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Spin Testing

By: Eric Sonnichsen of Test Devices, Inc.
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Spin testing is an important step in the prevention of centrifugal burst disaster. Rotating components used in modern, high-speed machinery operate under large centrifugal stresses and can fail with explosive force; so all developers and manufacturers of turbomachinery components need to test rotors for centrifugal strength. Developers need to calibrate and verify the results of stress analysis, and to establish the fatigue life of high-performance rotors; and manufacturers need to prove the strength of high speed disks before shipment and installation.

The vertical axis spin test that fills these various needs was originally developed to solve a problem with military aircraft turbochargers during World War II, and has been in wide use ever since. While there are other ways to test for centrifugal strength, the vertical axis, flexible shaft spin test is most commonly used because it is the most versatile and general method available to spin a high speed rotor without requiring a high cost, elaborate bearing system for each rotor.

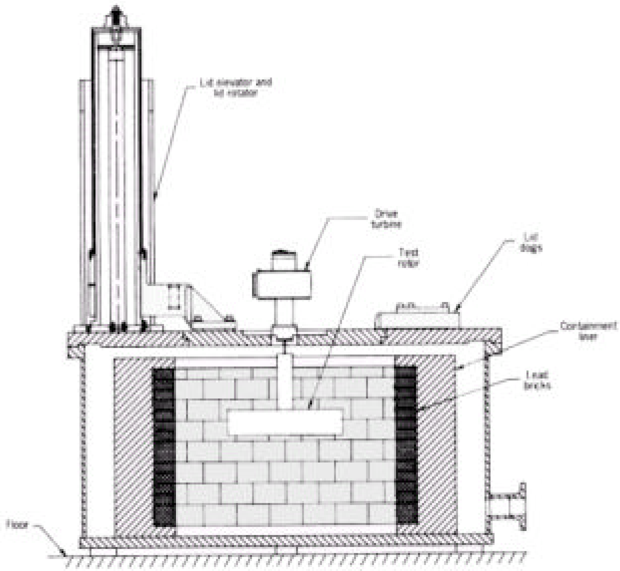

Figure 1
Typical Spin Test System Containment Diagram

The most common way to conduct a spin test is to suspend a rotor in a heavily armored vacuum chamber from a flexible spindle and to accelerate the rotor to high speed by driving the spindle with a compressed air turbine or electric motor. The flexible shaft allows the rotor to find its own balance axis, in much the same way that a child's top spins smoothly without any external support. The soft support eliminates the need for extreme precision in mounting or balancing, and limits the damage to the drive system in the event of a rotor burst. The armored chamber is often called a "spin pit" for historical reasons, but modern spin chambers are designed with adequate strength so they don't need to be in a hole in the ground. Properly designed spin pit armor is quite massive. A high strength forged steel cylinder with minimum thickness equal to 1/3 of the radius of the largest diameter test rotor is appropriate for most common applications. To reduce the magnitude of impact shock, the steel armor is commonly lined with a soft material like lead (see Figure 1 for a diagram of a typical spin test system containment).

Spin tests are usually conducted in vacuum to eliminate the high air friction losses that would make it difficult to drive most rotors at high speed, as well as to reduce the friction heating created if the test were conducted in air. The vacuum is an important safety feature since it reduces the risk of explosion of metal dust or oil fog during a rotor failure. It is also important in preventing unsteady aerodynamic forces from destabilizing the rotor. The necessary vacuum is of the order of 200 millitorr, or about 1/4000 of an atmosphere absolute pressure. Although not considered a particularly high vacuum level, maintaining vacuum in this range requires careful attention to chamber seals and imposes stringent requirements on the high speed seal used where the spindle passes into the chamber.

Destruction of good rotors by bad spin tests has been a serious problem since the first spin test was conducted more than 50 years ago. The original spin drive was brilliantly conceived and manufactured in a matter of weeks, to solve a serious problem for the military. Unfortunately though, few significant improvements to the process were made for nearly forty years afterward, and untold millions of dollars have been wasted as a result. The problems are caused by the inherent weakness of traditional spin test spindles and the inadequate performance of the vibration dampers intended to control the various resonant vibration modes of the spindle. These dampers behave unpredictably and cause the failure of the drive spindle and destruction of the test rotor. In one notable case, spindle failure destroyed half of all the rotors tested in a production operation. In another case it proved impossible to conduct a low cycle fatigue test on a critical jet engine rotor because the test assembly was always destroyed by spindle failure within a few hundred cycles of beginning the test.

