinetic energy. Conservation of momentum can be used to show that the fragment containing the greatest amount of energy is a tri-hub sector that encompasses one third of the rotor. Although such fragments are often assumed for the analysis of the containment of metallic rotors, experience has shown that composite rotors tend to fracture into much smaller pieces.

The seminal work in the analysis of composite flywheel breakup was performed by Coppa [12]. Coppa's model assumes an axially symmetric distribution of finite-sized fragments that impact the containment wall along a tangential trajectory. The momentum transferred to the wall is calculated assuming that the fragments hit the wall and then lose momentum progressively as the fragments crush. In the analysis described below, we have taken a somewhat simpler view that the flywheel burst itself produces sufficiently finely divided fragments such that the debris can be modeled as a continuum during its impact with the containment wall. Experimental results support this assumption.

Radial Wall Loading - The simplified geometry used for the debris loading calculations is shown in figure 6. The inner radius of the rotor is "a" and the outer radius is "b". For complete burst of the flywheel, "a" corresponds to the radius of the arbor, whereas for a partial burst, "a" corresponds to the inner radius of the outer ring. The inner radius of the containment is "c" and its thickness is "h". At time $t=0$, the rotor, spinning with an angular velocity ω , is assumed to instantaneously break into a large number of fragments of characteristic size Δm . Each fragment is assumed to travel an unimpeded trajectory "s" until it hits the containment wall.

The containment loading for finely divided debris can be determined by modeling the particles as a continuum rather than as discrete fragments. That is, the particles that originally occupied the rotor annulus between r and $r + \Delta r$ are assumed to impact the containment wall between time t and $t + \Delta t$, where $t=0$ is the time that the rotor disintegrates. The time t at which the particles from radius r reach the wall is related to the radius and the path length s by $s = r\omega t$. Because the particles

Figure 6. Load calculation geometry

traverse a tangential trajectory, the path length is related to the containment radius c and the original particle radius by the relationship

$$s^2 = c^2 - r^2 = r^2 \omega^2 t^2 \quad (1)$$

The first particles to arrive at the wall come from the outside radius $r = b$. The last particles to arrive at the wall come from the inside radius of the rotor $r = a$. The time span over which the impact event occurs ranges from t_0 to t_f , where, from equation (1)

$$t_0 = \frac{\sqrt{c^2 - b^2}}{b\omega} \quad \text{and} \quad t_f = \frac{\sqrt{c^2 - a^2}}{a\omega} \quad (2)$$

The time increment Δt over which the fragments from the flywheel annulus between r and $r + \Delta r$ arrive at the wall can be found by taking the differential of equation (1). In differentiating this equation, allowance is made for the fact that the containment radius is increasing during the impact period by a radial displacement $w(t)$. At any time t the containment radius is given by $c(t) = c_0 + w(t)$, where c_0 is the original radius at $t = 0$. Although w/c_0 is expected to be small, dw/dt can be significant compared to the impact velocity of the fragments. Differentiation of equation (1) gives

$$\frac{\Delta r}{\Delta t} = -\frac{c\omega^2}{[1 + \omega^2 t^2]^{3/2}} + \frac{dw/dt}{[1 + \omega^2 t^2]^{1/2}} \quad (3)$$

The mass of the material Δm that came from the radius between r and $r + \Delta r$ is given by $\Delta m = \rho L r \Delta \theta \Delta r$, where ρ is the

flywheel density and L is the flywheel length. Substituting this result into equation (3) yields the quantity of mass that impacts the wall during time Δt .

