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Spin Testing Improves Electrified Propulsion Rotor Design for Production and Certification

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Abstract

There is a demonstrated need for effective design verification testing to support certification strategies for nascent electric motors and electric propulsion systems. Design efforts pursue efficiency pushing electrified propulsion rotors to be lighter and incorporate greater power density; however, there is no clear path established for supporting structural integrity and durability test requirements as required by global certification agencies.

Application of new materials, unique rotor design characteristics, and modified certification requirements drive unusual requirements for rotor modeling substantiated by component test data that addresses complex stress distribution characteristics.

Our paper addresses testing electrified propulsion rotors using spin test protocols adapted to support integrity and durability test goals. We further incorporate key concerns for planning and executing component spin tests of rotating structures necessary to support global engine certification efforts. Results from component tests are effective for mitigating risks associated with the preservation of certification test schedules and potential end product safety issues.

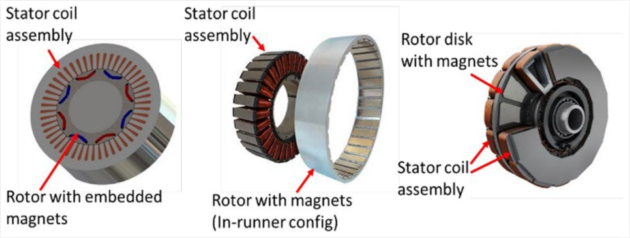
This paper presents data measurement techniques that are incorporated with specific spin tests to enhance the value of acquired data. Adapted test protocols include Overspeed and Low cycle fatigue (LCF) tests, which are more relevant types of spin tests for certification purposes.

Innovative measurement techniques for capturing the rotor growth behavior for both mappings the speed-dependent growth trends and the circumferential profile of deforming rotor under centrifugal load generate useful data to evaluate materials and structural behavior affecting performance up to failure.

Introduction

With the increasing efforts in the electrification of both ground and air vehicles, various innovative designs of high-performance electric motors are being developed. Predominant types of motor designs that we have been testing are 1) IPM (interior permanent magnet motors) – more common in electric cars, 2) radial flux design (magnet mounted on a rotor with high strength retaining band), and 3) axial flux design (magnet mounted on a disk). Note: The new designs of motors beyond the aforementioned types are emerging as we speak (e.g., externally excited synchronous motors).

FIGURE 1 IPM, Radial, and Axial Flux Motors (left, center & right). Courtesy of [1, 2, 3].



The design challenges surrounding these motors pursue higher power density that pushes the boundaries of weight-optimized structure design and material science. The pursuit of these efforts culminates in intricate designs that often result in stress concentration features subjected to complex stress fields and loading cycles.

In aerospace, safety is on the top agenda. The makers of flight hardware are required to demonstrate the robustness of their design, as well as a high degree of quality control of the products through extensive analyses and testing.

Specific to electric propulsion systems, there is an ongoing effort in establishing certification standards for eVTOLs and electric propulsion systems (for airliners). For critical rotating parts certification, emerging details of the requirements resemble pre-existing criteria for jet engines [4]. Traditional rotating parts type certification concerns overspeed and low cycle fatigue (LCF) tests.

Though certification requirements could be demonstrated through analyses for established propulsion rotors, new systems typically require engineering testing.

Spin testing is one of the established test methods for satisfying the certification requirements, such as FAA's 14 CFR Part 33 requirements [5, 7]. However, efficiently planning and executing the tests could require domain-specific expertise and careful planning to avoid unnecessary and costly surprises. In this paper, the authors present relevant capabilities of the modern spin test system that are most relevant to the developers of cutting-edge electric motors for both EVs and Aerospace propulsion units.

