Long Term Backup Bearing Testing Results

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Abstract

An energy storage flywheel was developed in 2005 to provide ride-through power for industrial UPS applications, and its application was expanded to provide regeneration power for mobile cranes. The flywheel, which operates in a vacuum, is supported by Active Magnetic Bearings (AMB) to minimize bearing losses, and has a high power motor/generator coupled to an efficient power conversion module. The flywheel can maintain energy for emergency use by holding at full speed or can be cycled up and down in speed to absorb and discharge energy rapidly. Over 400 Flywheel systems have been delivered and are operating in the field since product release.

In addition to the AMB, the Flywheel system uses a backup bearing system to support the rotor; 1- when the system is not in operation, including shipping; 2- during low speed safe spin-downs when external power is disconnected, 3- during intermittent overload events (only expected in crane systems as a result of crane motion) and 4- during high speed spin-downs when system events/failures occur. Low speed spin-downs typically start at 4,000 rpm in crane systems and can happen multiple times a day, while UPS systems typically start at 6,000-8,000 rpm and may only happen once a year. Overload events in crane systems can happen at any speed in the operation range of 10,000 rpm to18,000 rpm and last for up to 5 seconds.

The backup bearing system of every flywheel is tested with a series of backup bearing drop tests culminating with a drop and spin down from full speed. Additionally, several engineering flywheels have been used extensively for testing and development of the backup bearing system. The original system was capable of three 2.75 hour spin downs from 36,000 rpm and developed with the UPS system requirements in mind. Methodology and results for this test program were described in [1] and [2].

Recent testing has validated the system for use in crane system with added low speed spin-downs and momentary overload conditions at high speeds. In addition, incremental changes to the backup bearing system have resulted in extending the capability to eight 2.75 hour spin downs from 36,000 rpm for UPS applications. These changes are the result of continued analysis of backup bearing operation during spin-down. This ongoing test program is reported here – including a discussion of some of the test results.

1.0 Vycon Flywheel System

VYCON flywheels are primarily used in two applications, high reliability power backup in UPS systems (the VDC product) and energy recycling on rubber tire gantry (RTG) cranes (REGEN product, shown in Figure 1). In UPS applications the flywheels are floor mounted in data centers and hospitals to provide ride through power. On RTG crane applications, the flywheels are mounted on the crane and recycle braking energy to increase overall crane efficiency and lower peak power requirements.

Figure 1. Vycon VDC and REGEN (with Two Flywheels) Products

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The flywheel module, shown in Figure 2, is designed to store a total energy of 1.25 kWh at 36,000 rpm and deliver 225 kW for 13 seconds (0.81 kWh). The steel flywheel rotor weighs 1070 N (240 lbf). The AMB uses homopolar permanent magnet bias actuators to provide suspension of the rotor during normal operation. A magnetic bearing controller (MBC) is powered initially by power available at the user site, and switched to power from the flywheel generator when the speed increases to 6,000 – 8,000 rpm in UPS systems and 2,000 – 4,000 rpm in crane systems. For rotor support during non-operation (shipping, installation), power loss to the AMB, and during emergency/fault conditions of the AMB is a mechanical touchdown bearing (TDB) system located at each magnetic bearing actuator location as seen in Figure 2, as described by Hawkins [3]. A passive axial lifter is used to offset approximately half the rotor weight, reducing the steady force that must be supplied by the axial AMB. Since the passive lift is also present when the AMBs are not active, the weight load on the backup bearings is also reduced by half to approximately 535 N.