The flywheel fragments impact the containment wall at an oblique angle θ^* (fig. 6) which depends on the radius from which they originated. The component of velocity normal to the wall is just $v_{n1} = r\omega \sin \theta^*$, or, from the geometry of figure 6,

$$v_{n1} = \frac{c\omega^2 t}{[1 + \omega^2 t^2]} \quad (4)$$

It is assumed here that the tangential component of the fragment momentum is conserved during impact and the coefficient of restitution for the normal component is equal to zero. The normal velocity v_{n2} of the particles after impact is, therefore, equal to the wall velocity dw/dt . This implies that the debris follows the radial motion of the wall during impact, and is not reflected back toward the axis of the flywheel, potentially doubling the load. The assumption of plastic impact can be justified by the observation that the impact is likely to result in further fragmentation of the debris, and the centrifugal force from the rotational component of the fragment velocity will tend to keep the debris in contact with the wall.

During impact of the fragments with the wall, the radial impulse of the force per unit area, or pressure, P acting on a strip of width $\Delta \theta$ can be found by equating the impulse of the force with the change of momentum of the particles impacting that strip. That is,

$$-Pc\Delta\theta L\Delta t = \Delta m[v_{n2} - v_{n1}] \quad (5)$$

Substituting equations (3) and (4) into equation (5) and solving for the pressure gives

$$P = \frac{\rho c^2 \omega^4 t^2}{[1 + \omega^2 t^2]^3} \left[1 - \frac{dw}{dt} \frac{(1 + \omega^2 t^2)}{c\omega^2 t} \right]^2 \quad (6)$$

for $t_0 \leq t \leq t_f$. The impact loading function given by equation (6) can be used to drive a finite element model of the containment response, or can be combined with a simple ring model of the containment to yield a differential equation that can be solved directly for the radial displacement $w(t)$.

The containment loading model will be applied later in this paper to predict the loading on an experimental burst measurement device (fig. 12 and table 3).

Axial Loading on the End Plates - Experience has shown that a viable containment for composite flywheels must have adequate axial strength to withstand the impact from debris that is deflected axially following impact with the side walls. Unfortunately, little is known about the mechanisms that produce the deflection. Possibilities include

- 1) the development of axial pressure gradients in a fluid-like bed of debris that builds up on the containment wall,

- 2) scattering of fragments at the wall from the impact of incoming fragments, or
- 3) fracture of fragments along oblique planes as they hit the wall, creating a wedge that drives the two pieces toward either end of the containment.

Whatever the cause, equal axial momentum must be directed toward each end plate. An upper bound on this momentum can be found by assuming that the kinetic energy lost during impact with the wall is converted to axial motion of the fragments. Although the conversion efficiency has been assumed here to be 100%, a more realistic value could be determined experimentally, thus avoiding the need to model the complex process of debris deflection. It is further assumed that the debris does not accumulate at the wall, but splits into two streams with the same axial velocity. Since the radial component of the fragment velocity v_{n1} is known from equation (4), and the radial velocity of the fragments and the wall following impact is dw/dt , conservation of energy dictates that the axial velocity v_z of the fragments following impact is $v_z = v_{n1} - dw/dt$. If debris does not accumulate at the wall, it impacts the end plates with the same mass flow rate as it arrives at the wall. This rate is given by equation (3) and the relationship between Δm and Δr . Equating the change in momentum of this mass over time Δt with the axial impulse gives the axial force $F(t)$ on each end plate as

$$F(t) = \frac{1}{2} \frac{dm}{dt} v_z \quad (7)$$

Substitution of the previous results for dm/dt and v_z produces a force on each end plate that is just 1/2 the force exerted on the side wall by $P(t)$. Although the assumptions made here appear to be extreme, it is noted that the model typically yields kinetic energies imparted to the end plates and the axial motion of the debris equal to 3 to 5% of the rotor energy, which is consistent with the estimate from at least one rotor test that produced failure of the lid of the containment vessel [13].

