Quantitative Reliability Assessment of Ball Bearings versus Active Magnetic Bearings for Flywheel Energy Storage Systems

White Paper 111

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Objective

An industry myth heard frequently today is that energy storage flywheel systems that use magnetic bearings are more reliable than those supported by ball bearings. However, these claims are largely based on unsubstantiated, non-quantified presumptions. This paper reviews the basic differences between ball bearings and magnetic bearings used in flywheel energy storage systems and provides a quantitative reliability comparison which effectively refutes these claims.

Ball Bearing Construction

Many industry professionals are familiar with ball bearings, a specific form of the more general term “rolling element bearings.” In ball bearings, a cluster of balls are situated between inner and outer rings (races), each ring containing a groove (raceway) which nearly conforms to the geometry of the ball. A plastic or metallic cage or separator is used to distribute the balls uniformly around the raceway and may be snapped, riveted, or crimped in place. This cage is free floating and rides on the balls typically rotating at about one-half of the shaft speed. The inner race is firmly attached to the shaft and the outer race is held in a pocket in the stationary part of the machine.

Grease lubricated ball bearings are typically sealed for life, the grease simply being a reservoir for oil that keeps the bearing lubricated. These seals or shields keep dirt and other foreign materials out of the bearing and may be snapped into the outer ring or held in place with a retainer ring (snap ring). Shields are used to minimize rubbing friction and are generally preferred for higher speeds where the heat of friction would increase bearing temperatures. Seals are preferred for dirty and other aggressive environments. When high speed bearings are operated in vacuum environments, the shield also acts as a barrier to oil migration out of the bearing. Bearing grease operating in standard atmosphere degrades due to oxidation whereas the primary mechanism of degradation in vacuum is oil loss through evaporation. By minimizing the space between the stationary shield and the rotating inner ring, the oil evolved from the grease by evaporation remains inside the bearing where it continues to provide lubrication.

The construction of the ball bearing used in Active Power’s flywheel based CleanSource® UPS (uninterruptible power supply) system is simple and contains two races (inner and outer), two snap-in shields, nine balls, one retainer and one metered amount of grease. The entire bearing system consists of an upper and a lower bearing made up of thirty parts, all subject to rigorous dimensional verification and other quality control operations. From a parts count perspective, the simplicity of the design provides excellent potential for high reliability.

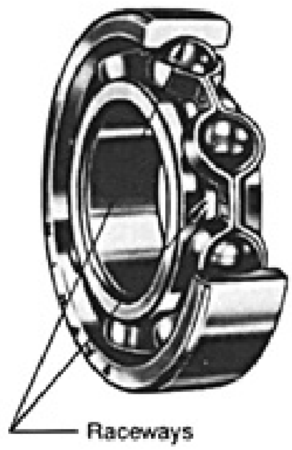

Figure 1: Cutaway view of a deep groove ball bearing showing balls, ball separator, inner and outer races and raceways.

Magnetic Bearing Construction

Magnetic bearings can be categorized as active or passive. The term active magnetic bearing (AMB) is used to describe those that derive power from an external source (power supply) as opposed to passive magnetic bearings that derive power from their own rotation, usually by incorporating a rotating permanent magnet. Some research flywheels using superconducting passive magnetic bearings are currently in development, but the need for cryogenic cooling systems makes these systems too expensive for UPS applications. Today, all commercially available flywheels for UPS applications use either mechanical ball bearings or active magnetic bearings.

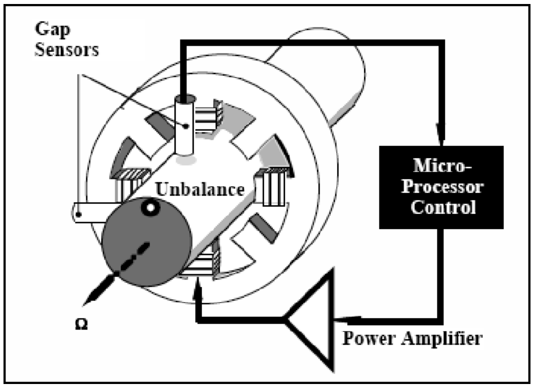

Figure 2: Fundamental representation of an Active Magnetic Bearing (AMB) design

The main elements of a generic active magnetic bearing are shown in Figure 2. Coils wound around steel pole pieces form the actuators that carry current and apply magnetic force to the rotating shaft. The magnetic fields applied by these actuator poles can only pull on the shaft so for each "axis" of motion one needs at least two actuators to hold the rotor in stable levitation between each pole. One needs to sense the motion (displacement) of the shaft and control the balance of motion between opposing actuator poles to keep it from crashing into the backup ball bearings that are an essential safety element of any magnetic bearing design.