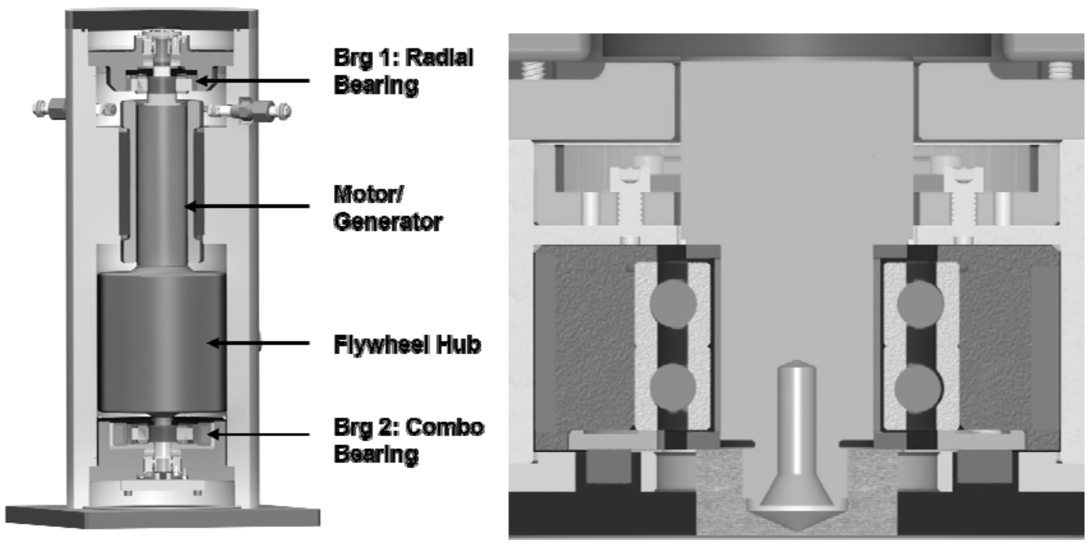

Figure 2. Vycon Flywheel and TDB Assembly

1.1 Vycon Flywheel TDB System

As reported by McMullen [1] and Hawkins [3], the TDB system used in the flywheel is comprised of angular contact duplex pair bearings with ceramic ball and vacuum compatible grease. The flywheel is oriented in a vertical position, with the bottom TDB supporting axial (vertical) as well as radial loads. The upper backup bearing carries only radial loads. Both pairs are identically mounted. The axial load is dominated by the weight of the rotor, where the radial loads are dominated by rotating dynamic loads. This arrangement is true for both the UPS flywheel as well as the crane flywheel. Radial clearance between the TDB inner race and the rotor is nominally 0.0065 inches.

The bearings have a 25 mm bore giving a standard speed parameter, DN = 900,000 at maximum operating speed. The outside diameter is 47 mm giving NDm = (47+25)/2*36,000 = 1,300,000. This relatively conservative speed parameter was chosen for this system because the worst case spin down time of the system is up to 3 hours. Additionally, with repeated long spin down times and high NDm, grease life can become the limiting factor in the life of the bearing system. In many applications such as centrifugal compressors, turbine, and generators, spin down times less than 1 minute are possible and backup bearings can be successfully designed with speed ratings up to 2.5e6 NDm.

The bearings are mounted in a compliant mount that provides both stiffness and damping. The bearing mount is intended to minimize impact loading during the drop transient and to lower the rigid body natural frequencies to minimize bearing loads. The compliance or radial flexibility is provided between the mount and housing, where a hard stop limits radial deflection. The net radial stiffness is 5.0e6 N/m, resulting in a lowest radial natural frequency of 40 Hz. Extensive testing has been performed on the backup bearing system to validate its performance. During development the backup bearing mount was modified to improve the dynamics of the flywheel during an emergency coast down event.

When the MBC detects sustained rotor contact with the backup bearings – whether due to temporary overload or hardware failure, the MBC commands delevitation and the rotor drops onto the backup bearings. To prevent continued operation during this event, a fault signal from the MBC is sent to the FESS controller, whereby the FESS goes into shutdown mode. The duration of operation on the backup bearings is then dependent on the type of shutdown present.

1.1.1 Dynamic Characteristics of the Backup Bearing Spin Down

Dynamic data for this flywheel system was described in detail by Hawkins [2]. The basic performance has been consistent from flywheel to flywheel. This data is repeated here for reference to establish the basic characteristics of the spin down. The data in Figure 3 is taken from the position sensors of the upper radial bearing from a time slice of the spin down when the spin speed is 32,700 rpm. Figure 3 (a) shows a 0.1 second time slice in time history form, and Figure 3(b) shows the x versus y orbit taken from the same time slice. In Figures 3(a), the dashed lines at ±0.18 mm (0.007 in) represent the nominal backup bearing clearance. Likewise, the dashed circle at 0.18 mm (0.007 in) in Figure 3(b) represents the nominal backup bearing clearance. Excursions past the nominal clearance represent deflection of the compliant mount and any bending of the shaft between the position sensors and the backup bearings. Figure 3 shows data for a spin speed of 32,700 rpm. The primary whirl orbit is forward whirl at 45 Hz with a much smaller synchronous component. The characteristic dynamic behavior in all tests was consistently a full circle forward whirl at 35-50 Hz around the backup clearance for all spin speeds above 2400 rpm. This is an important result because the low whirl frequency reduces the load reacted by the backup bearings. The small loops in Figure 3b represent the synchronous orbit which is about 0.012 mm (0.0005 in) at this speed. The synchronous loops on successive cycles fall on top of each other because the selected spin speed happens to be an integer multiple of the whirl frequency.