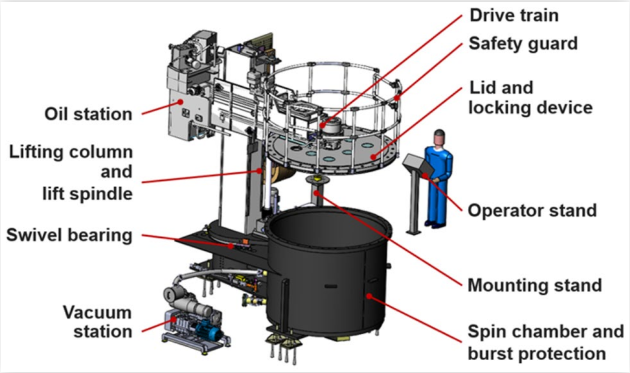
What is a Spin Pit and Spin Testing?

Spin pits are purpose-designed machines for testing rotors under high centrifugal load (CF load). Spin pits are designed to spin rotors at high speed – sometimes beyond their designed safe operational range to validate the stability and the design limit of rotors. The interaction of the CF load with the geometry of the test rotor often generates a complex stress field that is not easy to capture in a tensile test specimen.

Most modern spin pits are equipped with a high-speed drive unit. The drive and the test rotor are connected via a thin shaft (spindle) that dynamically isolates the drive from the payload. This design allows the test to continue even when the rotor exhibits a high level of vibration. Spin pits are also equipped with built-in barriers and safety features against a rotor failure (intentional or unintentional rotor burst) that may release fragments with a lethal level of energy.

Successfully spin testing a rotor at high speed comes with some unique challenges. Consider a rotor spinning at a high speed – It is subjected to a significant CF load, causing a structural deformation in the rotor (elastic and plastic), which could result in unbalances and subsequent instabilities. The significant dynamic load resulting from the deformation could quickly destabilize the rotor, and if not properly managed, fail the test before reaching its target speed.

FIGURE 2 An example of a spin pit and its key components.



A common limitation for performing a high-speed test in the original hardware - the bearing cannot support the dynamic load, or the clearance between the rotor & stator is not large enough. It is also true that attempting to test with the original hardware often limits the degree of instrumentation that can be applied. It would require careful modification to the original hardware to allow access to sensors and data lines while avoiding any inadvertent changes to the behavior of the machine. In some cases, customized sensors, and instrumentation may be the only option to test and measure data. It is not hard to see how this kind of work quickly becomes a complicated project. For testing rotors, the spin test offers simpler and more flexible solutions.

Besides spinning the test rotors to high speed, the rotors in an operating motor are subjected to the complex interplay between different forces and environmental factors. For example, electrified propulsion motors are not only subjected to the CF load, but also to various temperature conditions, vibrations, and other effects that come from the interaction of the rotor with the electromagnetic field.

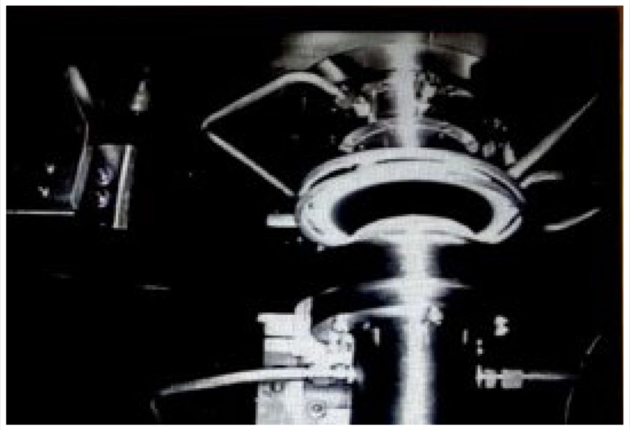
Though all these factors must be accounted for in safeguarding the performance of the final product, it is often beneficial to select some key factors and pursue the test to observe their direct effects. Being able to isolate and control the test condition to observe the test rotor's behavior in a specific condition would allow a more detailed examination and cleaner data for assessing the performance of the design. This is true for any engineering (or scientific) testing.

