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Recommended Practices for the Safe Design and Operation of Flywheels

Donald Bender

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Donald Bender
System Quality Engineering
Sandia National Laboratories
P.O. Box 969, MS9154
Livermore, California 94550

Abstract

Flywheel energy storage systems are in use globally in increasing numbers. No codes pertaining specifically to flywheel energy storage exist. A number of industrial incidents have occurred. This protocol recommends a technical basis for safe flywheel design and operation for consideration by flywheel developers, users of flywheel systems and standards setting organizations.

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NOMENCLATURE

kWh	kilowatt hour
MJ	megajoule

1. PURPOSE

This protocol is intended to establish design criteria and test procedures applicable to mechanical energy storage systems for the purpose of verifying and documenting the safety of these systems.

2. SCOPE

This protocol pertains to mechanical energy storage systems and their component parts as singular products or components of such systems intended to be assembled on site to comprise a mechanical energy storage system. This protocol specifically addresses rotary systems commonly known as flywheels storing more than 1 MJ of kinetic energy and operating with a maximum operating tip speed exceeding 200 m/s.

3. FOREWORD

3.1. Introduction

Flywheels are highly versatile power management systems. Since the 1980's, electrically connected flywheel energy storage systems have been deployed in a range of industrial and commercial applications. Many of these systems store appreciable energy and present potential hazards. As a precondition to operation, safety of the system must be assured. This is accomplished by developing a plan for safety and demonstrating conformance with this plan. As codes and standards have yet to be developed expressly for flywheels, flywheel developers often derive safety criteria arbitrarily, usually from first principals. This approach is weak as the unique failure modes of flywheels systems are not predictable from first principles and tend to be discovered during the operation of full-scale machines.

This protocol proposes the technical basis for safe flywheel design and operation. The document itself is not a standard nor does it warrant the performance or safety of any particular flywheel system. Rather, it is intended to communicate a rationale for consideration by the reader. The scope is limited to consideration of safety of the rotating machine. Other aspects (electrical, materials hazards, etc.) are considered only to the extent that these attributes affect safe operation of the rotating machine. Otherwise, they are beyond the scope of this protocol.

A flywheel system comprises a number of highly interdependent elements (rotor, motor/generator, bearings, and power electronics) where the interaction between one subsystem and another can effect the hazard associated with the entire system. Safety criteria presented here address the relationships between subsystems and the potential for cascading failures.

Flywheels used as power management systems are not unlike a wide variety of machines operating with the potential for hazard. Excellent, comprehensive safety standards are in global use for systems with the potential for a sudden mechanical failure or release of energy, such as pressure vessels. Where appropriate and relevant, criteria for flywheel safety are drawn from standards for structures using similar materials and presenting comparable hazards.

In order to be meaningful to a wide range of flywheel users and developers, the criteria must have the following characteristics:

- Applicability to a complete flywheel system.
- Verifiable through system testing.
- Design independent - applicable to systems of significantly different configuration.
- Traceable to relevant standards.

Throughout, speed is expressed in terms of the velocity of the outer surface of the rotor. For all rotor configurations, stress scales with the square of surface velocity. Therefore surface velocity is a more relevant metric than rotation rate. The scope of this protocol is limited to machines operating at high speed (>200 m/s) with corresponding high stress. While this methodology could also be applied to low speed rotors operating in an ambient environment, these machines tend to operate at much lower stress levels and are beyond the scope of this protocol.

3.2. Background

Standalone flywheel systems have been developed expressly for energy storage. These systems are differentiated from the automotive engine flywheel by being housed in an evacuated enclosure to reduce aerodynamic drag, being charged and discharged electrically, and by storing far more energy. Standalone flywheels are found in a variety of applications ranging from grid-connected energy management to electromagnetic aircraft launch. Stored energy ranges from a fraction of a kWh to hundreds of kWh. The prevalent rotor configurations comprise steel disks, solid steel cylinders, and thick-walled hollow cylinders made from carbon and glass composite or high strength steel [1].