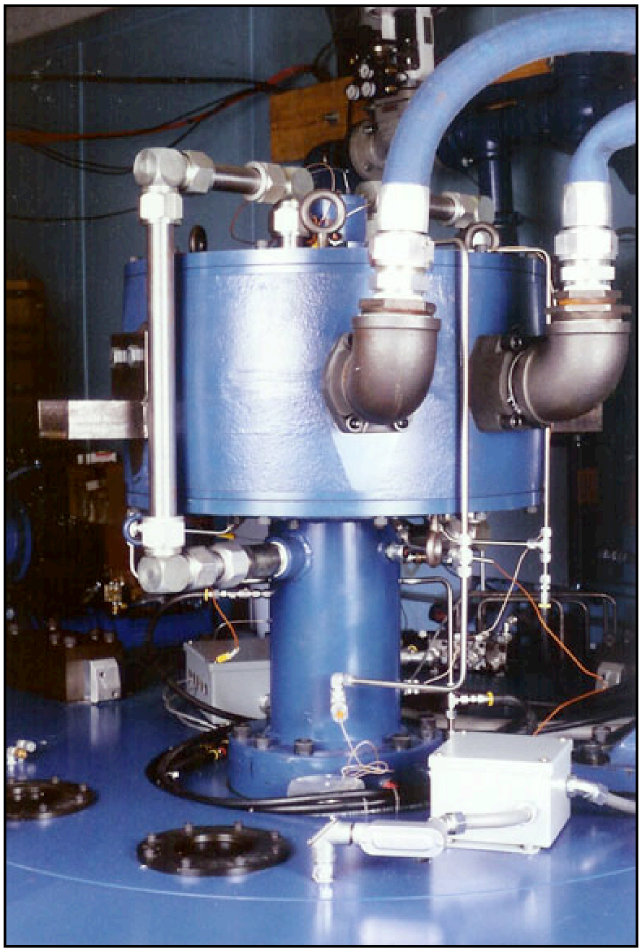

Figure 2
Ten Inch Compressed Air Turbine with Modern Damper System Mounted on Spin Pit

Fortunately, the problem has been solved by the development of substantially more robust spindle/damper systems not subject to the instability and failure modes that plagued users of the older drives. With modern spindle/damper systems, the risk of damage to a test rotor is virtually nil. With properly engineered drives and good vibration monitors, unbalance and stability problems which would otherwise have destroyed a good rotor now only result in test interruption and problem resolution.

The low power of the traditional air turbine test drives has been a handicap in the measurement of cyclic fatigue life. With the old drives, cycle times measured in minutes were common, and a 50,000 cycle life test required five months of continuous test operation. Modern high-efficiency air turbines reduce the cycle time to 10 - 30 seconds for typical jet engine rotors, reducing the total test time to about 2 weeks. The shorter test cycle allows shorter time to market and substantially reduces program schedule slippage.

Advanced Test Technology

Properly equipped spin facilities give developers the tools to perform important tests in addition to the conventional proof, burst, and Low Cycle Fatigue (LCF) protocols:

Figure 3
Modern Spin Test Console with Vibration Monitor, Heated Test Capability, Tachometer, PC Computer Interface, Slip Ring System and Radio Telemetry for Strain Measurenent and High Speed Camera Control

Hot Testing: Turbines and high pressure compressor rotors operate at high temperatures and need to be tested at those temperature levels, particularly when LCF life is being evaluated. Hot testing to 2000 °F is practical with proper selection of spindle material, installation of high performance spindle seals, and appropriate measures to control damper temperature. Although the vacuum eliminates most convective heat transfer, rotors can be heated by infrared radiation from resistive heating elements. Radio Frequency (RF) induction heating works well also, but is more costly and difficult to set up because of the need for special induction coils for each rotor configuration.