Using spin pits with advanced testing capabilities, test engineers can set up various test environment conditions that reflect the key facets of the operating environment of the test rotors. Professional test service providers routinely perform both cryogenic temperature and high-temperature tests at 1000°F-1500 °F for gas turbine wheels [10]. In some extreme cases, a thermal gradient testing capability with over 2000°F disk rim temperature has been demonstrated [11].

Unlike turbine disks, it does not need to consider extreme test temperatures for electrified propulsion rotors, testing it comes with some unique challenges. Current typical electrified propulsion rotors require a test temperature below 570°F. This may appear trivial compared to the significantly higher test temperature for gas turbine parts, but it is important that test engineers pay attention to the fact that rotors are made of very different materials. Some electrified propulsion rotors are constructed from non-metallic materials (such as carbon fiber composites, polymers, and adhesives) that may be more sensitive to how the temperature was applied to them. For example, one could overheat and damage the rotor (such as a composite banding of a radial flux motor) if the heat is applied rapidly to the rotor's surface. Incorrect application of the test environment could result in premature failure or a misleading test result.

Spin testing allows highly customized instrumentation and test setup design to allow the product designers to investigate and understand the behavior of the rotor fully. A well-designed spin test setup allows greater flexibility to reconfigure and adjust the test strategy in situ. The freedom to adjust the test plan or hardware/instrumentation during the course of the testing is a powerful tool to investigate and understand the performance of the parts. The resulting benefit is that the

FIGURE 3 An image from an advanced thermal gradient test with the capability to achieve the test disk rim temperature in excess of 2000 °F.



spin test can serve electrified propulsion designers and engineers to fill the information gap by enabling the engineering test in the earlier phase of product development.

Testing & Measuring Technologies for E-Propulsion

Test data is the main deliverable of an engineering test. In this section, we present different types of test data that could be generated from a spin test. The examples presented in this section are of the techniques with high relevance to electrified propulsion testing.

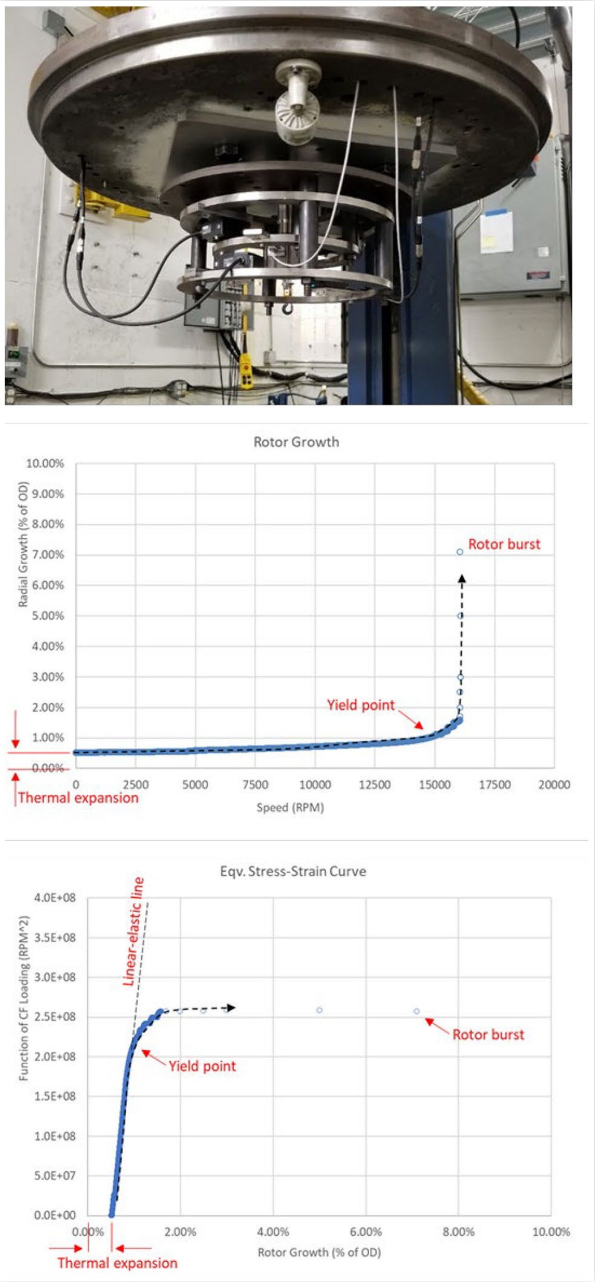
NOTE: The authors feel it is important to mention the topic of spin tooling design, which is an equally relevant and important topic for achieving a successful spin test. However, for the sake of the focus, it will not be discussed in this paper. This may be a topic for a future paper.