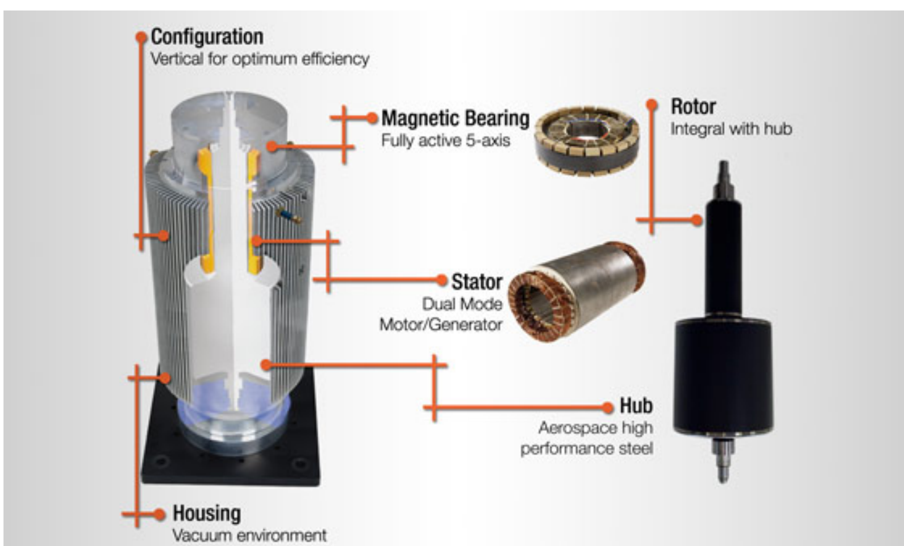

Figure 1. Elements of a Modern Flywheel (courtesy Calnetix Technologies LLC) [1]

3.3. Noteworthy Flywheel Failures

Flywheels have represented a potential hazard since the large steam engines of the industrial era. Engines of that time employed flywheels as large as 30 feet in diameter weighing as much as fifty tons. While massive, the rotors ran at a surface speed of 20 m/s [2] which is low by modern standards. Consequently, since kinetic energy scales with the square of speed, a 50 ton flywheel from the industrial age would store just 5 kWh. Flywheel bursts were fairly common, often due to overspeed caused by failure of a governor [3]. Even releasing just 5 kWh or less of kinetic energy, these flywheel failures could and did result in the destruction of the buildings in which they were housed [4].

In 1995, the intentional failure of a flywheel rotor during spin testing resulted in the death of one of the test operators. The test chamber lid was not bolted onto the test chamber and operators were in the same room with the test chamber. Large axial loads resulting from the failure of the composite rotor forced the lid open and ejected rotor material from the containment vessel at high speed. The test was conducted in Europe. The unit under test stored less than 1 kWh [5].

In 2003, a system comprising 10 flywheel modules was operated at a metro-rail line to demonstrate voltage regulation and energy recovery. Each module housed a carbon and glass composite rotor weighing approximately 200 lb and storing 3 kWh. A vacuum system failure cascaded into a rotor crash causing rapid deceleration of one rotor. The large, chaotic loads transmitted to the foundation during this event caused the remaining rotors to crash as well. The flywheel housings remained intact [6].

In 2011, two incidents occurred at a flywheel energy storage facility. In each incident, a 1 ton carbon and glass composite rotor storing approximately 30 kWh crashed but stayed substantially intact. The machines were installed below grade and the incidents, while dramatic, resulted in the release of a small volume of abraded composite material and posed relatively little hazard to personnel or nearby equipment [7].

In 2014 a steel flywheel rotor operating in a spin testing environment experienced a failure of the suspension system. The rotor continued to spin ‘like a top’ on a stub shaft until friction heating of the stub shaft led to heating of the rotor, annealing it, causing the rotor to burst. Because the event occurred in a test environment designed for this purpose, no hazard was created [8].

In 2015, a steel flywheel rotor storing approximately 100 kWh [9] and weighing more than five tons was installed in a test cell below grade when it experienced an event. The event was described as a loud explosion that shook the ground throughout and around the building in which the flywheel was located [10]. The incident resulted in severe damage to the building and injury to five people requiring hospitalization [11]. Material from the walls and earth of the test cell surrounding the flywheel were pulverized, effectively liquefying, and ejected through the roof of the building.

