ABSTRACT
There is a growing need for light and compact power generation in mobile and space-constrained platforms. The transient load profiles typical for advanced weapons demand energy storage that can be charged and discharged quickly and fail benignly. A composite flywheel-based electromechanical battery (EMB) operating at high-speed provides compact and lightweight energy storage and minimal degradation over a large cycle life without the hazards associated with a battery or capacitor failure. Moreover, it can be designed with a generator capable of rapid recharging, as the charge rate is governed by mechanical inertia rather than electrochemistry.

A topology that shows promise is an arbor-based EMB with an integral PM motor/generator for rapid recharging. An inside-out PM motor/generator allows the magnets to be structurally supported at the inner diameter of the rotating arbor/flywheel with an interior stator winding. The arbor connects the high-strain flywheel rim and a low-strain rotor hub while providing structural stiffness and torque transmission. A composite arbor enables a lightweight structure that can operate at top speeds several times higher than metals with material properties engineered to strain match the flywheel rim. The higher speed is important because the stored energy scales linearly with mass but with the square of velocity. So small high-speed rotating machines can have high power and energy density.

Even with the potential benefits, the technology is not commonplace because of two technical challenges. One is composite arbor development and the other is removal of rotor heat due to windage and magnet losses. An EMB concept with an integral PM motor/generator will be presented, which addresses these issues in the 100 kW power range and can store tens of MJ. Utilizing a composite arbor design validated by spin test saves significant development time and cost, and active rotor cooling enables a significant increase in performance.

Keywords—permanent magnet motor generator, composites; rotating machines; safety

INTRODUCTION
The electrification of the battle space increases the demand for power generation and energy storage that is power and energy dense. This is true for mobile applications, forward operating bases, and space constrained platforms like planes and ships. In a warship, there can be a diverse mixture of both large steady-state and transient loads that require power and energy solutions that are flexible and multi-mode. Advanced rotating machines are capable of supporting large transient loads and rapidly transitioning from absorbing power to supplying power [1], [2]. Rotating machines also feature high cycle life, known state of charge, and can be designed to pass thru a 26-inch hatch.

In many ways, rotating machines are a mature technology. However, to make them smaller, lighter, and more versatile requires changes in the materials used. Emerging carbon composites, including those augmented by advances in nanotechnology, are an enabling technology for a significant upgrade in rotating machine performance. Equally important are the design and manufacturing processes that allow components to be produced affordably and reliably with unique geometries. So, emerging technologies provide a path for significant improvement in size and weight for well validated topologies.

The use and utility of carbon composites in rotating machines is based on their high strength-to-weight ratio. The vast majority of composite structures used today are simple concentric rings that provide inertia at high speed and/or retention of other mechanical components, but the use is spreading to more novel geometries. Composite arbors, for example, improve energy density by reducing mass and enabling higher speed operation. Arbors provide the mechanical connection between the rotor...
shaft and rotor rim, transient torque capability, and dynamic stability. In addition to their ability to operate in regimes that conventional materials cannot, composite arbors can be engineered to match the mechanical performance characteristics of the rotor rim. Composite arbors, as shown in Figure 1, have been designed and manufactured for operation in an advanced rotating machine and can be adapted for use in a range of machine types including advanced motor/generators, alternators, and flywheels.

Figure 1: Composite arbors for a high-speed rotating machine have been designed, manufactured and tested.

Often, rotating machines require power and cooling connections at the rotor rim. This means that in addition to the primary mechanical requirements, the composite arbor must also support hardware for connection of power and cooling circuits.

An obvious guiding principle is that safety cannot be reduced to enhance performance. Simple composite cylinders have been widely used in rotating machines, but the use of novel composite geometries including arbors in high speed rotating machines is less widespread. So, significant development has been focused on understanding composite mechanical properties and how to design composite rotors safely, confirming manufactured components match prediction, and ensuring failure modes are understood and appropriate containment is included. This technology is sufficiently mature that it has been incorporated in a voluntary standard: ANSI/AIAA Standard S-096-2004.

This paper focuses on two key advances in rotating machine topology for directed energy applications. The first is the development of the PM motor generator and power electronics for a compact power supply for directed energy. The second is the design and test of a composite arbor suitable for this system and capable of supporting active cooling of the rotor rim. In addition, the standard approach for designing safe, high speed motors or generators incorporating carbon composite components to reduce weight and volume is summarized.

PM MOTOR GENERATOR
Permanent magnet motor generators (PM M/G) are not new. Many such machines have been designed, built, and tested. However, their use in high speed machines is less common. One trade study suggests the PM M/G is best suited for reducing system weight at lower power levels (< 8 MW) and high speed (> 10,000 rpm) [3]. Designs with rotating magnets eliminate the need for brushes, but restraining the magnets at high speed can be challenging.