Growth and Rotor Expansion Measurement Systems There are two levels of detail in measuring the changes in the diameters of a spinning rotor. Starting with the Growth Measurement System (GMS), which takes in the average dilation of a rotor diameter under the CF load. The growth data is a useful way to observe and correlate the change in the dimension to material behavior.

The example shown in Figure 4 shows data from a heated burst test. The GMS data shows the effect of thermal expansion (during a heat-up), linear elastic behavior, yield point, subsequent plastic deformation, and rupture (rotor burst). Understanding the direct relationship between the rotational speed (ω^2), and structural load (stress), plotting the data in speed-square vs. growth produces a comparative trend to the stress-strain curve of the rotor material, which could be useful to compare against the available tensile test data (Note the spin test data reflects the bulk material behavior).

Compared to the GMS, the expansion measurement system (EMS), developed by M. Hartnagel and A. Buschbeck [6], offers more intimate details of the rotor dilation behavior. The system maps the circumferential profile of the rotor as it expands under rotational load. An example of the expansion measurement data is shown in Figure 5.

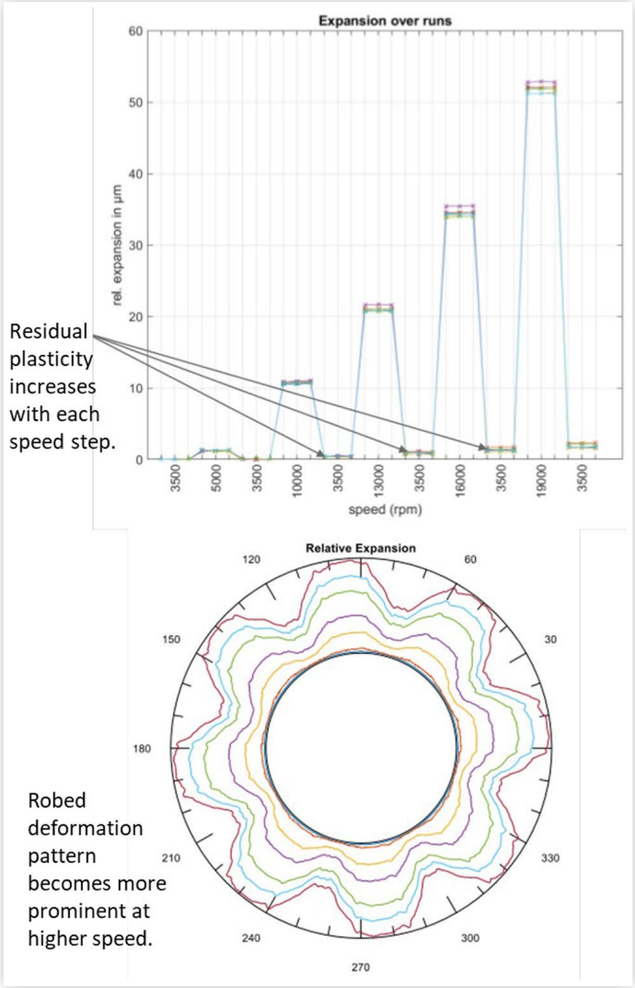
FIGURE 4 Growth measurement setup (top, note the heating system not shown), rotor growth data from a heated test (middle), and comparative representation of the growth data to a typical material tensile test curve (bottom).