3.4. The Nature of Flywheel Failure

Potential flywheel failure mechanisms depend a great deal on the configuration of the rotor and the materials used. Structural failure of the rotor is the most serious potential hazard. A structural failure of the rotor where the rotor disassembles into projectiles with significant kinetic energy is referred to as a *burst*. In theory, steel rotors are susceptible to a tri-hub burst where the rotor fails catastrophically by breaking into three pieces [12]. In reality, steel rotor failures are far more complex [13].

Composite rims are far less susceptible to this failure mechanism but they do have the potential to transfer destructive amounts of kinetic energy into the housing or surroundings. Containments of a rotor burst have been explored and tested but due to the substantial, oriented but multi-directional energy released in a flywheel failure, successful containment requires a structure many times more massive than the rotor itself [14]. The incorporation of adequate containment would multiply the weight and cost of the flywheel system defeating the objective of providing cost effective energy storage. Analogously, Federal Aviation Regulations recognize the impracticality of containing a turbine disk burst [15].

The energy released during a flywheel failure is highly directed. A steel rotor burst produces energetic projectiles travelling in a radial plane. Similarly, a loose rotor can engage a housing, produce an angular impulse that rips it from its foundation, and spin the housing, causing it to fail through centrifugal forces. This debris also travels in a radial plane. When the energetic fragments encounter resistance, such as the wall of a test cell or containment structure, the debris is redirected in an axial direction. Large axially loads have produced hazardous conditions, injury and at least one fatality in both test and operational environments. Even though this phenomena has been understood for decades [16], the presence of large axial loads in rotating machinery failure continues to surprise inexperienced designers as it did in the 2015 incident.

4. FOUNDATIONAL SAFETY CRITERIA

This protocol takes the position that because it is impractical to contain a flywheel rotor burst, flywheel rotors must be designed as safety critical or life critical components to avoid burst in service over the life of the system. Accordingly, flywheel safety has two main thrusts:

1. Qualification of the flywheel rotor design to assure that the rotor will be free from structural failure under all conditions over the life of the system.

2. Assuring physical and operational safety when the flywheel system experiences off-normal conditions, faults and other upset events. The principal aspect of assuring physical and operational safety involves assuring containment of a loose but largely intact rotor as would occur in the event of a bearing, hub or shaft failure

5. DESIGN MARGIN

Here the term *design margin* is narrowly defined as the ratio of stress at failure under test conditions to maximum allowable stress in normal operation. The term *safety factor* is often used interchangeably but for the sake of clarity only *design margin* is used here. Consistent with a systemic approach, the notion of design margin applies to the complete, full-scale flywheel rotor rather than to a material, structural element, or small scale test article. In determining the design margin it is presupposed that the top speed that can be attained by a rotating assembly is limited by mechanical failure of the rotor, that mechanical failure is attributable to stress in the rotor, and that stress scales with the square of rotation rate. No other assumption is made as to the nature of the stress, whether it is associated with radial stress in a solid steel rotor, hoop tensile or interlaminar shear stress in a hollow composite cylinder, etc.

5.1. Design Margin Based on Relevant Accepted Criteria

Accepted standards for equipment with characteristics similar to flywheels may be used to establish recommended design margins for flywheel rotors. In one example, military specifications provide detailed guidelines for establishing such margins for composites [17]. Through the rigorous application of standards like these it is possible to establish a design margin of 1.25 as has been done for some aerospace and spacecraft applications [18].

This process requires substantial materials property and process validation and yields a design margin that may be highly specific to a particular rotor configuration and method of construction. Here it is proposed that design margin for flywheel rotors be drawn from standards for other industrial equipment where the equipment presents a potential prompt lethal hazard. Pressure vessels share this trait with flywheels and have been the subject of the development of extensive codes and standards. Many of the elements captured in these standards are directly applicable to flywheels.

Two elements are particularly relevant:

- Allowable stress.
- Qualification and proof test[1] margins.

ASME pressure vessel code contains extensive information on the allowable stress for a range of materials as well as various design practices and qualification procedures [19]. For steel rotors with dimensions consistent with pressure vessel design, much of this information could be applied directly.