One concept for a high speed PM M/G under development is shown in Figure 2. In this topology, a rotating magnet array is supported inside an energy storage flywheel. The chosen magnet configuration is a Halbach array, which eliminates the need for back-iron and consequently reduces the dead weight loading on the flywheel. The carbon graphite composite materials within the flywheel are ideally suited to support the mass loading of the magnets. In addition to supporting the mass loading, the structure must limit and constrain any chipping of magnets that occurs during operation. The armature winding and stator laminations reside inside of the flywheel.

Figure 2: An arbor flywheel-based electromechanical battery (EMB) can provide 100s of kW of lightweight power and tens of MW of stored energy.

This type of machine shares many engineering challenges similar to other high-speed electrical
machines. Bearing selection is critical and depends largely upon shock and vibration requirements. The use of ceramic rolling element bearings are the most straightforward to incorporate but can be limited in life, shock tolerance, and acceleration rates. Non-contact bearings including magnetic and compliant foil bearings may be required for higher shock tolerance and load capacity. Magnetic bearings require additional power electronics and controls. Foil bearings must operate at a slightly higher ambient pressure, which can increase windage heating of the composite flywheel. Shaft seals may be required to limit windage.

Thermal losses are an important consideration in high-speed rotating machine design. For the inside-out PM M/G, sources of loss in the stator include resistive and eddy current heating in the stator windings, and core losses in the stator laminations. These are usually addressed by forced active cooling near or within the stator slots. Core losses in the stator are a function of the electrical frequency and magnetic field strength. Losses within the rotor are more challenging because active cooling is more difficult with high-speed rotation. The sources of thermal loss within the rotor are magnet losses and windage heating on the flywheel outer surface. Temperature increases within the magnets must be well-understood as they can effect magnetic performance and lead to demagnetization. As a result, active cooling of the rotor is likely required.

The majority of high speed flywheels utilize an arbor to connect to the rotor shaft with an arbor. The design and manufacturing of the arbor is challenging because it must connect a high strain flywheel rim to a low strain metal shaft. Arbors constructed with conventional metals, such as steel and titanium, are limited in tip speed due to high stresses and cyclic fatigue associated with operation at high speed. Utilizing a composite arbor significantly reduces weight, and enables a rotor stored specific energy for this topology of nearly 100 Wh/kg. However, the design and manufacture of a composite arbor is not as routine as it is for a metal arbor. Fortunately, this is a challenge that has been overcome, and design tools and appropriate manufacturing processes are available.

One such composite arbor was developed for an EM Gun application and demonstrated with hundreds of cycles at an operating speed of 15,000 rpm. The design was further challenged by the need for an additional arbor capable of supporting mechanical hardware for power and cooling connections to the rotor rim. As a result, a second composite arbor design was developed with additional reinforcing layers. The reinforced arbor had the same inner profile and rim growth matching characteristics as the first arbor, but included additional winding layers to support mass loading of the mechanical hardware. The reinforced version of this arbor, including hardware for active cooling of the rotor, is shown in Figure 3.

![Figure 3: Reinforced composite arbor supporting hardware for active cooling of the arbor rim.](image)

Utilizing a validated composite arbor design saves development time and cost, and active rotor cooling enables an increase in performance, but its suitability ultimately depends on performance requirements for the system.

**POWER ELECTRONICS**

Directed energy applications often require very tight control of current ripple, as low as a fraction of a percent of the current amplitude. This is further complicated because output voltage is directly proportional to speed, and the flywheel slows down as energy is withdrawn. As a result, the power electronics must be designed with this in mind. One such system, shown in figure 4, includes a controlled rectifier, DC-DC converter, and their integrated control system.

![Figure 4: FWB system including detail of power electronics.](image)
The output of the generator is connected to a controlled three phase full bridge rectifier consisting of IGBTs. The output of the rectifier feeds into the DC link for the dc-dc converter. The control system of the rectifier maintains the voltage of the DC link slightly above the rectified voltage of the generator. The control system triggers all the IGBTs of the upper legs together. In that instance, the generator is under short circuit and the current increases rapidly. However, when the IGBTs are turned off, the current flowing through the inductance of the machine produces an over voltage, thus, pumping current into the DC link capacitor. When there is no trigger provided to the IGBTs, the parallel diode legs of the switches are reverse biased because the DC link voltage is above the generator rectified voltage and no current flows. One can control the duty cycle of the IGBTs to control the voltage of the DC link. The switching of the top and bottom legs of the rectifiers is interlaced to share the switching duty and essentially doubling the switching frequency for the generators. The duty cycle cannot exceed 45% typically, as at 50% the top and bottom switches are on simultaneously thereby shorting out the DC link. In essence, this is akin to a boost converter only the input is AC instead of DC. As the generator slows down, one can modify the reference voltage of the DC link so that it is optimal for that speed so long as it is lightly above the rectified voltage of the generator.