Understanding the detail of rotor deformation shape allows engineers to confirm the geometry of the rotor in its operating speed. In some applications, such as high-performance electric motors, a subtle difference in rotor profile could affect the rotor performance as well as key design decisions, such as determining the amount of air gap in the rotor and the stator assembly.

It is worthwhile mentioning that predicting and determining the behavior of electric motor rotors can be a complicated

FIGURE 5 An example of the rotor expansion data: OD expansion profile vs. speed (top) A polar plot showing the dilation of rotor diameters at different speeds (bottom)



Residual plasticity increases with each speed step.

Robed deformation pattern becomes more prominent at higher speed.

effort to model. Take IPM motor rotors as an example – A typical construction involves the arrangement of magnets embedded in layers of thin metal wafers, and insulation coating, in some cases adhesives are applied between the layers. The behavior of a composite structure like this can quickly become complex and challenging to accurately predict with an analytical model. Test data from the EMS would help tune the analytical models and improve the accuracy of the predictions.

Figure 5 shows an example of EMS data from a test for IPM type motor: The first plot (Figure 5, top) shows the trend in the peak values of the deformation shape as well as the residual deformation values for each test speed increment. The polar plot (Figure 5, bottom) captures the circumferential profile of the deformed rotor at corresponding test speeds. The prominent region of the profile corresponds to the location of implanted magnets. The residual deformation shape captured from the EMS could be validated by the CMM (Coordinate Measurement Machine) measurement performed after the spin test.

The test data like this is becoming more relevant and important for designing cutting-edge high-performance electric motors. Intensifying competition from EVs and electrified propulsion systems push lighter and more power-dense motors.

High-Speed Video Imaging Knowing how and where failure starts in a structure is a critical step in improving the design to prevent a catastrophic failure. A high-speed rotor often stores a large amount of energy, and its failure modes are sudden and violent. Due to this reason, understanding the failure mechanism and location of electrified propulsion rotors are critical safety agenda.

The use of a high-speed video system is becoming a common approach to capturing the instances of a rotor burst. Modern high-speed video cameras offer amazing frame speed at good resolutions, allowing the users to capture excellent images over a range of test speeds.

However, capturing a clear detailed image at high speed requires a good understanding of the optics and the devices used in the imaging. Covering some basics, evenly applied illumination to the target rotor, and optimizing the video camera setup for capturing the fast-moving target requires some careful tuning. Figure 6 shows the relationship between the aperture, shutter speed, and ISO sensitivity (exposure), which dictates the lighting need and the clarity of the image relative to the speed of the target.

Figure 7 shows an example of a high-speed video image capturing a typical failure mode of an IPM rotor where the lamination stack failed by the localized load in the area with the implanted magnet. An optimally set up high-speed video allows us to capture not only the location and the manner of failure but also the subtle detail of structural deformation leading to an onset of rupture.

Analysis of Rotor Unbalances Unbalance in a rotor is the primary factor that dictates the severity of vibration, noise, and in some cases durability of the machines. This is particularly true for machines with high-speed rotor(s).

Measuring the change in unbalance during and after a spin test, often provides important insight to engineers and designers. Repeatability and the stability of unbalance in a rotor is a good indication of its structural stability. Modern

FIGURE 6 Exposure triangle showing the relationship between lighting, ISO, and frame rate.