However, thick steel rotors intended for operation at very high speed (>400 m/s) must address an additional engineering challenge. In order to operate at such high speed, exceptionally high strength steel is required. The strength required for these rotors is attained through forging.

[1] ASME applies the term 'proof test' both to tests that qualify the design as well as other tests used for product acceptance. In this protocol, the term 'qualification test' is used for design qualification and 'proof test' is used for product acceptance.

Forging is a process through which metal is deformed plastically under extremely high pressure to reorient the grain structure of the metal thereby improving its strength, typically involving the application of high temperature as well. The process is performed using massive hammers, presses and rollers and is broadly used in the production of high strength plates, fittings, rings and engine components. The influence of forging on material properties decreases with thickness and forged steel parts thicker than several inches are relatively uncommon. This presents a concern for large forged steel flywheel rotors since the highest stress in a solid steel flywheel rotor occurs along the centerline. Material properties on the centerline are critical yet difficult to control and impossible to inspect in the finished part. Parts that are sufficiently thick fall outside ASME pressure vessel guidelines for allowable stress.

Composites are engineered materials in the sense that the constitutive properties of the composite are created when the part is manufactured. The stiffness matrix of thick composites can be quite complex and will be dependent on design. Consequently, pressure vessel codes offer limited guidance for allowable strength of thick composite flywheel rotors.

Various codes do offer useful guidance for design margin. Various standards and practices for related structures support design margins in the range of 2.0 to 2.4. For example, certain NHTSA standards for hydrostatic testing of a CNG fuel container using carbon composites call for a ratio of burst pressure to service pressure of 2.25 [20]. ASME Pressure vessel code calls for similar margins when qualification testing [21] in order to qualify the design.

The minimum qualification test pressure needed to qualify a pressure vessel design is 2x the maximum service pressure. Here it is proposed that flywheel developers adopt the same margin for the qualification of a flywheel design. Because stress in a flywheel rotor scales simply with speed squared, this implies that a flywheel operated at 70% or less of design qualification test speed would have a design margin of 2.

Thick filament wound composite rims and thick forged steel disks or cylinders share the trait that material properties are inherently more difficult to understand and control than for thin windings or forged plates, respectively. For this reason, coupon tests or sub-scale component tests should not be regarded as sound evidence for the qualification of design margin for a full-scale rotor.

5.2. Design Margin Qualification Test

The design margin of a rotor must be verified through a design margin qualification test. The test would involve accelerating the rotor to a maximum speed at which the rotor would either remain intact or fail. Subsequent production rotors would be operated at no greater than 70% of the speed attained in the qualification test irrespective of whether the rotor failed or not. The equipment used for rotor design margin qualification testing may also be used to explore low cycle fatigue, rotordynamic behavior, and other properties of interest to the flywheel developer.

Here, a design margin qualification test is proposed with the following elements:

1. The test article must be substantially similar to deployed articles per Section 6 below outlining criteria for homology.

2. The test may be conducted in a dedicated spin test facility.

3. The test article should be a new rotor and it must meet the manufacturer's quality assurance requirements for a production unit.

4. The rotor should be cycled several times within the nominal operating speed range in order to assess stability of the balance and allow for rebalancing, if necessary. The rotor should then be accelerated to the maximum speed of the test.

5. Three such tests should be performed with substantially identical rotors.

6. If maximum speed results in mechanical failure, failure speed should be repeatable to within ±3% of the average failure speed for a minimum of three tests.

6. PHYSICAL AND OPERATIONAL SAFETY

Assuring physical and operational safety is defined as providing protection so that neither subsystem failure nor external insult can create a burst or other hazard through their potential effect on the rotor.

6.1. Assure Restraint of Loose Rotor

An important class of flywheel system hazard is the occurrence of an unsupported rotor within the housing. Depending on the specific configuration of the system, this may be due to ball bearing failure, magnetic bearing failure, failure of a shaft or failure of a hub. This condition is referred to here as a loose rotor event. The hazard associated with this condition arises from the possibility of high speed rubbing between the outside of the flywheel and the inside of the enclosure. This type of contact couples energy from the spin axis into whirl modes resulting in large loads and destructive forces. These loads can lead to the transfer of extremely high torque from the housing to the foundation and failure of the housing itself.