Torque- The calculations given above for the normal loading on the containment wall and the end plates assumed that debris does not accumulate at the wall, but rather is deflected by the wall and the end plates toward the center of the containment where, presumably, much of the remaining energy would be dissipated by collisions between the fragments. If this were the case, the swirling motion of the debris would not exert a significant centrifugal or torsional loading on the containment. Although this picture may be reasonable if the free volume inside the containment is large, it would not be reasonable for the other extreme. Here a debris bed would likely form between the intact portion of the rotor and the wall. An alternative model has therefore been developed to estimate the upper bound for the torsional loading on the containment, recognizing that the model is not consistent with that used to calculate the normal force on the wall and the end plates during initial impact. In calculating the maximum torsional loading, all of the debris is assumed to accumulate next to the wall as it swirls inside of the containment.

Figure 6 can also be used to model the debris bed geometry. Here, each fragment is stopped at the inner radius of the debris bed, instead of reaching the wall. Again, the flywheel is assumed to break up instantaneously. The fragments from the outside of the flywheel impact the wall at the same time t_0 given previously in equation (2). These particles now remain against the wall. Particles from flywheel radius r impact the inner radius $r_2(t)$ of the debris bed at a later time. The inner radius of the debris bed can be found from the conservation of mass and the porosity of the bed γ . Furthermore, the time t at which the particles impact the inner radius is related to their tangential velocity at the time of breakup. The geometric relationships indicated in figure 6 are also valid here if the radius c is replaced by r_2 . In a manner similar to the derivation given previously, these relationships can be used to calculate the rate at which mass is added to the debris bed and the radial and tangential components of the velocity of the fragments as they join the bed. The change in angular momentum of the debris at the wall consists of two components. One is due to the addition of new debris from the disintegrating flywheel, and one is due to the slowing down of the debris from the torsional forces at the wall. Assuming that the layers of the debris bed are locked together by the random packing of the fragments, the common angular velocity of the fragments ω_d and the torque T_p on the containment wall can be calculated by equating the torsional impulse with the change in angular momentum.

The pressure exerted on the containment wall from the centrifugal force of the swirling debris can be calculated by considering the equation of motion of a differential element of the debris. The radial component balances the centrifugal force and the differential pressure on the radial faces of the element. However, unlike an intact flywheel rotor, the debris cannot support a tensile load in the hoop direction. The equation of motion therefore reduces to

$$\frac{d}{dr}(r\sigma_r) = -\rho(1-\gamma)r^2\omega_d^2 \quad (8)$$

Equation (8) can be integrated from the inner radius of the debris bed r_2 to the outer radius c . The pressure at the inside radius is small because the normal velocity of the particles impacting the bed is small. Integration of equation (8) then gives the pressure at the wall N_p as

$$N_p(t) = \rho(1-\gamma)\omega_d^2 \frac{(c^3 - r_2^3)}{3c} \quad (9)$$

The torque on the containment ring T_p is just

$$T_p(t) = 2\pi c^2 L \mu N_p(t) \quad (10)$$

where μ is the coefficient of friction between the fragments and the wall. In general μ has to be determined experimentally. However, if torque is limited by the interlaminar shear strength of the composite fragments (100 to 120 MPa), the effective coefficient of friction could not exceed about 0.3. This is in reasonable agreement with the value of μ (0.36)

needed to match the model results with the torque and spin-down times measured by Steele and Babely [14] during failure of a 0.695 MJ composite rotor.

The torque predicted by equation (10) can be significant and in some applications may be excessive (see predicted torque for a partial rotor burst presented in table 3). For vehicle applications, for example, it is likely that some torque mitigation features must be incorporated into the containment. A discussion of containment concepts which can reduce torque loads is presented later in this paper.

TESTING AND CONTAINMENT DESIGNS

TEST RESULTS - To aid in the design of candidate containment devices, a number of tests will be performed. These include spinning composite flywheels to failure to understand and identify failure modes. Flywheels will also be spun to failure in heavily instrumented burst measurement structures to measure loads. Measuring and understanding flywheel failure loads is key to successful containment designs. Finally, flywheels will be spun to failure in real containment structures to proof test these designs.

Recently, UT-CEM successfully burst a multi-ring, pre-loaded composite flywheel. This flywheel design was an altered operational design. The operational design, which delaminates before bursting, was altered by substituting weakened graphite material in the fabrication of the outer ring.