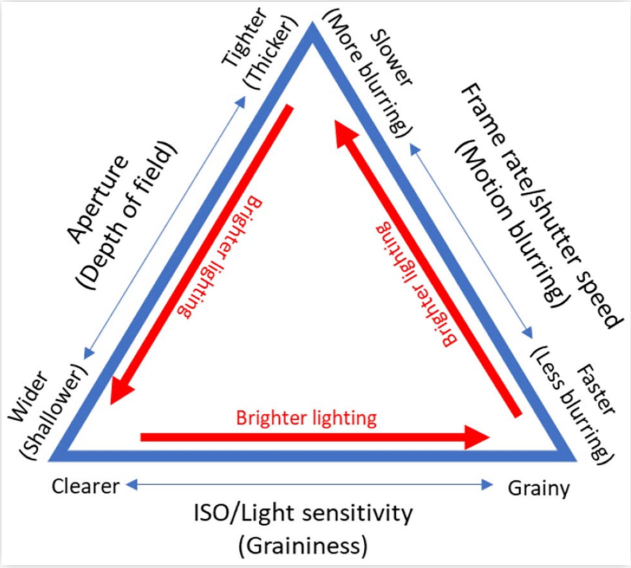
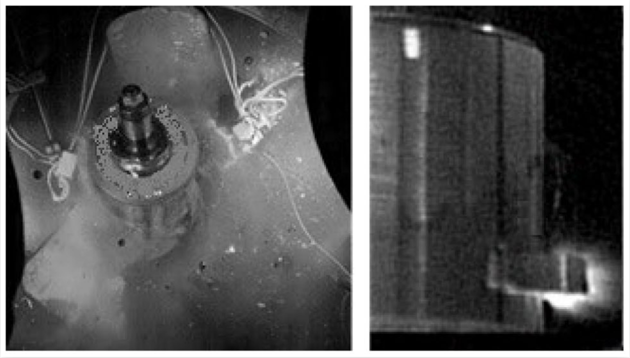


FIGURE 7 An example of high-speed video images capturing a rotor burst, bottom view (left), and ejection of magnet from a laminar stack, side view (right).



balancing machines are very sensitive and capable of subtle changes in the structure of the rotors undetectable by other means, such as CMM.

Specific details in the topic of unbalanced analyses can be broad and deep. This may be a topic of a separate future paper.

LCF Test & Schedule Concerns Another type of spin test (besides the overspeed test) that are typically relevant for certification requirements is the Low Cycle Fatigue (LCF) test. The "cycle" in the LCF typically refers to the operational cycle of the equipment. For example, for a commercial aircraft propulsion rotor, the cycle is defined by each flight operation (take-off and landing).

Fatigue failure has been an ongoing subject of research for many years. Leading airframe and jet engine OEMs have developed a material database and sophisticated system to calculate the fatigue life of structures. The introduction of new material involves a set of specimens testing to generate necessary fatigue data followed by careful studies to confirm the correlation of the computed life to the prediction from the model.

Computation of fatigue life for an aerospace structure typically requires a significant pool of material coupon data capturing various loading and environmental conditions and sophisticated analytical models to translate the coupon test result to the relevant machine part [9]. The goal of a fatigue analysis model is to reliably predict the safe operating life of the machine parts by capturing the various factors that affect the durability of the parts ranging from material properties, manufacturing processes, operational conditions, and potential damages from operation and handling.

Historically, the spin test (LCF) was used to provide component-level data to validate the analytical model. Spin testing (LCF) involves testing a rotor from the production line (or the one that underwent an equivalent process). Due to the fact that the spin test (LCF) specimen needs to be representative of the production version, the test rotor and test requirements typically come in the later part of the product development, and the completion of the test often becomes a concern for the product launch schedule.

In planning an LCF test, the interest in expediting the schedule often competes with the risk of prematurely cracking the rotor. According to the guidelines, engine makers can claim the fatigue life of the part based on the validated "damage-free" state [7]. In other words, the test rotor must be inspected and confirmed "crack free" to the claimable fatigue cycle count (or in case of the failed rotor to count the fatigue striation marks to the initiation. A time-consuming task, especially if it involves investigative work of piecing together fragments of the destroyed rotor). The frequency of the inspection is decided by carefully weighing the risk and the confidence in the predictive model.