Magnetic bearing systems used on high speed flywheels are typically 5-axis designs. For a vertically oriented shaft, there is one vertical axis and two horizontal axes at either end of the machine. Since each axis must control motion in two directions, a 5-axis active magnetic bearing contains at minimum 10 actuators; 10 amplifiers and associated circuitry; five feedback sensors and associated circuitry; and one control processor. The number of total components including individual circuit board elements is in the hundreds. From a parts count perspective, the active magnetic bearing is subject to numerous potential component failure modes.

Reliability of Magnetic Bearings

The reliability of a magnetic bearing is usually based on standard calculations such as those presented in Military Handbook MIL-HDBK217[1] using generic failure rates for individual circuit components. Failure of electronic components represent only one potential failure mode with magnetic bearings. Other potential failure modes not factored into component analyses include spurious signals (noise) on the rotor position feedback loop, controller software bugs and excessive load from either internal sources (for example large shift in rotor balance) or external sources (impact forces, for example).[2,3]

Source	MTBF (hours)	Notes
Calnetix	122,640	MTBF of 14 years based on MIL-HDBK217 calculation of the magnetic bearing controller electronic components. Excludes reliability of rotor position sensors and bearing actuators. Vycon is a spinoff from Calnetix. Calnetix magnetic bearings are used in the Vycon flywheel. Ref: http://www.calnetix.com/magneticbearingcontroller.cfm Last accessed Feb. 10, 2008
S2M	200,000	Turbomolecular vacuum pump spindles Ref: http://www.s2m.fr/magnetic_bearings.html Last accessed Feb. 10, 2008
Yates	40,000	Markov analysis of a magnetic bearing controller algorithm Ref: Yates, SW, and Williams, RD, A Fault-Tolerant Multiprocess Controller for Magnetic Bearings, IEEE Computer Society Press, v8, issue 4, August 1988, pp 6-17.

Figure 3: Active magnetic bearing MTBF estimates from various sources

The published MTBF (mean time between failure) of various magnetic bearing systems are presented in Figure 3. MTBF is a useful metric for comparing failure rates of equipment such as electronics whose failures tend to be random. The reciprocal of MTBF is the failure rate, λ, and is constant with time. However, this does not mean the reliability is constant with time. In fact, the reliability of the component decreases the longer the system is deployed. The time dependent reliability of the exponential (constant failure rate) probability distribution is given by:

$$R(t) = \exp^{-\lambda \cdot t}$$

The MTBF for the Calnetix AMB controller is reported to be 122,640 hours and the constant failure rate is 8.15 failures per million hours. The reliability as a function of time is shown in Figure 4. While the MTBF for the AMB seems like a reasonably high value, the reliability decreases to less than 25 percent over the 20-year life of the flywheel system. Since the probability of failure P(t) = 1 – R(t), one sees that the probability of failure by the end of the design life of the product is at least 75 percent. Interestingly, a known characteristic of the exponential failure distribution is that the failure rate is not improved by preventative maintenance (PM) of the components as the failures are still expected to be random and not due to wear-out.

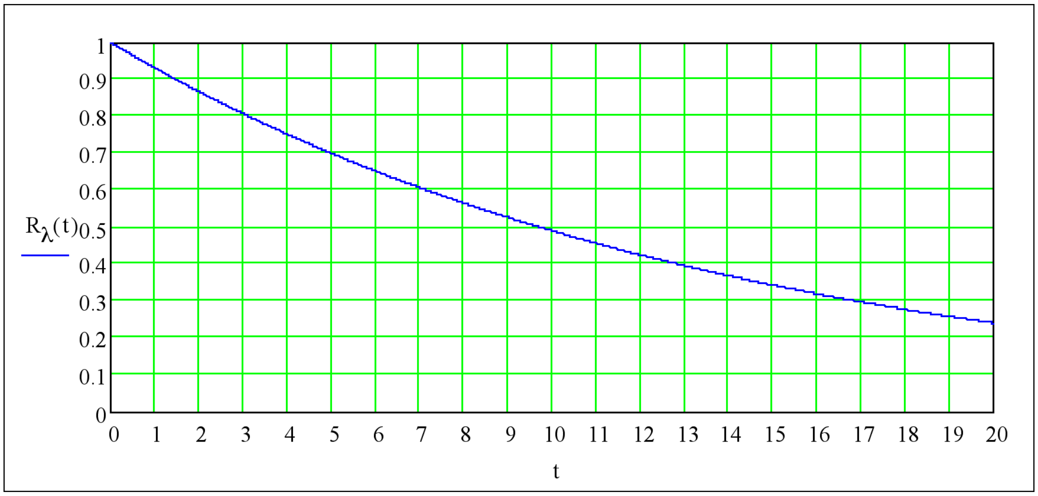

Figure 4: Time-dependent reliability for an active magnetic bearing controller having MTBF of 122,640 hours (14 years)

