Test, Analysis, And Scale-Up
Of A 1-Kwh Flywheel Rotor Design

A. C. Day, P. E. Johnson, M. D. Higgins, M. Strasik, J. Mittleider,
J. Edwards, J. R. Schindler, K. E. McCrary, and R. A. Hawkins
Boeing Phantom Works, Seattle WA[1]

Abstract
Boeing has investigated a novel approach to flywheel rotor design that may have significant cost advantages for high-volume production. A small version of this design, nominally for 1 kWh of storage, has been tested on a passive magnetic suspension. In this paper, the performance of the rotor and its dynamics will be discussed, together with considerations for scaling the design to larger sizes.

Introduction
One of the persistent problems of flywheel design is the attachment of the rim (typically made of filament-wound carbon fiber composite materials) with a hub that mates to bearings and a motor/generator. Centripetal forces act differently on materials of varying densities and Young's moduli, which tends to result in either separation of parts at high speeds, or very high radial stresses (tensile or compressive). A common way to attack the problem is to make the rim of many layers of composite, each press-fit to the others to preload the assembly in radial compression. Fibers of very high strength and stiffness may be required on the outer layers to limit radial growth while staying within allowable hoop stresses. When designed with considerable care, these steps make it possible to connect a thick rim to a relatively small diameter metallic hub without separation of the interfaces.

The disadvantages of the multi-rim approach are cost and weight. Fabrication, trimming, and assembly of the many composite layers is expensive, as are the more exotic fibers used in the outer layers. The rims are also relatively heavy for the energy stored because the inner layers of composite will not have nearly as much kinetic energy per pound as the outer layers.

Design
Toray Composites patented an alternative approach to the hub/rim problem that uses a splined interface to accommodate different radial growth rates. It has been called the 'GS hub,' for the inventors, Chris Gabrys and Dennis Simmons. Boeing extended their approach, minimizing the amount of material in the hub to reduce weight. The modified GS hub is shown incorporated into a full flywheel rotor assembly in the schematic of figure 1.

This design was scaled to achieve 1 kWh of storage at a speed of 24,000 rpm while maintaining safety factors of 2 or higher on the composite rim. In the Boeing version of the splined hub, there are two hub/rim interfaces, one at the top of the rotor and one at the bottom. The hub itself is metallic, the mating spline is a plastic material of much lower modulus, and the outer rim is a hoop-wound composite. The spline surfaces allow for uniform radial slip, removing the need to growth-match the hub and rim. In spite of this ability to slip, there is a substantial lateral stiffness because the teeth at 90 degrees to the direction of hub displacement are loaded in shear.

On the 1-kWh flywheel the hub also has adapters on the ends to accept a 3-kW motor/generator on the top, a permanent magnet ring below the motor for lift, and a second permanent magnet stage on the bottom for stability. Stability arises through flux-trapping effects when the magnetic fields interact with a superconducting stator, shown below the magnets in figure 1.

[1] arthur.c.day@boeing.com
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The fully assembled flywheel is shown in figure 2. Tests of this system were begun two years ago and included a high-speed spin on superconducting bearings last year. However, the structural and dynamic attributes of the concept have not been well understood. Recently we have carried out simple experiments and modeling to improve our understanding, with the goal of scaling the design to larger rotors.

Experimental Progress

Testing to date of the system includes spin testing on the superconducting bearing at speeds up to 12,000 rpm (ref. 1), quill testing to 20,000 rpm, and tap-testing of the stationary rotor to determine structural mode frequencies. A run profile of one of several tests on the superconducting bearing is shown in figure 3. The figure shows speed on the left axis and rotor position (vertical and horizontal) on the right axis. The positions, recorded continuously throughout the run, indicate the vibration levels as the envelope of the motion. Through most of the run the vibration levels are approximately 0.4 mm p-p, with the exception being a rigid-body bearing mode at around 400 rpm. Otherwise, there have been no indications of instability through any of the test runs. The rotor was not well balanced, which should largely account for the fact that vibration levels were not much lower overall. Spin testing was taken only to 12,000 rpm because of limitations predicted for parts of the bearing structure. Later versions of the bearing have been designed to reach speeds of at least 24,000 rpm.

Tap testing was done by acquiring accelerometer data (from a sensor placed on the flywheel's rim) in response to the excitations caused by calibrated hammer taps applied at various locations on the structure. A typical response spectrum is shown in figure 4. The strongest peaks by far were located at frequencies of 380 Hz to 405 Hz. By acquiring response data at several positions on the rotor it was possible to construct a mode animation in software, showing that this mode represents a trunnion-type rotation of the hub with respect to the rim. This mode shape should therefore be highly dependent on the stiffness of the spline interfaces. A favorable comparison with model predictions is described in the next section.