Controlled Atmosphere Testing: Inserted blade turbines often show shorter life in a heated vacuum spin test than they do in engine operation. The source of the problem is accelerated fretting at the fir tree caused by the lack of air. This problem can be eliminated by operating the spin pit at absolute pressures significantly above the conventional 100 - 300 millitorr level. High power drives, careful control of aerodynamic losses by baffle and shroud design, and special temperature controls are necessary, but a properly engineered system is capable of running a heated spin test at any pressure up to and including one atmosphere. (It should be emphasized that running heated tests with an air atmosphere carries the serious risk of oil fog or metal dust explosion, and must not be done without critical safety measures).

Blade Vibration Testing: High frequency fatigue of blades has become a serious problem in the operation of advanced performance jet engines. These problems can be explored and resolved quickly with a well equipped spin pit. Use of special high power drives makes it possible to set up and run a bladed rotor in the spin pit without vacuum, again using well designed baffles and shrouds to reduce pumping losses. Using a high speed slip ring and hollow spindle to conduct strain signals to external instrumentation, blade modes are explored by exciting vibrations with external air jets or electromagnetic fields. These tests allow rapid measurement of blade vibration response and rapid evaluation of the effectiveness of proposed changes when a problem needs to be solved. If blade mode mapping were done this way as a routine part of rotor qualification, it could reduce the number of blade vibration problems discovered in the field.

Scale Model Testing: A very limited number of spin facilities are available for testing large gas turbine engine rotors. With the trend toward very large turbines for power generation, and large fans for jet engines, the size of the rotor assemblies to be tested now exceeds the size of the available spin pits. Until new facilities are constructed, it will be necessary to do development testing with scale models. Fortunately, the scaling laws for centrifugal strength are quite simple and scale model testing can produce reliable results. To perform a scale model test, the model must be an exact scale replica of the full size assembly, including all bolt holes, fittings, and fasteners. The scaling law requires that the model must be run at a speed equal to the running speed of the full size rotor divided by the scaling ratio, so a ¼ scale model needs to be run at four times the speed of the full size rotor.

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It should be emphasized, that even though scale model testing can provide valid information about the centrifugal strength of a new design, testing a model does not satisfy the cardinal rule of testing: always test what you will ship, including the smallest, apparently insignificant detail. Scale model testing is only valid if the test assembly is an accurate model of the full size article.

Containment Testing: Recent accidents in commercial airline service have renewed interest in the problem of jet engine rotor burst. The FAA Aircraft Catastrophic Failure Prevention Program is addressing the problem by working toward development of fragment barriers and debris mitigation techniques. Spin pit burst testing of individual rotors and candidate containment structures allows rapid evaluation of new designs at reasonable cost. Advances in video recording technology allow the test engineer to study the interaction between the bursting rotor and the containment structure, validating dynamic models and pointing to improvements in containment design.

Strain Survey Tests: Despite continued advances in Finite Element Analysis (FEA) technology, computer models need both verification and initial physical parameters that sometimes only testing can supply. In particular, new kinds of non-isotropic materials including organic and metallic matrix composites are difficult to model in the three-dimensional centrifugal stress field that exists in a high speed rotor. A spin test with strain gauges placed on critical locations is very important for validating the model and understanding the performance of complex structures. Modern, advanced performance slip-rings are available for speeds up to about 90,000 rpm, and with capacity of 100 channels of strain data or more, so multiple gauges can be monitored in a single run. High temperature gauges are expensive but available, so it is even possible to evaluate the effects of temperature on the strain field.

Figure 2
This 36" spin test system was used by Test Devices Inc. to burst a rotor and demonstrate that the containment structure would satisfactorily support the event (see "Anatomy of an Accident"). However, the system, which included a spin chamber, turbine - atop the pit with two blue hoses entering the side - and vacuum and oil pumps, was later destroyed in an accident.

Real-Time Detection of Cracks: During a Low Cycle Fatigue test it is important to monitor the health of the accelerating and decelerating rotor in real time to prevent bursts. Classical spin test protocols require removing the rotor for inspection at fixed intervals, with no insight into the health of the rotor during the actual test. Without this instrumentation a spin test engineer is “flying blind”, and relies only upon experience and luck to select the correct time to remove a part for inspection. Much the same thing happens in the field with a high-performance rotor. Components are removed at fixed intervals and are inspected, but there is rarely an on-line indication of a potential problem, except for perhaps an indication of raw vibration.