The DC-DC buck boost converter is shown in figure 5. Switch ‘S’ is instrumental in controlling the voltage and the current through the load ‘R’. The trigger for the switch is based off of a current control loop to maintain a tight tolerance on the current. The arbors were designed with a UT-developed design tool known as CEM-WIND, which allows direct translation to and from 2D and 3D Structural FEA and the winding layup input to a McClean Anderson 5 axis filament winding machine. Each arbor consists of carbon fiber tow-preg and is wound in as a pair on a mandrel matching the desired arbor inner profile. Tow-preg, or fiber bundles pre-impregnated with resin, has typical fiber volumes in the range of 60 to 70 percent by weight and provides tighter control during manufacture of the fiber/resin content than more common wet winding processes. The full length winding is then split in the middle to create two individual arbors, as shown in figure 2. An arbor consists of approximately 15 cure increment layers with the majority of these being full length. Cure increments are typically limited to thicknesses of less than 0.2” to improve control of fiber/resin content and material properties. Additional s-glass is added at the large and small end outer diameters, as needed for sacrificial machine stock at assembly interfaces. Each single arbor, shown in figure 1, is approximately 9.5” in length with a small end ID of 9.5” and a large end OD of 21.5”.

The first two arbors, manufactured as a pair, as shown in Figure 6, were subject to mechanical performance characterization including natural frequency, or “rap” tests. An additional static axial deflection test on the second arbor was completed prior to its spin test by loading the arbor in a hydraulic press and measuring load versus deflection. The load was limited to 5,000 lbs. to ensure the arbor was not damaged.

**Figure 5: DC-DC buck-boost converter.**

**COMPOSITE ARBORS**
With the desire for smaller, lighter, and faster rotating electrical machines with high power densities, machine designers are driven to innovative topologies. Several designs for advanced alternators and PM generators have been developed that rely on composite arbors to connect the rotor rim to the rotor shaft. Composite arbors enable high speed operation because they can be designed to growth-match the rotor rim and they improve energy density by limiting mass, except where it contributes most to increasing rotor inertia. One such rotor topology for an air-core machine operating at 12,000 rpm included a rotor rim supported exclusively by six composite arbors.
Then, each arbor was installed on a steel hub and subject to spin testing. The goal of the first arbor spin test was to demonstrate the arbor’s tensile hoop strain capability. This arbor featured an unpreloaded structure with a thin graphite rim layer intended to limit radial growth to what the arbor would see in operation. The arbor was successfully tested to 15,750 rpm, with dwells at intermediate speeds to determine if viscoelastic effects were apparent. The second arbor, shown in figure 7, was fully preloaded with a representative rim structure to simulate the full arbor strain excursion from at rest to full speed. This arbor was successfully demonstrated to 15,000 rpm, and subjected to 1,000 cycles from 7,500 to 15,000. After the spin tests, both arbors were subject to static axial deflection and rap tests. These results were used to assess structural changes as a result of the spin tests.

Figure 6: Structural arbors before (top) and after (bottom) being removed from winding mandrel.

A set of laser position probes were used to measure deflection perpendicular to the arbor inner surface in the cone and rim region. Three probes in the cone region were located at increasing radii in the same plane and the other 180° apart. Another three probes were located at the rim, one was positioned to measure axial deflection at the rim face and the other two of these positioned 180° apart and looking at the rim ID. Figure 8 shows deflection vs. time data from the first arbor test sequence, which included 15-minute dwell periods at 9,000, 12,000, and 15,000 rpm. Viscoelastic response was observed during the 12,000 and 15,000 dwell periods. At the cone locations, arbor deflection increases slightly at the start of the dwell. During the slowdown, deflection data is relatively constant during the step-down dwell periods, but there is a noticeable offset compared to the step-up deflections, but the deflections return very close to the original zero, suggesting there is a time factor to the restoring forces and deflections in the arbor during spin down.

Figure 7: Structural arbor with representative rim structure prior to spin test.

The second arbor test plan called for the arbor to undergo 1,000 cycles from 7,500 rpm to 15,000 rpm. Instrumentation setup was similar to the first arbor spin test. Figure 9 shows arbor displacement data at the beginning and end of the fatigue test. The traces show that the excursions were virtually the same at the beginning as at the end. The maximum and minimum rim displacements showed very little change in amplitude during the fatigue test, indicating good behavior of the arbor with minimal visco-elastic response.