Quill testing in a spin pit is now underway to verify the structural and dynamic integrity of the rotor up to higher speeds. The magnet stages were removed for these tests. As of late October 2003, the rotor had been taken to 20,000 rpm without encountering a hub/rim critical speed. This was as expected, based on a model run without magnets that showed the critical speed moving up to well over 30,000 rpm.

Modeling and Scale-up

As discussed in the Design section above, the spline interface provides radial stiffness through the sides of the teeth, which generate shear forces and deformations near the roots of the outer teeth. A finite-element model was created to calculate the radial stiffness for the 1-kWh test article. For that rotor, the actual thickness of the splined plates was 0.5 inch. Figure 5 shows the somewhat simplified geometry used in the model, and the mesh used to define the elements. The rim and the internal spline were given very high stiffnesses, characteristic of aluminum or steel, and the outer spline was given the properties of nylon, i.e., Y = 420 ksi. The nylon, being of much lower modulus than the metals, is the predominant factor determining the effective stiffness of the assembly.

The stiffness is found by inducing a lateral displacement in the model and then calculating the restoring force. For the plate as shown in figure 5 the calculated stiffness was 1.327×10^6 lbf/in. This value was then inserted in a rotordynamic response model for the complete flywheel created in XLRotor (ref. 1). XLRotor uses cylindrical beam elements of the correct dimensions, densities, and elastic moduli to calculate mode frequencies as a function of rotational speed. It used stiffnesses for the magnetic bearings derived from prior experiments; these stiffnesses were low enough to have a negligible impact on high-speed modes. The XLRotor model approximated the splined plates as discs, with the disc OD taken as the average of the spline ID and OD, and used the interface stiffness given above from the finite element calculation.

The results of the combined finite-element and rotordynamic models are shown as a mode speed map in figure 6. The modes of the system at rest are given by the Y-intercept values (0 rpm). The modes of interest are the rigid-body (bearing-related) modes at 4.4 and 12.5 Hz, and the trunnion mode associated with the spline interface at 417 Hz. The rigid body modes were below the cutoff of the tap test/accelerometer system, but the 4.4 Hz mode becomes an observable critical speed (i.e., synchronous with rotation speed) at 354 rpm in the model. This can be compared with about 360 – 375 rpm observed experimentally for the flywheel on the magnetic bearings. There is little energy in the flywheel at this speed and it has been able to pass through the resonance without difficulty (see the position envelope on the right side of figure 2). More importantly for this study, the hub/rim trunnion mode prediction of 417 Hz was also quite close to observed values, in this case the tap-test frequencies of 380 – 405 Hz. Thus the modeling approach for the spline and flywheel has been validated in its essentials and should be a useful tool for the design of similar systems at larger or smaller scales.

One additional step was taken to extend the ability to model these systems. The radial and trunnion stiffness of each plate scales with the diameter of the splined interface but also varies as the tooth dimensions change. Important dimensions include the tooth width *w*, height *h*, and the gap at the end of the tooth *h1*. A single-tooth finite-element model was set up to study the variation in stiffness with these parameters. Some results for *w* and *h1* are shown in figure 6.

The 1-kWh flywheel was then scaled up to a 5-kWh version with a slightly larger and thicker pair of splined plates. Some overall rim dimensions and weights are shown in Table 1 below. (It should be noted that the new rim design was derived with a different set of materials and processes than the 1-kWh rotor and therefore is not proportional in mass.)

Table 1. Dimensions and masses of 1- and 5-kWh flywheel rotors. Masses include hubs and magnets

Design	Rim ID (inches)	Rim OD (inches)	Mass (lbm)
1 kWh	9.25	18.00	103
5 kWh	10.25	22.75	296

The viability of this design was checked in part by recalculating the critical speeds for the rotating system. This was done using dimensions and stiffnesses for the scaled system in XLRotor, with the results shown as the speed map of figure 7. The predictions include an ability to operate free of high speed criticals up to nearly 30,000 rpm. Subsynchronous instabilities cannot be ruled out, but are becoming better understood through quill testing of the 1-kWh system as described above. No show-stoppers have been identified to date.

Conclusion

A 1-kWh flywheel has been tested to determine its structural mode frequencies, both at rest and as a rotating system. The frequencies are characteristic of a splined hub/rim interface approach that is being investigated due to potential advantages for reducing the cost and complexity of flywheel rims. The results show very good agreement with the predictions of finite-element and rotordynamic models of the interface and the flywheel. These models can now be used as design tools to scale up to larger systems. An initial design for a 5-kWh flywheel was analyzed and appears to be workable system.