The Calnetix data presented in Figure 3 is reportedly based on the controller electronics hardware alone and does not address control software failure modes. The paper by Yates addresses the MTBF of the control software and not that of the hardware. It can be seen that including software failure rates can significantly reduce the reliability of the active magnetic bearing. Another factor not accounted for in the MTBF data of Figure 3 is the reliability of the input power source to the controller power supply.

Magnetic bearings require a UPS in order to prevent the rotor from setting down on the backup bearings during normal operation. It is also well known in the industry that a high speed flywheel rotor drop onto backup bearings can only be tolerated a few times at best. One would think this would not be an issue in systems designed for UPS applications, but this deserves a closer look.

Most flywheel energy storage systems (FESS) derive control power from the output of the UPS to which they are connected. This renders the control of their magnetic bearing system vulnerable to factors that influence the output of the UPS. One factor in particular is the potential for human error such as engagement of the UPS system's emergency power off (EPO) before the FESS is shut down. Industry data suggests 12 percent of all dropped loads are due to actuation of the EPO as shown in Figure 5.[4]

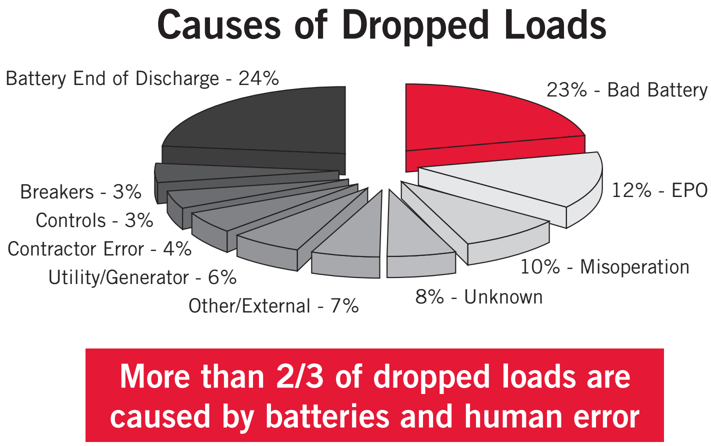

Figure 5: Causes of dropped loads in mission-critical facilities

The user manual from one high speed flywheel contains the following cautionary statement.

CAUTION

The AC power supply must remain connected at all times. Precautions must be taken to ensure that the connection is not broken. Disconnection may cause damage to the equipment

It is apparent that not only is the reliability of the magnetic bearing dependent upon the output of the UPS that it supports, but the mechanical integrity of the flywheel is dependent as well. One should question manufacturers whether damage to the flywheel system caused by actuation of the UPS EPO or any other break in the protected AC power supply line is covered by warranty. Furthermore, the reliability of the active magnetic bearing should also include the expected failure rate of the UPS output which, while low, is finite and is not factored into any of the above MTBF calculations.

Reliability of Ball Bearings

The primary factors that affect rolling element bearing life and reliability are load, speed and adequate lubrication. Bearing life varies with the cube of the load and is directly proportional to speed so limiting bearing load is an important prerequisite to improving bearing service life and reliability. Because of the relationship between bearing life and load, Active Power incorporates a unique means of using the flywheel generator magnetic fields to effectively reduce the weight of the rotor that rides on the lower bearing. This patented “magnetic unloading” feature is a key factor contributing to the high bearing reliability that is achieved in service.

The reliability of rolling element bearings was originally investigated by Weibull (1939)[5] and was extended by Lundberg and Palmgren (1947)[6]. The analysis by Lundberg and Palmgren forms the basis for modern bearing load-life reliability relationships with adjustments for updated materials, processing and lubrication performance. These relationships are incorporated into American National Standards Institute (ANSI) / Anti-Friction Bearing Manufacturers Association (AFBMA) Standard 9 – Load Ratings and Fatigue Life for Ball Bearings. While this standard offers useful metrics for general purpose design, it does not account for the most recent advances in bearing technology such as ceramic ball bearings, nor does it account for lubrication factors for operation in vacuum. Because of the numerous application dependent factors that affect ball bearing life in flywheel systems, a more useful measure of the true reliability is through the accumulation of field data for a large population of systems.