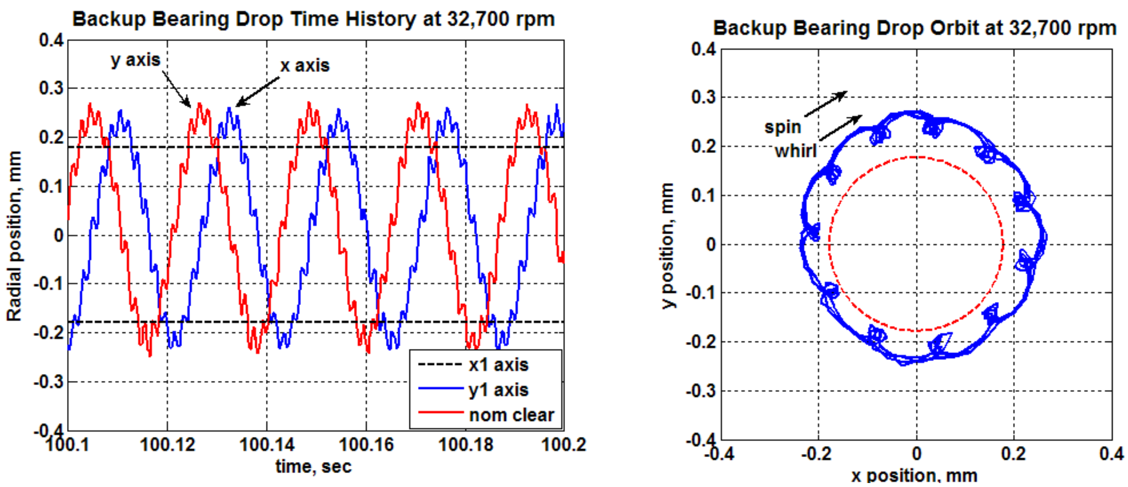

Figure 3: Time History (a) and Orbit (b) from X & Y Position Sensors at 32,700 rpm

1.1.2 Backup Bearing Loads and Life

The flywheel backup bearing system has been used successfully since 2005 with currently over 400 systems delivered. Two engineering flywheels have been used for periodic development testing to try to extend the backup bearing life to 10 unassisted spin downs from 36,000 rpm. As part of the process, loading conditions were reviewed to assist in making small changes. The loading conditions on a backup bearing are generally quite different than for a bearing in normal service. Many non-standard factors have to be considered, some which are: 1) impact load from a drop transient, 2) rapid spin up of inner race and subsequent heating of the inner race, 3) impact loads from traverse of the rotor through the clearance space, and 4) misalignment. Regardless, some load related scheme must be used to initially size backup bearings and to evaluate some changes to the system.

The nominal expected external loads for the backup bearings during spin down are summarized in Table 1. Since the magnetic bearings use permanent magnet bias, a load is imposed by the actuator negative stiffness even when the rotor is delevitated. The lower backup bearing pair carries the static weight load which is offset by the passive lift force mentioned above. The synchronous loads due unbalance load can be reasonably estimated with standard unbalance response analysis in cases where the rotor remains in contact with the backup bearing inner race. As observed in the dynamic data above, this is the case for this flywheel. Of course, the load will vary as a function of spin speed so for initial sizing or for comparison purposes as intended here, the load at maximum spin speed is used. The dynamic whirl load is due to the rotor whirling about the large clearance space or dead band between the rotor and the bearing inner race. Experience has shown that with vertical machines, the rotor will generally exhibit forward whirl about the clearance space at a frequency much lower than spin frequency. This flywheel characteristically whirls at 35 – 50 Hz so 50 Hz is used here.