Acknowledgment

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References

1. Day, A. C., Hull, J. R., Strasik, M., Johnson, P. E., McCrary, K. E., Edwards, J., Mittleider, J. A., Schindler, J. R., Hawkins, R. A., and Yoder, M. L., *"Temperature and Frequency Effects in a High-Performance Superconducting Bearing,"* IEEE Trans. Appl. Superconductivity, June 2003.

2. XLRotor is an Excel-based rotordynamics program written by Dr. Brian Murphy and sold through his company, Rotating Machinery Analysis, Inc. of Austin TX.

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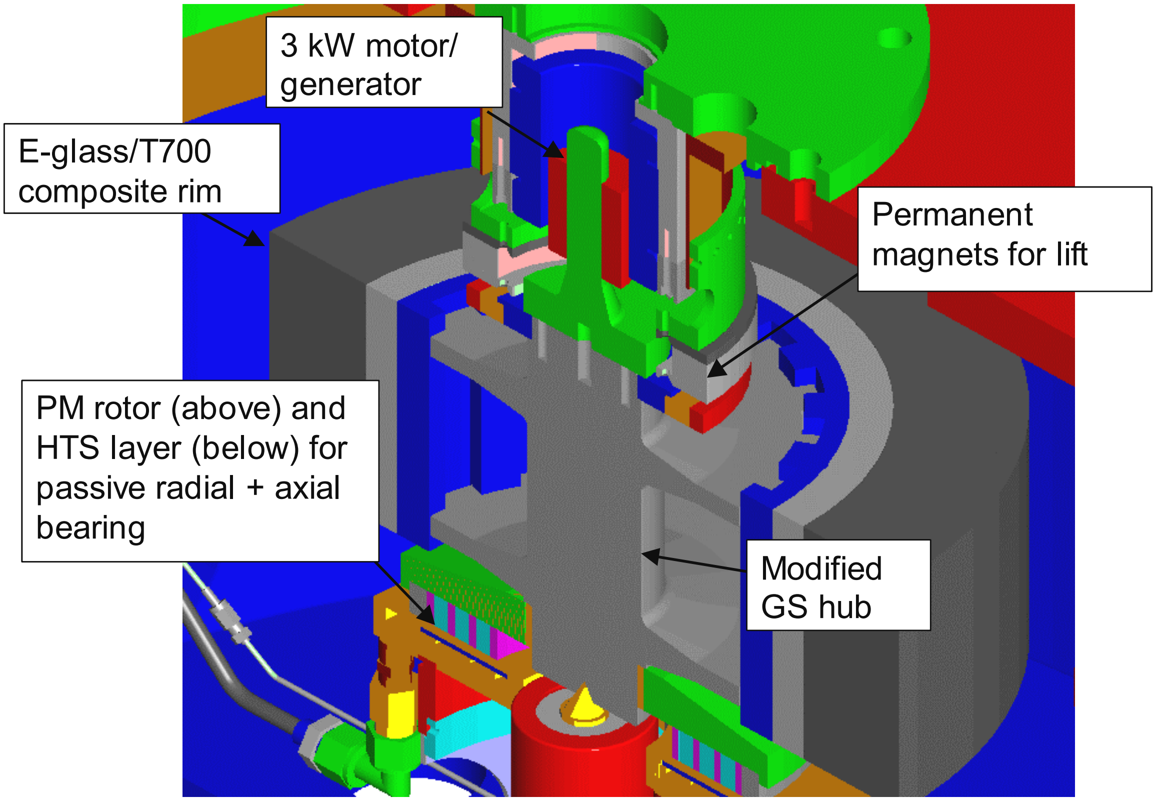


Figure 1. Features of 1 kWh flywheel with splined hub and all-passive bearing system.

Figure 2. Complete 1 kWh flywheel including magnets and motor rotor.