A method has recently been developed to monitor and evaluate the integrity of a spinning assembly continuously throughout a test. The method uses a non-contact eddy-current probe to measure the vibration vector of the part, then compares the amplitude and phase of this vibration to a baseline that has been previously established. Any distortion in the strain field of the disk, or any relative movement of the components that make up the assembly will cause a minute unbalance and will appear as a distinct amplitude and phase change. The vibration vector change usually indicates that a disk crack has developed, but sometimes discloses some other important change in the assembly such as a loose tie bolt, etc. (see Figure 4 for a diagram of the elements of a Crack Detection System).

In the spin pit this signal is used as an early warning of a crack to determine when the part should be taken out for inspection, or as a diagnostic tool to determine if there has been some slipping, fretting or movement between the pieces of the assembly. Monitoring simple vibration amplitude is not helpful in detecting signals of interest here, since the relevant changes in vibration are very small vector quantities and often have no observable effect on the overall vibration level of a rotor.

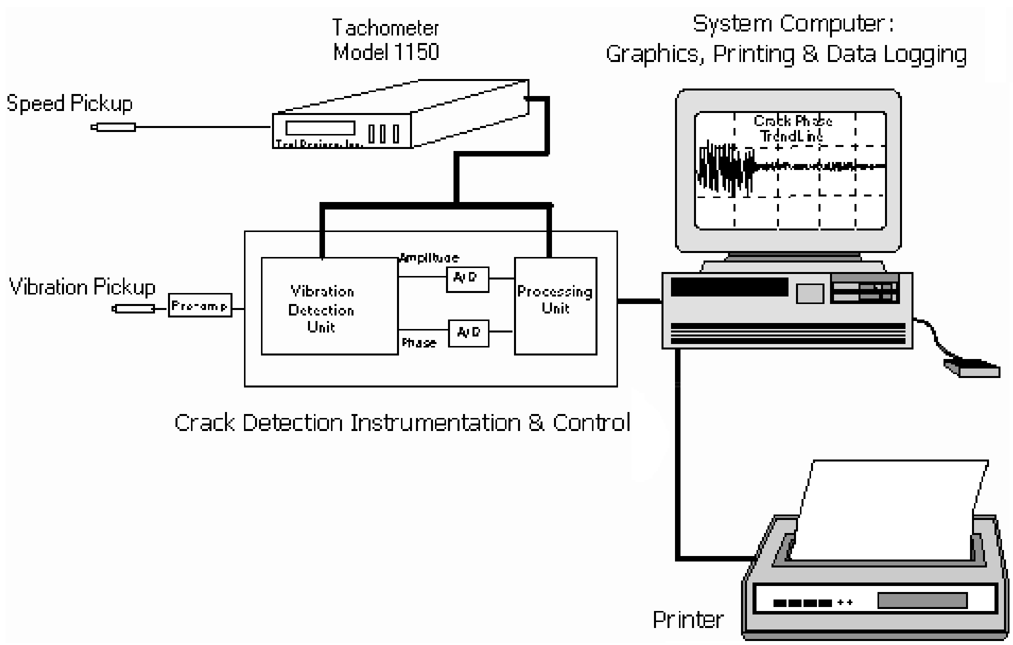

Figure 4
Crack Detection System Block Diagram

With this technology it is possible to terminate tests just prior to disk burst, preserving the entire assembly for analysis. Preventing a burst allows the metallurgist an opportunity to view the disk with no collateral damage and to determine the crack initiation site with complete certainty. Preventing a burst also reduces the cost of the test by eliminating the high costs associated with facility repair after a failure; and further savings are realized by preserving arbors, blade sets, and other associated tooling and attachments.

Safety

Spin testing is potentially dangerous. The kinetic energy of typical turbomachinery components is very high at burst speed, and the fragments of a disk can do serious damage to structures and people if containment is inadequate. For example, a 200 lb steel disk spinning at 18,000 rpm has a kinetic energy of approximately 5.2 million lb-ft, the equivalent of a 22 ton truck traveling at 60 miles per hour. A recent fatal spin test accident in Europe underscores the need for careful consideration of the potential hazards inherent in operating spin pits. A large number of the spin test facilities in the United States are home-made, designed by engineers who may have been unaware of some of the more subtle hazards of spin test operations. Many of them are unsafe. Some of the commercially manufactured spin pits were designed