Main objectives of the spin test were to demonstrate a controlled composite flywheel burst and then to attempt "soft capture" of the flywheel fragments using a Kevlar catch ring. As designed, only the outer flywheel ring failed at burst. An overview of test results are presented in table 2.

The test flywheel stored 5.8 MJ of energy at burst speed and released 1.1 MJ during the burst event. The flywheel prior to testing is shown in figure 7 and is shown again in figure 8 after testing. Other than failure of the outer composite ring as intended, little damage occurred. Damage was limited to surface wear as shown in figure 9.

Table 2. Overview of test results

<ul style="list-style-type: none"> Outer flywheel ring successfully burst at 35,200 rpm (830 m/s) within the predicted burst speed range of 33,400 rpm to 37,600 rpm
<ul style="list-style-type: none"> Outer ring burst did not cause the remaining flywheel rings to fail
<ul style="list-style-type: none"> 57% of the failed ring material was recovered following the test
<ul style="list-style-type: none"> Significant mass of flywheel fragments (80% of the recovered material) was captured by the Kevlar catch ring
<ul style="list-style-type: none"> During multiple low speed runs with dwells and the final run to burst, the flywheel maintained excellent mass balance
<ul style="list-style-type: none"> After outer ring burst at 35,200 rpm and separation from the spindle, the remaining flywheel fell to the bottom of the pit and "spun down". Afterward, inspection of the flywheel showed no damage other than surface wear

S 8301.0079 bw

Figure 7. Composite flywheel prior to burst

S 8301.0096 bw

Figure 8. Composite flywheel after burst

S 8301.0095 bw

Figure 9. Surface detail of composite flywheel after burst

Other flywheel developers have attempted to induce flywheel bursts with mixed results. This test delivered a remarkably clean burst event. Advantages of achieving a successful burst are twofold.

First, bursting a composite flywheel ring clearly establishes both induced and allowable load limits of the composite laminate structure. This correlates analytical tools for designing safe flywheels.

Second, a flywheel design that can be tailored to deliver specific burst energy levels to candidate containment designs presents a valuable tool to assist the DARPA Flywheel Safety Project. Attempts to catch burst fragments are relevant since evaluation of their shape and size may lead to additional insight for improved containment designs.

Flywheel fragments recovered from the Kevlar catch ring varied in size with a high percentage (30%) of significant size. An example of some of the larger flywheel fragments recovered from the catch ring is shown in figure 10.

Figure 10. Captured composite flywheel fragments

UPCOMING TESTS - Upcoming tests include additional flywheel bursts early this year. The bursts will occur inside an instrumented steel burst measurement device with the objective of measuring radial, axial, and torque loads.

While the tests described above will use rings designed to burst at overspeed, another test will use a preloaded flywheel designed to delaminate. The purpose of this test is to explore this failure mechanism and its consequences.

Using the loading estimate model previously described, the burst measurement device is being designed to survive burst testing without permanent deformation, allowing it to be reused for repeated tests; an illustration of the device appears in figure 11. Loading calculations for this device appear in table 3, and a curve for the predicted radial impact loading is shown in figure 12.

The burst measurement device will be instrumented so that loads predicted by the loading estimate model can be verified by experiment. In addition, the device is designed so that energy-absorbing materials can be inserted inside the vessel, allowing testing of some of the concepts presented later in this paper.

Figure 11. Burst measurement device

Figure 12. Predicted radial impact loading

DESIGN CONCEPTS FOR CONTAINMENT - Because of the lack of operating experience and test data with composite flywheels, design of adequate containment presents a formidable challenge to the designer. There is a substantial body of experience dealing with metallic flywheel failures, but as discussed earlier, it is unclear how much of that experience can be applied to composite flywheels. In spite of this fact, a number of containment strategies are emerging as potential approaches to the problem. Each has its own set of advantages and disadvantages and each must undergo intensive testing to prove its suitability as a viable containment strategy. In the following discussion, it is assumed that the containment structure must contain a true flywheel burst, which is thought to present the highest forces and energy levels to the containment structure. In all the design concepts discussed below, the containment will be considered successful and effective if fragments from a burst flywheel are completely contained within the containment structure.