Bearing	Radial Bearing	Combo Bearing (Radial)	Combo Bearing (Axial)
Parameters			
Bearing Reference Name	Brg 1	Brg 2	
Coordinate Names	x1,y1	x2,y2	z
Dynamic Load Capacity, N (lbf)	9,650 (2,163)	9,650 (2,163)	
Net Negative Stiffness, N/mm (lbf/in)	950 (5,400)	1,600 (9,100)	1,400 (8,000)
Backup Brg Gap, mm (in)	0.165 (.0065)	0.165 (.0065)	0.152 (.006)
Loads During Continuous Spin Down			
Negative Stiffness Load N (lbf)	219 (49)	366 (82)	250 (56)
Static Weight N (lbf)	-	-	535 (120)
Dynamic Unbalance, 600 Hz Ecc=5 um (0.0002 in) N (lbf)	112 (25)	67 (15)	-
Dynamic Whirl, 50 Hz N (lbf)	856 (192)	1560 (350)	-

Table 1: Backup Bearing Load Data

Approximate life for sizing and comparison purposes can be calculated using the Modified L10 life calculation given by ISO 281 [4].

$$L_{10,Modified} = a_1 a_{2,3} \left(\frac{C_o}{P}\right)^3 \frac{10^6}{(60)N} \tag{1}$$

Where N is the spin speed in revolutions per minute, Co is the dynamic load capacity specified by the bearing vendor, P is an equivalent load calculated from the radial loads and axial loads (static and dynamic) using factors from [4] or from the bearing manufacturer. Internal preload should be included in P and this allows consideration of the impact of temperature rise of the inner race relative to the outer race and any external constraints. The life adjustment factor a_1 is for calculating reliability other than 90%. The life adjustment factor a_{23} accounts for material and lubrication conditions. This factor is generally provided by the bearing manufacturer and is heavily dependent on operating temperature as it influences the lubricant viscosity. Additional life adjustment factors can be included if desired to account for other factors such as misalignment or impact loading. Using this basic formula, with a 36,000 rpm spin speed and an expected operating temperature of 150F – basic L10 lives can be calculated from the loads in Table 1 of 15,700 and 2,800 hours for the upper and lower TDB pairs. This calculation provides a reasonableness check on the suitability of the bearing design, but should be augmented by a more sophisticated analysis that calculates Hertzian contact stresses and other parameters.

Equation 1) does allow for a relative comparison of different loading and temperature conditions. Temperature will affect the life factor a_{23} through its effect on viscosity. Temperature can also have an impact on preload if there is not enough thermal compliance in the system. Duplexed backup bearings which are normally mounted face-to-face are sensitive to a temperature increase of the inner race relative to the outer race.

1.1.3 Acceptance Testing

Acceptance testing of the TDB in production is accomplished with multiple coast downs on every flywheel. Coast downs on the TDB are performed at 5,000 rpm, 12,000 rpm, and 18,000 rpm, bringing the bearing to its operating temperature and validating bearing operation. In addition, on UPS systems, a motor down TDB drop from 36,000 rpm is also conducted to validate operation. Data is gathered for each of these tests for the initial 4 minutes of the

drop for each axis. This data captures position as a function of time for each axis, as well as speed verses time. The data is used to review any anomalies that may be observed during testing.
Figure 4 below presents a sample of data for the 36,000 rpm drop for a production rotor that passed this series of tests.