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during a time when rotor fragment energies were lower than those of advanced performance, modern turbomachinery equipment, and are inadequate in several important areas. Some of these old designs are still being offered on the market. A well designed test facility has the following important features:

1. Strong Lid/Cover Retention. Nearly all of the serious spin testing accidents have been the result of axial containment failure. Aluminum or titanium dust can produce pressures in excess of 100 psi, with a very rapid rise time. Lubricants, including "fire resistant" hydraulic fluids are nearly as hazardous. The chamber must be designed for explosive pressure rise of this magnitude and the cover must be held with substantial clamps or bolts or lid dogs, adequate to contain the explosion. Vacuum force is not sufficient by itself to safely retain the cover, and explosion ports cannot vent the chamber rapidly enough to prevent overpressure.

2.Strong Radial Containment. The containment should be a single steel cylinder to prevent multiple sequential shear penetration failure, and it must be free to rotate with respect to the vacuum chamber as a bursting rotor transfers its angular momentum to the liner during a burst. Spectacular accidents have occurred when the burst liner was constrained from rotation and the bursting rotor had enough energy to tear the spin pit from its mountings and cartwheel it around the room.

3. Secondary Protective Barriers. Operators and bystanders should NEVER be directly exposed to an operating spin pit. Despite all the efforts of safety engineers, the high rate of energy release by bursting rotors can cause unpredictable results, endangering people and equipment. The spin chamber needs to be located in a reinforced concrete test cell, with the operator station located outside. No one must be allowed in the test cell when the machine is running, and safety interlocks must be in place to prevent the pit from being opened under unsafe conditions.

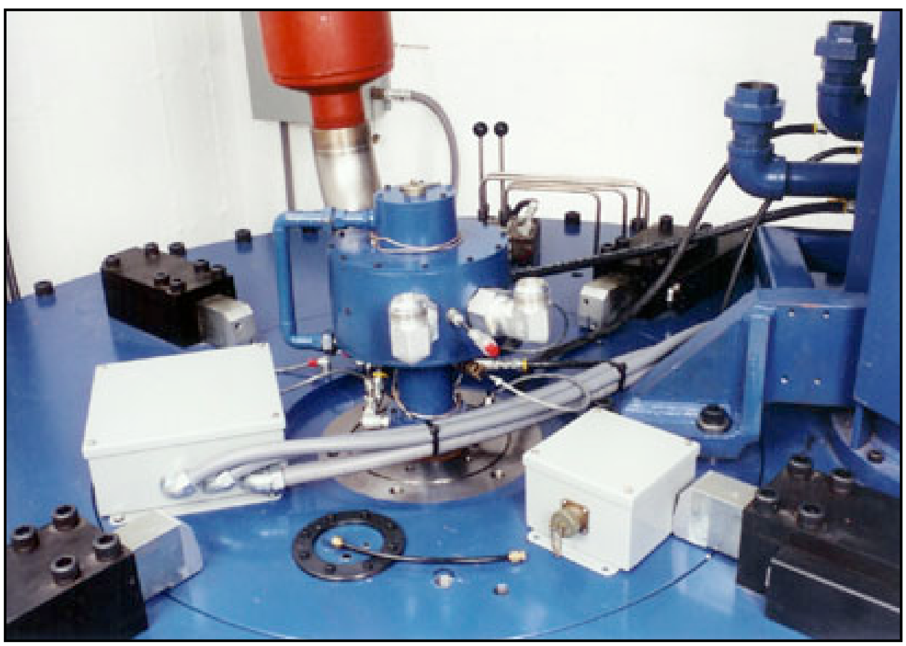

Figure 5
Top of Spin Pit with Air Turbine Mounted in Center Showing Lid Dogs Used for Axial Lid Retention

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Summary

Spin testing is the most cost-effective and reliable way to evaluate centrifugal stress. Many problems with spin testing in the past have been solved with advanced high technology developments in damping systems, high-performance turbines, hot testing, reduced vacuum testing, and non-destructive methods to detect cracks in real-time. Spin testing can be a dangerous activity and the equipment must be designed and installed appropriately to minimize the risks inherent in the rapid energy release of a rotor burst. Advanced technology rotors made of new materials present special challenges to existing spin test systems, and these need to be examined on a case by case basis.

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