Rigid Pressure Vessel - In this approach, a heavy-walled pressure vessel envelops the flywheel, as illustrated conceptually in figure 13. This is a very direct approach to the problem:

the vessel has sufficient strength to contain burst forces without the use of any dedicated energy absorbing materials, although it is acceptable for the vessel itself to sustain permanent deformation during the burst event. In fact, it is probably desirable for the vessel to deform plastically, absorbing a substantial portion of the flywheel energy in the process. Advantages to this approach include simplicity of design and the possibility of substantial safety margins. Disadvantages include difficulties in limiting torque loads on the mounting system and high containment system weight.

Table 3. Burst measurement device load conditions

Load conditions for a flywheel outer ring burst at 35,000 rpm inside burst measurement device

Rotor Information:		
Outer Ring Outer Diameter	0.445 m	17.5 in.
Outer Ring Inner Diameter	0.414 m	16.3 in.
Length	0.127 m	5 in.
Speed at Burst	35,000 rpm	35,000 rpm
Mass	4.46 kg	9.84 lb
Tip Speed	815 m/s	2660 ft/s
Stored Kinetic Energy in Outer Ring	1.38 MJ	1.02×10 ⁶ ft-lb
Measurement Device Shroud Ring Information:		
Radial Thickness	0.051 m	2 in.
Inner Diameter	0.521 m	20.5 in.
Material	4340 Steel	4340 Steel
Predicted Measurement Device Loads:		
Radial Impact Load Duration	42 μs	42 μs
Max. Radial Impact Pressure	225 MPa	32,600 psi
Max. End Force	2.33×10 ⁷ N	5.24×10 ⁶ lb
Approx. Max. Hoop Stress in Shroud Ring	883 MPa	128,000 psi
Shroud Ring Max. Radial Displacement	1.12 mm	0.044 in.
Shroud Ring Max. Strain	0.4%	0.4%
Shroud Ring Max. Torque	1.00×10 ⁶ N-m	7.39×10 ⁵ ft-lb

Rotating Liner - The strategy incorporated in this design approach reduces the torque that must be transmitted from the flywheel battery to its mounting system (fig. 14). A rotatable liner inside the containment vessel is impacted by the swirling debris from a rotor burst, absorbing debris rotational energy. The overall effect of the liner rotation is that tangential loading forces acting on the containment are spread over a longer period, thus reducing the maximum torque loads on the containment vessel. In addition, a liner braking mechanism is provided to impart a braking torque to the rotating ring, limiting its maximum angular velocity and dissipating rotational energy. The primary advantage to this approach is that the torque capacity required in the FESS mounting system is reduced. This is achieved at the cost of increased containment system complexity.

Energy Absorbing Liner - This approach includes an energy-absorbing material within the containment, designed to absorb a substantial portion of the debris kinetic energy (fig. 15). As presently conceived, the energy-absorbing material would be located inside a rigid backup structure. Since the maximum loads acting on the containment are reduced by the absorbing material, the outer structure can be lighter than that required for the rigid pressure vessel concept.

Combination of Approaches - It is also possible to combine the approaches listed above into a single containment device. For example, an energy-absorbing liner could also be allowed to rotate, reducing torque loading. For application in the transportation industry where containment size and weight are primary concerns, a combination of approaches may be the most likely solution to providing adequate containment.