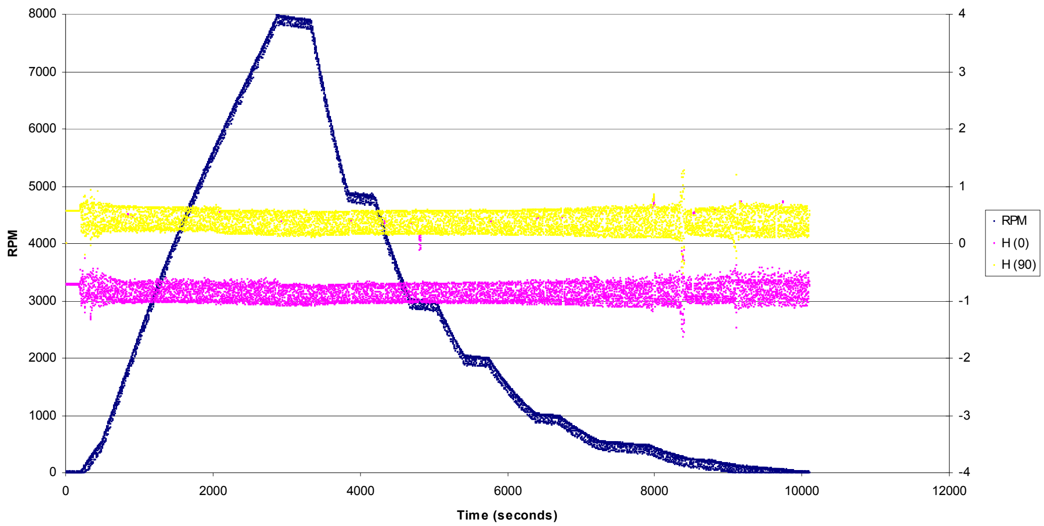
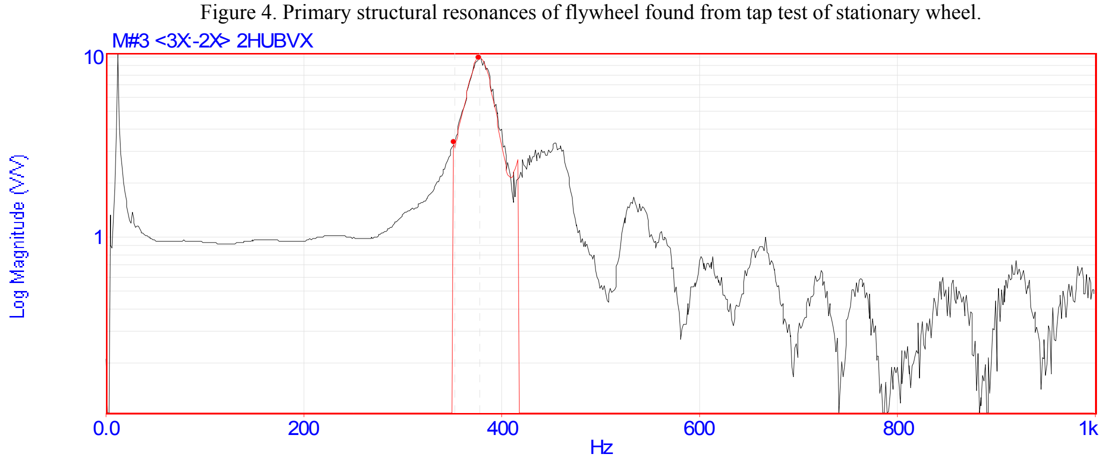


Figure 3. Run profile for flywheel showing speed and position/vibration levels.

Figure 4. Primary structural resonances of flywheel found from tap test of stationary wheel.



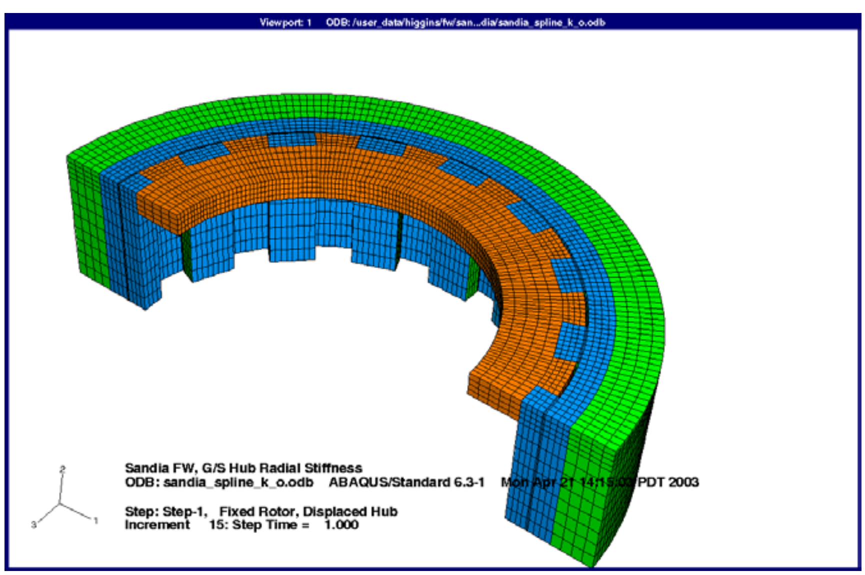


Figure 5. Finite-element model of splined interface and part of flywheel rim.