Active Power tracks the bearing life of all flywheels in its service database. In 2007, the company collected operating life data from 453 fielded flywheels that included a combination of original bearings, plus several that had been replaced at or around the recommended replacement interval, plus one bearing that had failed in service. Using Weibull++ software from ReliaSoft, Active Power fit the data to a Weibull distribution using maximum likelihood estimator (MLE) procedures. The curve fit takes into account both uncensored (failed) and censored (non-failed) bearing lives including the life of the one failed bearing, the life at the time of preventive maintenance for all replaced bearings, plus a snapshot of the life of bearings still in operation at the time of the study.

Figure 6 shows the probability density function of the mechanical bearing data which appears to closely match a normal distribution, a special case of the Weibull distribution. The “mean” of this distribution is centered on 6.94 years (58,640 hours). If stopped here, one might conclude the active magnetic bearings are more reliable than mechanical bearings. However, one should remember mechanical bearings have non-constant failure rates and thus the mean of the Weibull distribution is not an appropriate parameter for comparison to the mean (MTBF) of the exponential distribution. Instead, one needs to compare the failure rate and reliability (or its converse, the probability of failure) with the PM interval of the mechanical bearing taken into account.

Figure 7 shows the time dependent failure rate for the Active Power ball bearing system according to the Weibull distribution. Given a recommended replacement interval of three years, the failure rate at that point in time is expected to be 0.0229 failures per year or 2.61 failures per million hours. For the 122,640 MTBF magnetic bearing controller, which does not include actuator assemblies, software or the UPS failure rates, the failure rate at that same time is at least 8.15 failures per million hours – more than three times that of the mechanical bearing. When the mechanical bearing is replaced, the failure rate of the new bearing returns to zero. This is in stark contrast to the magnetic bearing whose failure rate is assumed to be constant. In reality, the constant failure rate assumption for electronic components applies only to the flat portion of the bathtub curve that is associated with these types of components. In reality, the initial failure rate is higher due to infant mortality associated with quality issues and at some point component wear-out (for example electrolytic capacitors) becomes a factor near end-of-life timeframes.

When considering flywheel energy storage technologies for UPS application, the most important desired feature is high reliability. High reliability equates to low probability of failure which lessens the risk of exposing a customer’s critical load to unprotected utility power. Unlike batteries that are prone to failure on demand, flywheels (from any manufacturer) rarely fail on demand. Given that PM bearing changes can be done in a few hours and can be done with the system online in N+1 configurations or with the system in bypass and on generator, the risk of outage exposure during bearing PM is minimal.