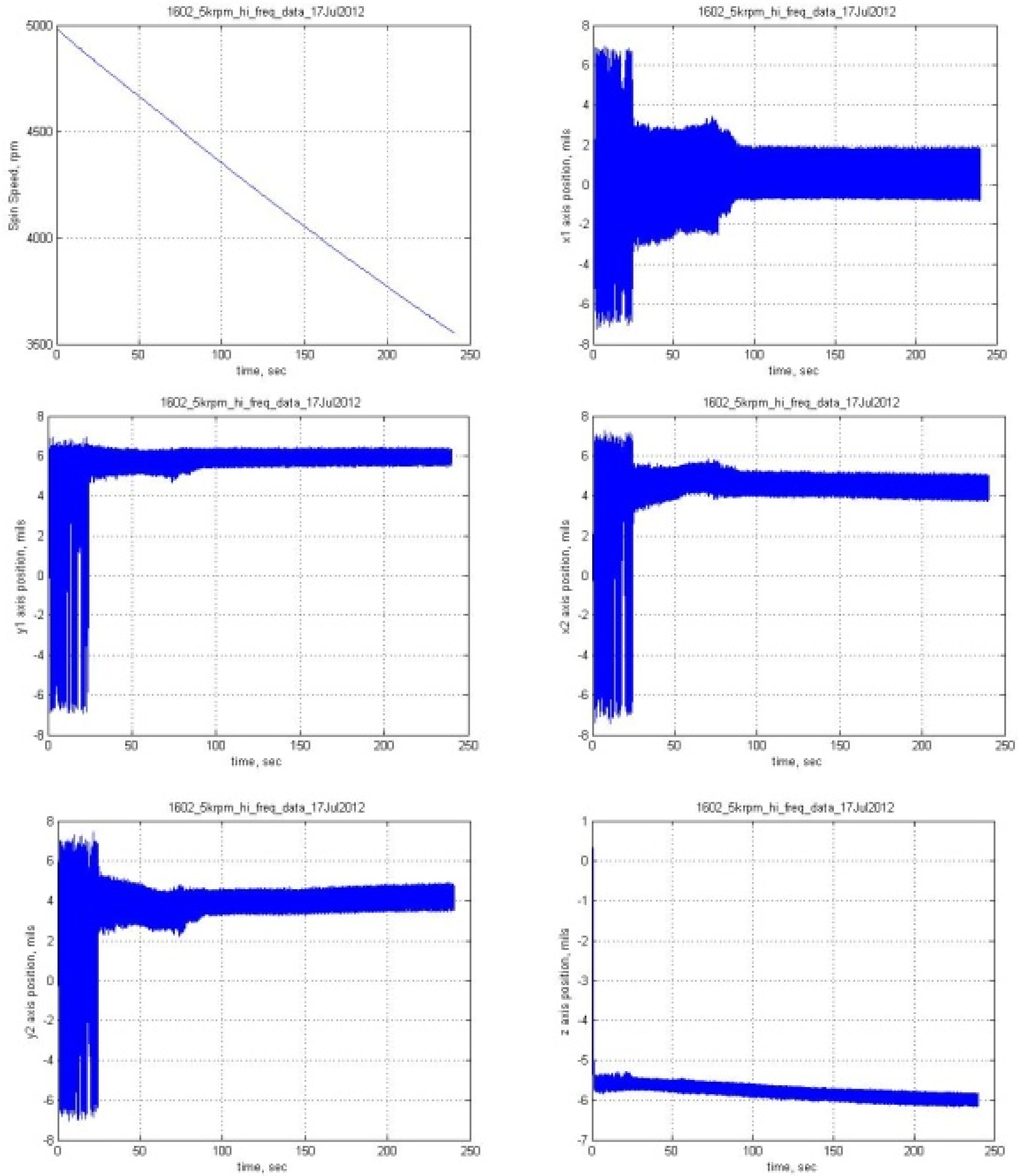

Figure 4. TDB Test Data from 5,000 rpm Coast Down

The current TDB system was developed based on the UPS application, and intended to:

- Remain undamaged due to shipping loads
- Support 100’s of low speed (<8,000 rpm) power off shutdown coast downs, and
- Survive up to 3 full speed coast downs

Prior testing as reported by McMullen [1] have validated baseline performance. While still adequate in meeting these criteria, effort has been conducted to improve TDB performance to increase this capability for UPS applications and to validate performance of the system in Crane applications. Incremental improvements in the TDB configuration have been made to facilitate improved performance.

2. Operating Requirements

In UPS applications the TDB system would typically only see loads during shipment and normal shutdown. Normal shutdown of this system would result in a low speed drop on the backup bearings at 6,000 rpm - 8,000 rpm, with the flywheel rotor coasting to zero speed over approximately ½ hour. This normal shutdown is very infrequent, and would only occur if there is a system maintenance or a severe problem in the overall power system of the UPS. The TDB system would also see operation at high speed during a fault condition in the AMB system. These would be very short duration, with the system motoring down the rotor to zero speed in 15 minutes. If there is ever a multiple system fault involving the AMB and power system an unassisted spin down from full speed can occur. This is the most difficult operating condition for the TDB's, taking 2½ to 3 hours to spin down from 36,000 rpm to zero speed.

In Crane applications the TDB system would typically only see loads during shipment and normal shutdown. Normal shutdown consists of a low speed drop on the TDB at 2,000 rpm - 4,000 rpm and the flywheel rotor coasting to zero speed over approximately 5-10 minutes. This normal shutdown is frequent, as this system is dependent on crane operation for power. The cranes can be cycled on/off one or more times a day, each time resulting in a system shutdown. The TDB can also see intermittent duty due to magnetic bearing overload. The crane system is mounted on a RTG, shown in Figure 5, that can experience impact loads due to holes in the road, container drops, or even trucks striking the crane. These impact loads are typically very short (less than 2 seconds) and have no significant impact on bearing life.