Figure 13. Rigid containment structure

Figure 14. Containment with rotating liner

Figure 15. Containment with energy-absorbing liner

SUMMARY

- FESSs are being developed for power averaging applications in the transportation industry.
- A potential for flywheel bursts exists with FESSs that incorporate composite flywheels.
- Failure mechanisms of composite flywheels historically have been poorly understood due to lack of operating experience and experimental data. Test programs are underway which are improving the understanding of these systems.
- Failure modes of composite flywheels are design and material dependent; some designs may prove to fail in a benign manner.
- In the near-term, FESSs using highly stressed composite flywheels should incorporate containment as protection against flywheel bursts.
- A DARPA-sponsored containment development program brings together prominent flywheel developers in an effort to identify a methodology for safe composite flywheel and containment design.
- A theoretical model has been developed to predict containment loads during burst conditions; a testing program has begun to confirm the theoretical predictions.
- In the long-term, operating experience may show that composite flywheels can be designed to fail in a benign manner, so that containment is unnecessary. Alternatively, a better understanding of flywheel failure behavior may lead to lightweight containment designs that take advantage of energy-absorbing features.

ACKNOWLEDGMENTS

The authors wish to thank Robert Rosenfeld of DARPA and Alan J. Sailer of Houston Metro for their support of this work. In addition, we wish to thank Lori Moore, Daniel Gleesing, and Roy Pena of UT-CEM for their assistance in the publication of this paper.

REFERENCES

- [1] Reiner, G., "Current State in the Application of Magnetodynamic (Flywheel) Storage Systems in Urban Transport Buses," presented at Flywheel Energy Storage Technology Workshop, Oak Ridge, Tenn., November 1995.
- [2] Drawe, J., Bluebird Body Company, Fort Valley, GA, personal communication, December 1996.
- [3] Reiner, G., et. al., "Experiences with the Magnetodynamic (Flywheel) Storage System (MDS) in Diesel Electric and Trolley Busses in Public Transport Service", presented at Flywheel Energy Storage Technology Workshop, Oak Ridge Tenn., Nov. 1993.
- [4] Carey, J. "Where's the Juice?", Business Week, pg. 110, May 30, 1994.
- [5] Tsai, Tom and Price, John, "Advanced Non-Electric Propulsion System for High Speed Rail," 1995 International Mechanical Engineering Congress and Exposition, San Francisco, CA, November 1995.
- [6] Stull, S. and Post, R.F., "A New Look at an Old Idea" Science and Technology Review, pp.12-19, April 1996.
- [7] "Spin Test Tragedy" Performance Materials, pp1-3, Volume 11, Number 4, Nov. 20, 1995.
- [8] Rabenhorst, D.W. and Small, T.R., "Spin Test of the University of California Lawrence Livermore Composite Flywheel at the Applied Physics Laboratory of the Johns Hopkins University", UCRL 13910, pp 1-14, July 18, 1978.
- [9] Coppa, A.P., "Composite Flywheel Containment Housing Design and Testing", Section V, pp 1-12, UCRL 15448-Vol.2, DE85 001042.
- [10] Kass, M.D. et al, "Evaluation of Demo 1C Composite Flywheel Rotor Burst Test and Containment Design" pp. 14-20, Oak Ridge National Laboratory TM-1315, March, 1996.
- [11] "Project Summary of Flywheel Testing and Evaluation," R.S. Steele, Oak Ridge National Laboratory, CONF-820827--7, 1982.
- [12] Coppa, A. P., Flywheel Containment and Safety Considerations, Proceedings of the NASA Flywheel Inertial Energy Storage Workshop, NASA Conference Publication 2346, pp. 243-253, Huntsville, Alabama, Feb. 7-9, 1984.
- [13] Sonnichsen, H. E., Ensuring Spin Test Safety, Mechanical Engineering, Vol. 115, pp. 72-77, American Society of Mechanical Engineers, New York, December, 1993.
- [14] Steele, R. S., Jr., and E. F. Babelay, Data Analysis Techniques Used at the Oak Ridge Y-12 Plant Flywheel Evaluation Laboratory, Proceedings of the 1980 Flywheel Technology Symposium, pp. 423-433, CONF-801022, Scottsdale, Arizona, 1980.