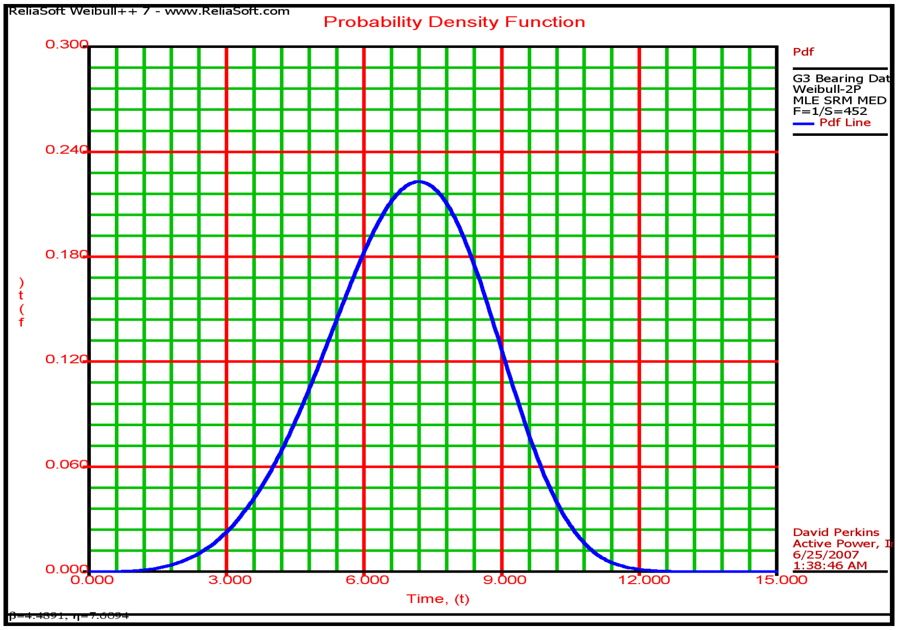

Figure 6: Probability density function of CleanSource flywheel UPS bearings

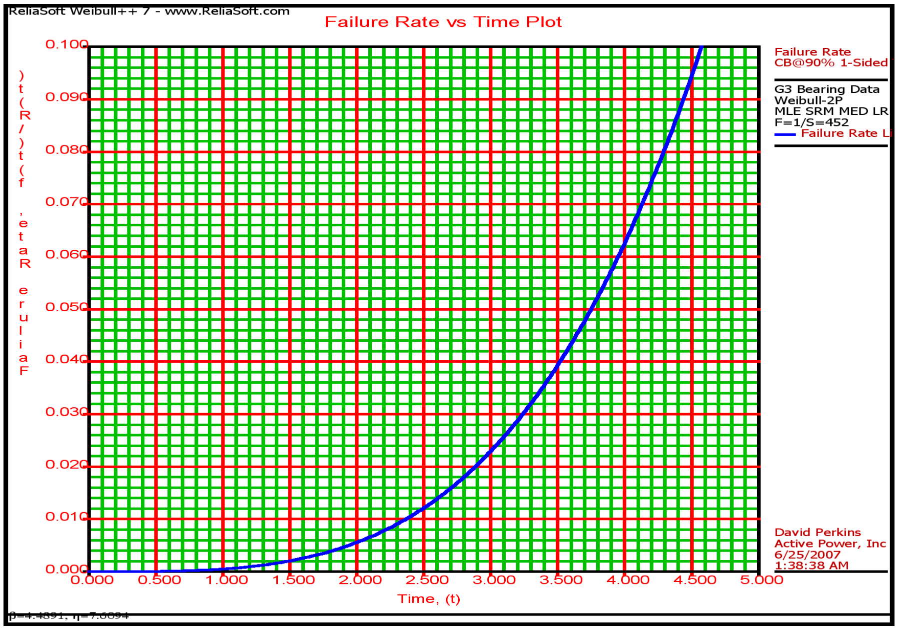

Figure 7: Time dependent failure rate of CleanSource flywheel UPS bearings

Figure 8 compares the time dependent reliability for the Active Power CleanSource flywheel ball bearing system which varies according to the Weibull distribution with the 122,640 MTBF magnetic bearing controller whose reliability varies according to the exponential (constant failure rate) distribution. At the three year bearing PM interval, the mechanical bearing system has a mean reliability of 98.5 percent. Because the data is based on a large flywheel population, one can state with 90 percent confidence the reliability is at least 95.3 percent, but not more than 99.7 percent. The confidence bounds on the mechanical bearing data are shown in Figure 9.

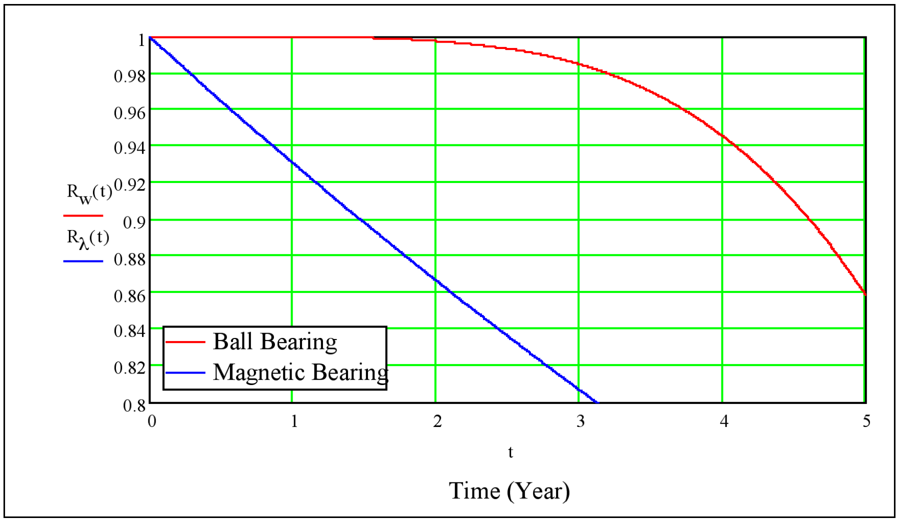

Figure 8: Time dependent reliability comparison between Active Power CleanSource flywheel ball bearing system and a magnetic bearing system with 122,640 hr MTBF