Figure 5. Vycon REGEN Installed on RTG

The TDB system can also see operation at high speed during a fault condition in the flywheel system. This speed can vary within the normal operating speed range of the flywheel, 10,000 rpm to 18,000 rpm. As in the UPS, most of these are short as the system would motor down the rotor to zero speed in less than 5 minutes. If there is ever a multiple system fault involving the AMB and power system an unassisted spin down from full speed can occur. This is the most difficult condition for the TDB's to operate as it requires extended time at high speeds, taking 1 to 1½ hours to spin down to zero speed.

Failed test bearings used for extended life testing have shown brinelling of the inner races, as seen in Figure 6. These have been diagnosed by bearing manufacturers as having seen excessive thrust loads. It is unclear how such loads can occur since the thrust load on the bottom bearing is fixed by the weight of the rotor with no external events or forces placed on the system. It is believed that the bearings are in fact growing thermally, but being constrained radially and axially due to housing components. Once these constraints are reached, the bearing preload increases and causes thermal runaway. In failed TDB cases the preload rises to overload and brinells the races and seizes. This is captured at the time of failure by the AMB detecting excessive rotor displacement on the TDB and re-levitating.

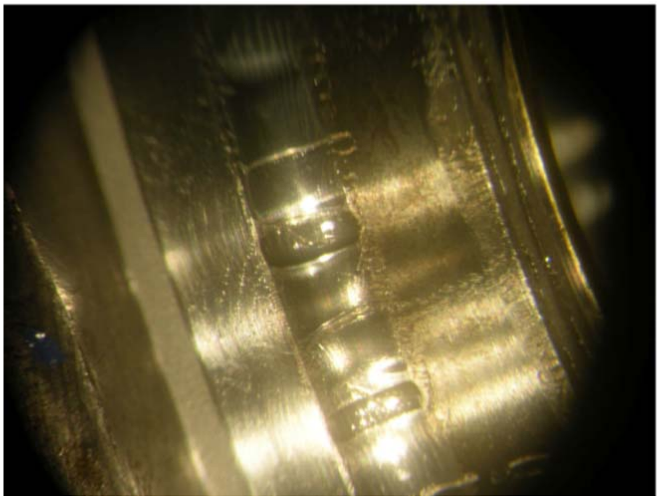

Figure 6. Failed TDB showing Inner Race Brinell Marks

To improve bearing life, incremental changes in the TDB have been made:

1) Axial compliance was added to the axial TDB assembly to reduce impact loads during rotor drop and to limit the growth in preload with temperature.
2) The surface finish of the TDB rotor targets was improved to a Ra of 32 microinches to reduce friction heating during initial race spin-up.
3) Tolerance changes to the rotor target and housing resulted in tighter control of operating clearances in the TDB.
4) Build control and quality was also improved through rigorous inspection on TDB associated components to ensure they meet design requirements.
5) Grease distribution and run-in procedures have been improved.

3. Test Results

3.1 TDB Operating Temperature

Temperature measurements of successful TDB production testing taken at the outer race of the TDB are presented in Figure 7. The TDB maximum temperature rise during the 18,000 rpm coast down test is 44C, while only 27C maximum temperature rise was recorded during the full speed motor down test. Typical acceptance testing is accomplished in one day, but due to the extra time in monitoring and recording, a second day of testing was required. First day testing included the 5krpm, 12krpm, and 18krpm, identified as "first time" data. The second day include the 5krpm and 36krpm unassisted, identified as "second time" data. Figure 8 focuses on comparing the results of the 5,000 rpm coast down data. As seen, on the second coast down the temperature rise is significantly less than on the initial coast down. This is most likely the result of the TDB grease being channeled or distributed as a result of the high speed runs, thus reducing heating during subsequent operation. Additionally, the initial runs serve to smooth minor asperities in the race surfaces remain from the manufacturing process.