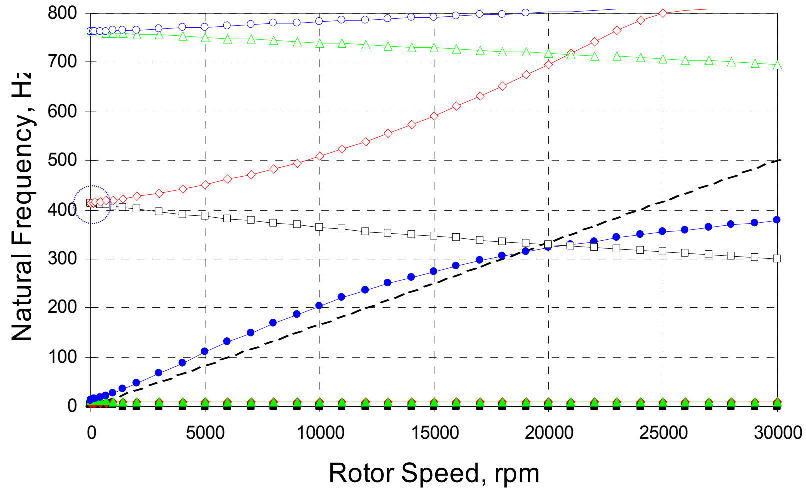


Figure 6. Mode speed map (Campbell diagram) of the 1 kWh flywheel on a magnetic suspension. Zero-speed mode at 417 Hz compares well with the tap-test results of 380 – 405 Hz.

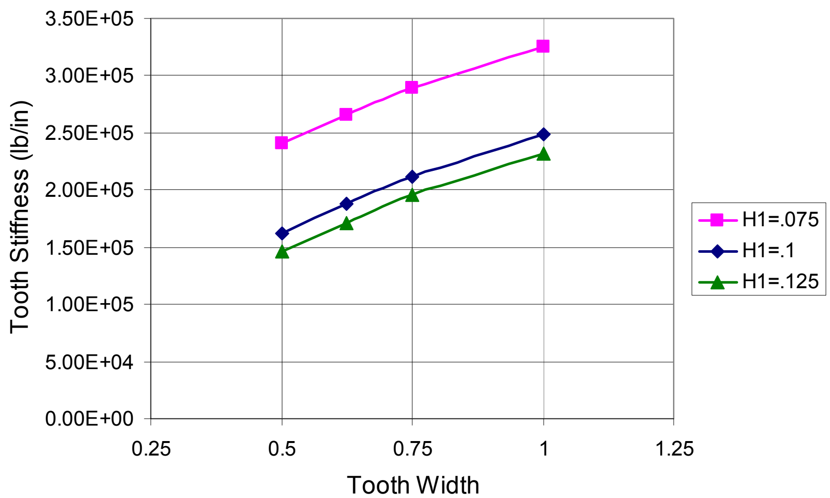


Figure 7. Results of model study of the stiffness as a function of tooth dimensions.

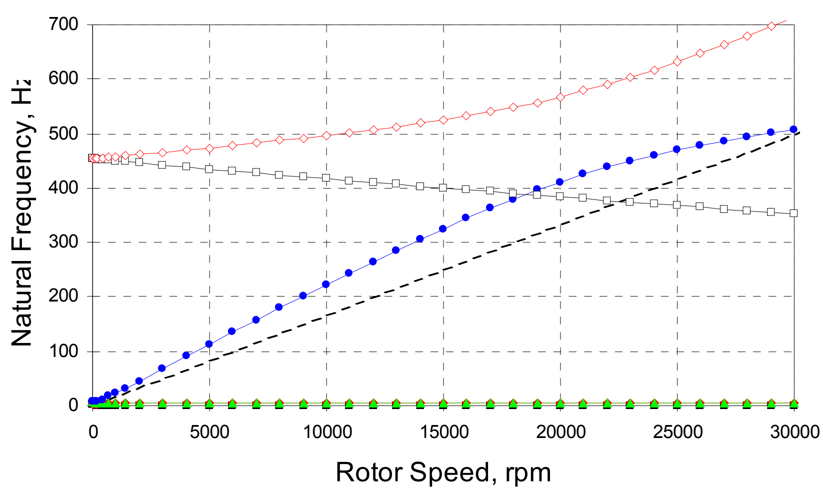


Figure 8. Mode speed map of a flywheel scaled to 5 kWh using the tools validated with the smaller wheel.