The maximum possible torque can be estimated from a consideration of past crash events. The most rapid deceleration of a flywheel rotor from full speed to a stop due to whirl from a rotor crash appears to be on the order of several seconds. Therefore, it is reasonable to design the housing and the mount to be able to withstand torque sufficient to stop the rotor in several seconds.

The flywheel system should have design features to assure that a loose rotor condition does not create a hazard to the surroundings. Here it is proposed that these features be passive and not rely on the detection of and active response to a loose rotor event.

6.1.1. Bushing/bearing restraint of spindle

An effective method for preventing high speed rub of the rotor during a loose rotor event is to apply a physical restraint to the flywheel spindle, if the configuration includes a spindle, or to the interior of the rotor if the rotor is annular and does not have a spindle. In the case of a spindle, the restraint would be a bushing or bearing. For instance, backup touchdown ball bearings are almost always used in conjunction with active magnetic bearings. In the case of a hollow cylindrical rotor without a spindle, this structure could be a stationary post.

In either case, the restraint should have the property that at operating speed, clearance all around between the rotating assembly and the restraint is smaller than the clearance between the rotating assembly and the enclosure. Management of these clearances should take into consideration compliance of the bearings and the bearing foundations, dilation of the rotor at its maximum operating speed, etc.

The restraint must control rotor movement in such a way that further degradation to the rotor is avoided. For instance, restraining a rotor with a spindle in a bushing can result in substantial heating of the spindle. In at least one instance, this has been shown to compromise rotor strength resulting in rotor failure. Consequently, restraint of a loose rotor should be implemented in conjunction with a method of braking the rotor to protect against this failure scenario.

6.1.2. Demonstrate with Drop at Full Speed

It is proposed that in order to qualify the design as safe, the adequacy of a rotor restraint be demonstrated by inducing a loose rotor event at the full rated speed of the rotor. This test should be done in a test environment specifically designed to avoid hazard in the event of a mechanical failure of the rotor. Rules for homology between test articles and deployed articles must apply.

6.2. Withstand Externally Applied Loads

Externally applied loads may cause a loose rotor event or a rub by causing bearing failure or large rotor excursion. For both stationary and mobile systems, it is necessary to demonstrate that reasonably expected externally applied loads do not create a hazard.

Demonstration of the ability to withstand external load would be done through testing during which the flywheel is subjected to an appropriate set of external loads while operating at maximum normal operating speed. This is a safety test rather than a performance test. The outcome of the test is considered successful if the rotor is restrained either by its bearing system or by a loose rotor restraint.

For systems with defined external load requirements such as MIL–STDs for shock and vibration, specified crashworthiness requirements, or specified seismic loading, the flywheel should be subjected to the loads defined in the specification while operating at full rated speed. This can be accomplished using a variety of means including but not limited to shaker tables, drop tests, unmanned mule vehicle tests, and operation in an off normal orientation such as with a horizontal axis or with the rotor inverted.

6.3. Protection Against Overspeed

The flywheel systems of the class considered here will almost invariably be accelerated to operating speed and controlled with DSP or microprocessor based power electronics systems dedicated to this purpose. It is necessary to assure that the Flywheel System has inherent features that will prevent the occurrence of overspeed. Since the manner in which overspeed may be prevented is specific to a power electronics design, no specific design approach is identified or advocated here.

It is proposed that prevention of overspeed be predicated on two key principles.

1. The method of prevention should defeat any deliberate attempt to overspeed the flywheel.

2. The flywheel developer must produce a safety plan for the motor drive identifying the means through which overspeed is prevented and a test procedure to demonstrate this capability.

Testing should demonstrate the ability of the method of protection to prevent overspeed under at least two conditions: 1) the deliberate setting of software parameters in order to allow for overspeed, and 2) the deliberate overvoltage of the DC bus which would provide additional motive force to overcome back EMF of the flywheel.

7. SYSTEM FAULT TOLERANCE

A number of system faults have the potential to put the flywheel rotor at risk. These include:

- Loss of vacuum
- Loss of coolant (for liquid cooled systems)
- Loss of DSP/microprocessor control voltage for power electronics
- Loss of DSP/microprocessor control voltage for magnetic bearings
- An electrical short which could cause overcurrent in the flywheel stator
- Loss of control signals (e.g. phase angle, bearing temperature, etc.)