Figure 8: Arbor test data with deflection (mils) vs. time (seconds).
A comparison of test and analysis results pertaining to both arbors was compiled for the spin test, static deflection tests, and rap test. Finite element models that simulated the arbor tests were constructed using the CEMWIND winding layup definition the arbors were constructed from. A material parameter study was also done to investigate the effect of derating the arbor material extensional and shear moduli.

In general, test results indicated slightly more compliance in the wound structure than analysis predicted. A decrease in arbor stiffness compared to the theoretical stiffness can be due to differences in fiber volume, wind angle, thickness, and internal damage or delamination. The second arbor showed a closer correlation of analysis and test results than the first, and the natural frequencies obtained from the rap test were very close to those predicted by analysis, with the exception of a ring mode at 700 Hz. The post-spin natural frequencies for arbor 2 were slightly lower than the pre-spin numbers, indicating that there may have been minor fatigue damage done during the 1,000 cycle fatigue test. However, the largest difference in frequency was less than 2% and some modes showed no degradation of arbor stiffness whatsoever; so differences could likely be attributed to test setup.

The reinforced version of the arbor, shown with cooling tubes in Figure 10, was also subjected to spin test. The reinforced arbors were subject to a full speed dwell test, 5% overspeed test, and 333 deep cycles. The arbors performance agreed closely to analysis predictions. In addition, the arbors demonstrated well-behaved, stable operation meaning no significant change in deflection over the test and no change in balance of the test article before or after the test.

**DESIGN OF SAFE AND RELIABLE COMPOSITES**

Design aspects of safe composite high-speed flywheels and associated containment systems (if necessary) are well understood and rooted in decades of analysis and experimental testing. Much of this understanding was developed under DOE centrifuge development well before the 1980’s and 1990’s, when commercial and defense applications began to employ high performance composite flywheel systems. In the 1990’s, DARPA funded a major multi-year effort that was both experimentally and analytically focused. Through the Center for Transportation and the Environment (CTE), the DARPA program funded a consortium of flywheel developers, Oak Ridge National Laboratory, Lawrence Livermore National Laboratory, the University of Texas Center for Electromechanics (CEM), and Test Devices, Inc. (TDI). CEM and TDI served as co-leads for the program and program technical reports as well as all test reports are archived at CTE. Following the DARPA effort, NASA initiated development of ANSI/AIAA Standard S-096-2004; “Space Systems – Flywheel Rotor Assemblies” based on results from the DARPA program and additional NASA cyclical/fatigue testing. Approaches for design of safe high performance
Hydroburst samples are instrumented with several hoop and axial strain gage sensors, as shown in figure 11, along the circumference at 90° increments. The samples are loaded in a hydraulic fixture where they are uniformly expanded in the hoop direction until failure. The recorded strains, also shown in figure 11, provide the machine designers with empirical data including strain to failure, hoop modulus, and statistical material allowables. Initial samples are wound with primarily hoop-wound material to characterize and qualify the material lot. Once a winding layup has been defined for a particular composite component, samples with representative percentages of hoop and off-axis layers can be wound, cured, and tested. Since rotor composite components are wound with similarly thin cure increments, the material property data is directly relevant to the as-manufactured composite components.

Figure 11: Photo of hydroburst test sample and strain-to-failure test data.

CONCLUSIONS

High-strength composites are an enabling technology for the development of advanced rotating machines with high power and energy densities. The use of composites has been studied for decades and the design methodologies for operating them safely are well-understood. No longer limited to flywheels constructed with preloaded composite cylinders that store energy and enable higher speed operation, unique geometries or functions can also be made using composites. To underscore the widespread potential use of composite materials, several innovative designs have been presented.

A PM machine topology was presented that utilizes a composite arbor to achieve close to 100 Wh/kg specific rotor stored energy and shows promise as a mobile power supply for directed energy. The primary challenges to the proposed PM M/G are development of the composite arbor and active cooling for an arbor-based rotor. These challenges are addressed by the use of

Characterization of composite material properties prior to fabrication is critical to achieve the expected mechanical performance. Consequently, the research team developed a material qualification hydroburst test to empirically verify the towpreg material properties [4]. Hydroburst testing involves winding and curing a thin ring of the composite material in question and cutting it into ring test sections approximately 0.5” in axial length.
a validated composite arbor capable of supporting hardware for active rotor cooling.

On the component level, the composite growth matching arbor was successfully designed, fabricated, and tested. The arbor performed as expected in spin tests to well above design speed and demonstrated stable and repeatable mechanical performance. Further, a reinforced version of the composite arbor capable of supporting mechanical hardware for active rotor cooling was presented that has also been validated.

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REFERENCES

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