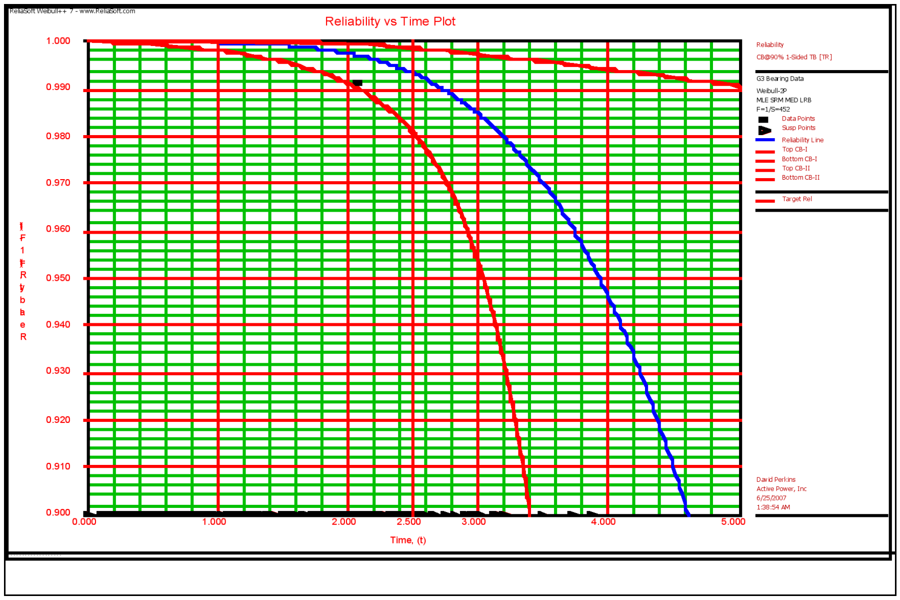

Figure 9: Time dependent reliability of the Active Power CleanSource UPS ball bearing system showing upper and lower one-side 90 percent confidence bounds on reliability

As a further indication of mechanical bearing robustness, this level of reliability is not dependent upon the presence of the UPS since the loss of bearing load control simply results in an increase in bearing load to the full rotor weight for a very brief period of time. These effects are included in the field data for the ball bearings since periodic application of full rotor weight on the bearings occur in the normal course of operation and so is inclusive of all contributing factors in the operation of the bearing system. As a result, fault tolerance of the mechanical bearing system is significantly higher than that of the magnetic bearing system. Mechanical bearing fault tolerance is one reason they are so widely used in aircraft engines compared to other bearing types.

Finally, it is a characteristic of mechanical bearings that impending failures are detectable and offer the opportunity for proactive replacement. By monitoring bearing temperatures and vibration, bearing deterioration can be detected thus signaling the need for replacement. The use of commercially available bearing condition monitors further improves this detection capability.

CONCLUSIONS

Quantitative reliability analysis was performed to compare expected performance of mechanical and magnetic bearing systems used in UPS flywheel energy storage products. CleanSource UPS systems employ rolling element ball-bearings that make them highly reliable. Indeed, these bearings have an expected reliability of 98.5 percent at the time of recommended PM replacement with the reliability being renewed to nearly 100 percent at that time. In contrast, a typical maintenance free active magnetic bearing system will have an expected reliability of not more than 81 percent based on analysis of the controller alone and will continue to decrease as life of the system increases.

Mechanical bearings are much more fault tolerant than magnetic bearings particularly in any scenario where controller input power is lost, including human errors introduced by improper shutdown sequence or failures in UPS output. In fact, fault tolerance of rolling element bearings is one of the primary factors that contribute to their continued use as the bearing of choice for all commercial and military aircraft engines – applications where reliability is of utmost concern as the lives of millions of passenger per year depend on their service.

References

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[4]Preparing Your Data Center for Blade Servers, Server Blade Summit Tutorial 2B, Sever Blade Summit 2006, April 18-20, 2006.

[5]Weibull, W., The Phenomenon of Rupture in Solids, Ingeniors Vetenskaps Akademian, No. 153, 1939.

[6]Lundberg, G. and Palmgren, A., Dynamic of rolling Element Bearings, Acta Polytechnica, Mechanical Engineering Series, Vol. 1, No. 3, Stockholm, 1947.