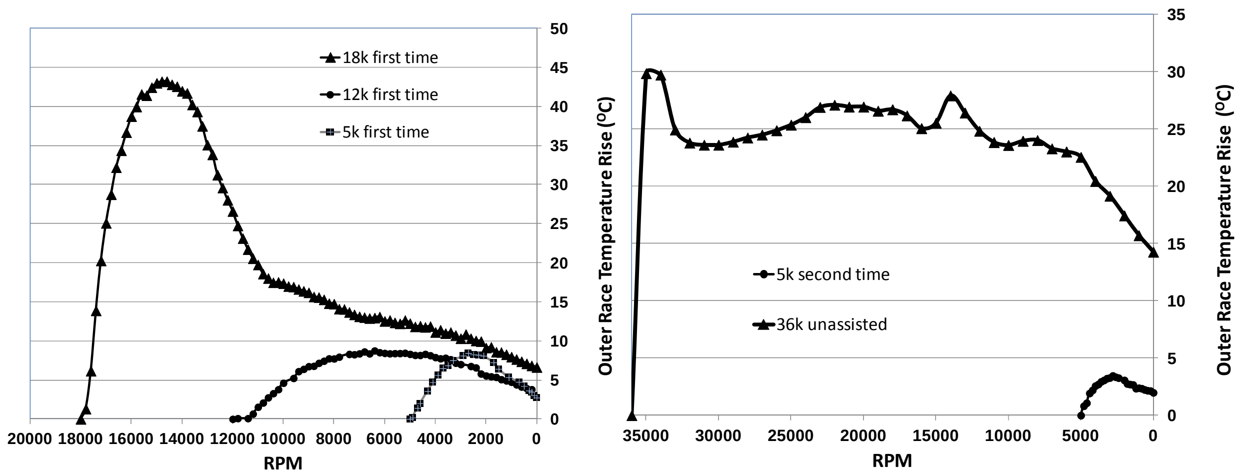

Figure 7. TDB Outer Race Temperature Rise during Production Testing

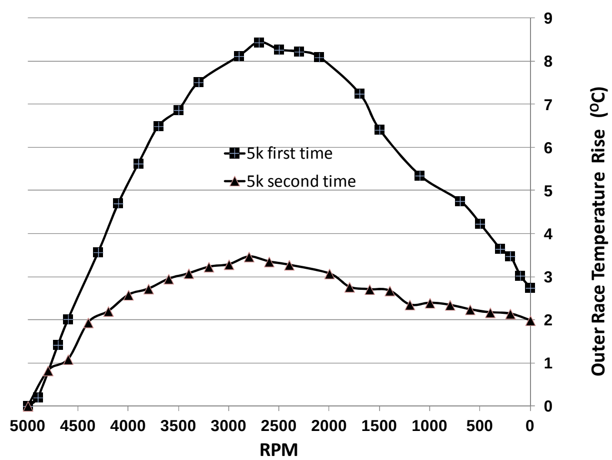

Figure 8. TDB Outer Race Temperature for 5,000 rpm Coast Downs

Temperature data indicates the bearing operating temperature does not rise more than 45C above starting temperature during testing, and confirms the bearing is not overheating, at least during acceptance testing. Further temperature testing is underway during un-assisted coast down operation.

3.2 REGEN System Extended Backup Bearing Test Results

With a baseline RTG power cycling once a day, 5 days a week, 50 weeks a year, 500 low speed coast downs would be the equivalent of two years of operation. Following low speed coast downs a set of high speed coast downs are used to simulate multiple AMB faults. These high speed coast downs, after performing the low speed coast downs, were used to validate bearing fault performance after 2 years of normal operation. Twenty drops from 10,000 rpm and 10 drops from 15,000 rpm were performed in this part of the testing. In an actual REGEN following a multiple point failure, the system will not restart until it is reset by service, thus preventing these multiple drop events from occurring as tested.

Testing was conducted on an in house fully assembled REGEN system, with flywheel mounted in a gimbal. Test data, presented in Table 2, from the AMB controller is the result of an automatic calibration routine, converted to inches of total displacement. Each axis moves the rotor within the backup bearing clearance and measures position.

	X1 Disp	Y1 Disp	X2 Disp	Y2 Disp	Z Disp
Baseline	0.0130	0.0130	0.0130	0.0130	0.0125
After 500 2krpm drops	0.0156	0.0132	0.0127	0.0138	0.0131
After 20 10krpm drops	0.0159	0.0136	0.0132	0.0136	0.0159
After 10 15krpm drops	0.0146	0.0127	0.0117	0.0122	0.0179
Percent Change First-Last	12%	-2%	-10%	-7%	44%

Table 2. REGEN Extended Testing Results

Test results show the total radial displacement at start and at the end of each test set. The variation is inconsistent with rotor sleeve wear. For example, the X1 total displacement increased 12% from baseline test to after ten 15krpm drops. Yet all other radial axes show an overall reduction in radial displacement. Inconsistencies in measurements during each test are also present, leading us to conclude the calibration of the total displacement is subject to other factors not considered. One of these may be the temperature of the TDB's, which was not recorded during testing. The test was automated, and calibration timing was not controlled. It appears calibration displacement grew consistently from baseline following the first two set of tests, possibly contributed to by bearing temperature. It is not clear when the final measurement of calibration was taken, but it is significantly different than prior measurements. We have assumed this final test was done at the same temperature as the baseline, which would indicate radial axes are not showing wear, while the axial target is showing wear.