It is necessary to demonstrate that the occurrence of any or all of these system faults will not adversely impact the safety of the flywheel system. This can be done by deliberately creating fault conditions while the flywheel system is operating at full rated speed. This test should also be done in a test environment specifically designed to avoid hazard in the event of a mechanical failure of the rotor.

8. HOMOLOGY OF TEST ARTICLE WITH RESPECT TO PRODUCT

The preceding sections are based on testing dedicated test articles and using the results of these tests to qualify a design. In order to assure validity of these tests, it is necessary for the test article to be equivalent to deployed articles within a defined tolerance.

A set of controls is proposed to assure correspondence between the test article and deployed equipment. These controls focus on the flywheel rotor. Similar controls should also required for the remaining mechanical and electrical elements of the flywheel system as the performance of these elements may influence the hazard associated with the rotor.

1. *Same material*: The source and specification of carbon, glass, matrix material or metal should not be varied.

2. *Same design*: Rotor design should not vary.

3. *Same manufacturer*: Deployed rotors should be produced by the same manufacturer under the same process controls as the test rotors.

4. *Same product quality control*: Inspections, tolerances, and acceptance criteria used for the test rotors should also be applied to the deployed rotors.

5. *Allowance for spin pit testing*. For rotors storing less than 2 kWh, some tests are most effectively or economically accomplished using a dedicated spin test facility. The method of suspension of the rotor will be different (quill shaft) from that of a deployed system (bearings). Tests performed in a dedicated spin test facility must take this into account and be conducted in such a way as to minimize the influence that rotor suspension may have on the tests conducted in this way.

It is proposed that any deviation from these controls should necessitate a series of tests comprising design margin qualification tests, rotor drop tests, external load tests, and system fault tests.

9. PRODUCT ACCEPTANCE SAFETY TESTING

Some form of product acceptance testing should be conducted for each deployed flywheel unit.

9.1. Rotor Proof Test

Here it is proposed that rotor proof testing be conducted for every production rotor using stress levels derived from the standard hydrostatic test for pressure vessels. The 2013 ASME Boiler & Pressure Vessel Code, UG-99 Standard Hydrostatic Test, calls for testing every pressure vessel to 1.3 times the maximum allowable stress [22]. Applying this rationale to flywheels and recalling the square law relationship between stress and speed would suggest that every flywheel be operated at 114% of its maximum normal operating speed.

9.2. System Fault

If the flywheel system uses automatic self protection, such as self discharge to a dump resistor, etc., it is proposed that automatic self protection be demonstrated for each unit by applying sensor inputs that would simulate the detection of fault conditions.

10. DOCUMENTATION

Qualification and proof testing must be performed according to a technical plan and must be documented. In the absence of commonly accepted standards for flywheel system safety it is proposed that the technical basis for system flywheel system safety and the responsibility for risk and liability be determined through an agreement between the flywheel developer and the informed flywheel system user. This agreement may take the form of a purchase order, lease agreement, or other instrument involving the flywheel developer and the user.

11. SUMMARY

Table 1. Design Qualification Safety Objectives and Tests

	Characteristic	Goal	Method
1.	Design margin	2.0 with respect to stress at maximum operating speed.	Design qualification spin test(s)
2.	Loose rotor restraint	No hazard created outside of flywheel enclosure.	Drop test(s)
3.	Withstand external load	No hazard created outside of flywheel enclosure.	Performance testing under dynamic load an other environmental factors.
4.	Protection against overspeed	Demonstrate speed control with incorrect speed setpoint and excessive DC bus voltage.	Overspeed prevention safety test
5.	Fault tolerance	No hazard created outside of flywheel enclosure.	System fault tests

Table 2. Product Acceptance Safety Objectives and Tests

	Characteristic	Goal	Method
1.	Rotor proof test	No defects or unbalance.	Proof test to 114% of maximum normal operating speed.
2.	Fault tolerance	Proper operation of safety systems.	Demonstrate response to simulated faults

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