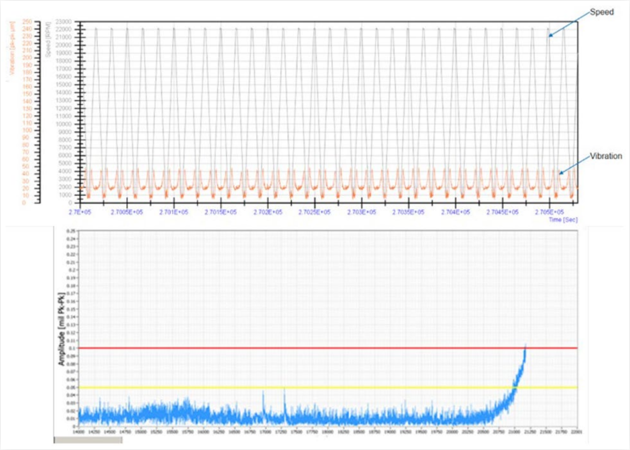
There are several plausible paths to expedite an LCF test schedule. The obvious choice is not to do the test but doing so requires a fully matured and validated predictive model which typically is not a situation for new products, including the electrified propulsion systems.

There are some ongoing efforts to shorten the duration of the LCF cycles, which involve designing more powerful drives that can accelerate and decelerate the test rotors more rapidly. However, pursuing this approach often involves taking risk of the test machine itself failing from the increased loading from faster acceleration/deceleration loads.

The third path is to minimize the number of interruptions in the LCF test by means of a condition monitoring system that is sensitive enough to detect the onset of a small crack. The Real-Time Crack Detection System (RT-CDS), a method developed by Test Devices [8] monitors the emerging crack in the test rotor during the LCF by trending the change in the unbalanced vector of each LCF cycle.

In a nutshell, the RT-CDS monitors the shaft order components of the vibration signal and logs it for each cycle when it crosses a user-defined threshold (often at a high speed). The first-order component is known to be strongly correlated to the unbalance in the rotor, which will be influenced by the change in the structural deformation shape caused by an emerging flaw. The sensitivity to the change is enhanced by collecting the trend data at high-speed (high CF load = more deformation), and via proprietary signal processing code. Figure 8 shows an example of LCF test cycle data and the output from the RT-CDS.

FIGURE 8 Example of LCF test cycle data showing the rotor speed and shaft vibration (top), and an example of the crack indicator from the RT-CDS (bottom).



The RT-CDS offers a way to expedite the LCF test schedule by eliminating the need for interim inspections, saving significant time for the test schedule. Further time saving could also come from avoiding unexpected rotor failure, which includes the effort involved in failure mode investigation and the cleanup.

In addition to expediting the LCF test schedule, it is an emerging interest for some electric motor engineers to observe and understand the mechanism behind the change in the rotor unbalance that appears to manifest over the course of LCF test cycles.

Summary/Conclusions

The race to higher performing motors drives more design optimization and the use of new materials towards developing robust and durable propulsion systems. In parallel with this effort, testing such as spin tests, and the ongoing development of data measurement technologies play a crucial role.

Unlike traditional turbomachinery rotors, the material and the construction of the emerging electric motors is new (especially relative to the high-speed environment). The designs and the structures of these motors are very different and often consist of complex assemblies. There is more to be understood about the behavior and damage mechanisms of high-performance electric motors.

In this paper, relevant examples of test techniques and data measurement methods are presented and discussed. The authors hope that the content of this paper is helpful for gaining an overview ad developing a better test strategy.

The use of spin testing could create some strategic advantages to the developers of the EV drives and electric propulsion systems if planned thoughtfully as a part of the product development strategy. Spin testing would be an economical method for demonstrating the Certification Requirements.

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Definitions/Abbreviations

RPM - Revolutions per minutes
CF - Centrifugal force
LCF - Low cycle fatigue
HCF - High cycle fatigue
FAA - Federal Aviation Authority
RT-CDS - Real-time crack detection system
CMM - Coordinate measurement machine
NVH - Noise vibration harshness
EMS - Expansion Measurement System

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