The axial displacement growth of 0.0054 inches has taken place on the axial TDB surface of the rotor. While the TDB system is able to meet the requirements of the testing, the rotor TDB surface is showing wear that over extended testing may result in the rotor exceeding its available clearance. Further refinements in the test process and support system to enhance performance and life are planned.

3.3 UPS System Backup Bearing Test Results

UPS backup bearing testing focused on multiple failures resulting in an unassisted drop and coast down of the rotor on the TDB's. Unlike the crane, low speed drops onto the TDB's should be infrequent. For the test system, since drop testing takes 2½ - 3 hours a test, only 2 drop runs can be conducted in a day. Each of these was preceded with a drop from 5,000 rpm to ensure the system was warm, as it would be in operation. Table 3 presents the data from coast down testing conducted on the system for 8 successful full speed unassisted drops on the TDB's. On the 9th coast down the TDB's were not able to maintain a consistent orbit and were relatively loud, resulting in the operator stopping the test. Subsequent disassembly showed the bearings were near failure.

		February 3, 2012				February 6, 2012	
	Base	5k RPM	12k RPM	18k RPM	36k RPM	36k RPM	36k RPM
Drop Number					1	2	3
Start Time	-	7:17 AM	8:33 AM	10:15 AM	12:46 PM	8:18 AM	12:02 PM
Vacuum	**-**	**33.2**	**33.5**	**35.6**	**42.6**	**25.0**	**27.1**
Housing Temp	-	22	22	21	25	25	28
End Time	-	7:38 AM	9:23 AM	11:10 AM	2:59 PM	10:46 AM	2:29 PM
Vacuum	**-**	**33.7**	**34.7**	**39.1**	**41.8**	**26.2**	**26.5**
Housing Temp	-	23	24	26	29	29	30
Z Up Position	6.12	6.13	6.08	6.03	5.88	6.00	6.02
Z Down Position	**-6.20**	**-6.29**	**-6.44**	**-6.80**	**-7.70**	**-7.54**	**-7.88**
Total Position Travel	12.32	12.42	12.52	12.83	13.58	13.54	13.90

		February 7, 2012		February 8, 2012		February 9, 2012	
	Base	36k RPM	36k RPM	36k RPM	36k RPM	36k RPM	36k RPM
Drop Number		4	5	6	7	8	9
Start Time	-	8:22 AM	11:57 AM	8:28 AM	11:42 AM	8:38 AM	12:00 PM
Vacuum	**-**	**22.8**	**24.2**	**21.0**	**24.7**	**20.4**	**22.4**
Housing Temp	-	25	27	23	26	23	27
End Time	-	10:52 AM	2:25 PM	10:55 AM	2:11 PM	10:46 AM	**Test Failed; EPO due to overly large orbit and excessive noise from bearings**
Vacuum	**-**	**23.6**	**24.0**	**22.2**	**23.1**	**22.6**	
Housing Temp	-	28	29	26	29	28	
Z Up Position	6.12	5.93	5.94	5.82	5.84	5.56	
Z Down Position	**-6.20**	**-7.69**	**-8.22**	**-8.06**	**-8.26**	**-8.03**	
Total Position Travel	12.32	13.62	14.16	13.88	14.10	13.59	

Table 3. UPS Drop Test Results

As in the REGEN testing, rotor axial touchdown surface wear is confirmed from calibration information on the bearings taken at the start of testing and following each test after a one hour wait period. As seen, axial wear from the testing is very small for the runs being conducted, indicating the wear on the rotor is not a root cause for TDB failure. Failures in prior testing have been seen on the TDB's supporting both radial and axial loads of the rotor during spin down. These have been found to be seizing with the axial rotor touchdown surface showing excessive wear as a result.

4. Conclusions:

Results indicate the TDB system is capable of surviving a large number of long duration high speed coast downs in both UPS and crane systems. Axial rotor target wear does occur and results in added axial rotor travel, a possible long term issue for the AMB system if multiple high speed coast downs occur. The wear found during this testing does not appear to affect the bearing performance. While performance in both applications is adequate, there remains room for improvement in the TDB system for extending operational life. Further improvements to the bearings, mounting, and rotor surface, in addition to additional testing, are planned to increase TDB operational life.

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